Australian Building Codes Board

Sanitary Plumbing and Drainage Pipe Sizing

Sanitary Plumbing and Drainage Pipe Sizing Report

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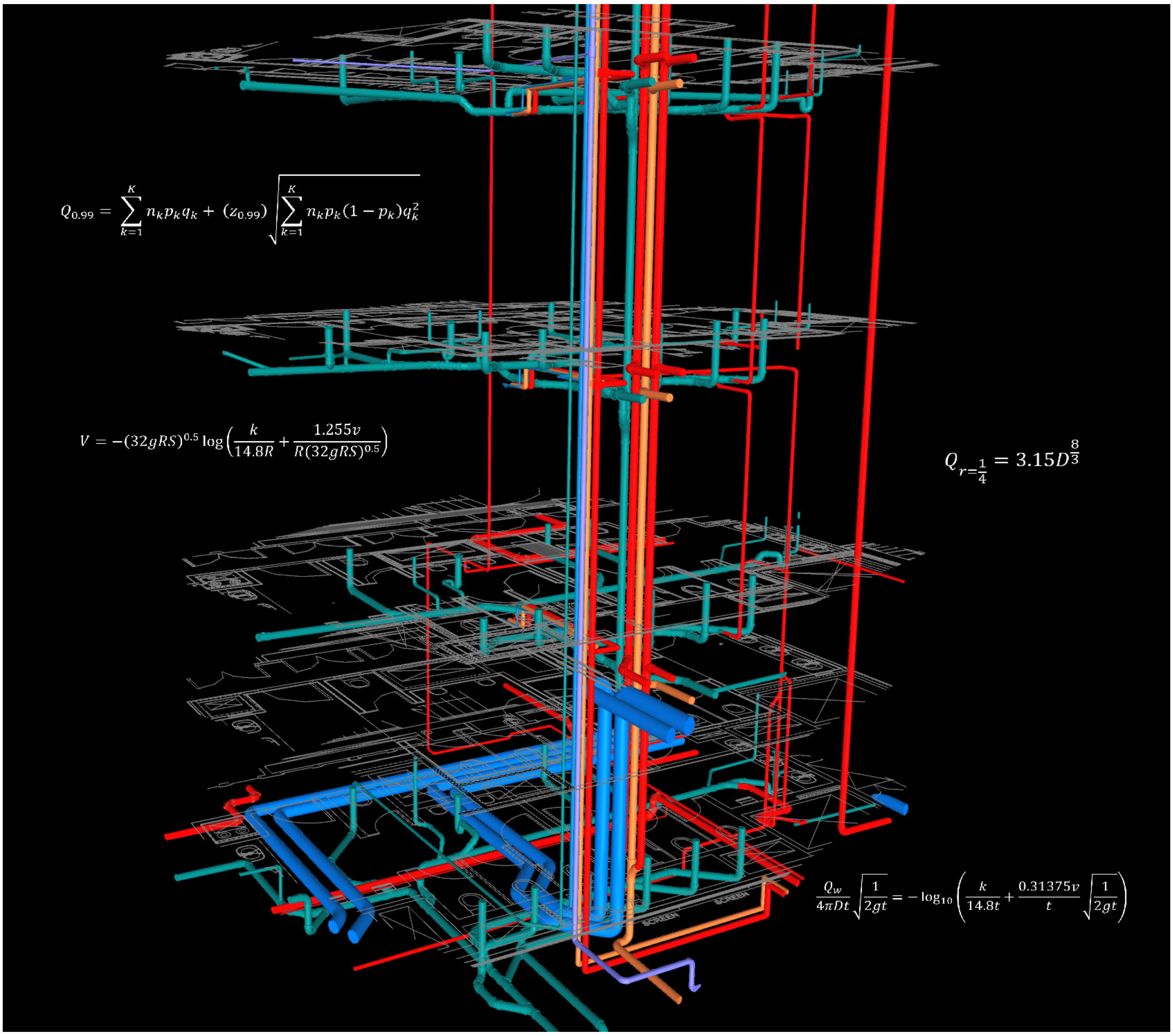

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Executive Summary

This report considers the current methods for sizing sanitary plumbing and drainage systems used within Australia, taking into account industry trends and recent observations to determine whether the current design methods are appropriate for plumbing and hydraulic designers going forward or whether there is an opportunity to improve these methods. The goal of this report is to draw on the work done within the industry to date and plan for the next steps to provide an accurate sizing methodology which has a clear scientific backing and can be modified to suit different building types, fixtures and configurations so it can be adopted more broadly as our industry continues to develop, starting with its inclusion in the National Construction Code Volume Three, Plumbing Code of Australia due to be released in 2025.

A broad technical review of recent work as part of this larger Sanitary Drainage and Pipe Sizing project commissioned by the Australian Building Codes Board including work by Lucid and GHD as well as recent and dated studies available from the wider plumbing research industry has been undertaken. As part of this project, we have drawn on the expertise from Heriot-Watt University's (HWU) drainage research team led by Lynne Jack, whose work is referenced within this report.

There are some common industry concerns which have developed over recent decades in conjunction with technical advancements in sanitary ware, fixtures and appliances, largely driven by an environmental desire to reduce water consumption, is perceived to have resulted in 'over-sizing' of drainage systems and an inherent risk of solid stranding resulting in blockage issues. This report therefore considers the impact of these reductions and whether as a result, there is an opportunity to rationalise the way building services engineers design and size systems. This could result in the opportunity to rationalise sizing outcomes to potentially allow a reduction in material usage and, the positive impact that will have on the environment as a whole, whether it be through saving space within a building or reducing the actual material that is manufactured, transported, installed and ultimately disposed of or recycled.

It is widely accepted in the Hydraulic Industry within Australia that there are limitations within AS/NZS 3500.2 Sanitary Plumbing and Drainage where a common Fixture Unit (FU) is applied for each fixture across all type of buildings without further consideration of usage probability or a rationalisation factor applied outside the FU itself. Whilst the origins of this FU method can be traced and their use has been tried and tested in Australia for decades, the scientific and mathematical formulas resulting in its derivation are unclear thus, we are unable to suggest a method to adjust this approach for a more accurate outcome reflecting modern day fixture use.

With increased uptake in performance based plumbing designs in recent times, designers look to other reputable global design standards where a building type or installation may not fall within the limits of AS/NZS 3500.2. BS EN 12056.2 Gravity Drainage Systems Inside Buildings which is adopted by the Institute of Plumbing (IOP) Plumbing Engineering Services Design Guide, provides a fixture discharge rate for each common fixture type with a probability usage factor developed by considering time between use and time of operation applied to the square root of the total calculated flow rate. This allows final flow rates to be adjusted to suit different building use, resulting in a more accurate and considered method for sizing the sanitary plumbing and drainage system. Whilst this approach certainly has its merits and has been tried and tested over a number of years, it has its limitations, particularly around sizing of vent pipework and sanitary plumbing in high rise buildings, and importantly the lack of opportunity to refine the discharge rate or probability usage factor given the scientific backing behind its development is unclear from our research.

With its limitations in mind, it still appears that the BS / IOP method offers a more robust and accurate sizing approach which could be applied at the designer's discretion to calculate system flow rates and pipe sizes in an otherwise AS/NZS 3500.2 compliant system. Using this approach requires consideration around which stack clearance requirements, junction configuration limitations and venting arrangements should be adopted.

The recent introduction of Wistort's method and the Modified Wistort's method used for water supply which is currently being reviewed by university research groups globally appears to provide a more accurate pathway going forward. The ability to adjust key input parameters such as flow rate, time between use and probability of simultaneous use makes it a method worth further investigation. We acknowledge its limitations for smaller buildings, with the Modified Wistort's Method requiring a minimum of approximately

63 fixtures for residential buildings. However, we think this aligns with an approach of a performance-based method for larger more complex buildings using the Plumbing Code of Australia verification method pathway, where the limitations of the AS/NZS 3500.2 fixture unit method restrict the designer to inaccurate outcomes which can negatively affect the performance of the system. As part of this report, we have tried to manipulate the Modified Wistort's method into a more simplified mathematical equation with the aim to create a more user-friendly formula for easy adoption amongst the industry. Whilst this effort was unsuccessful, we do believe there is scope to improve the method in this way.

We understand there has been little work to date applying Wistort's or the Modified Wistort's method to sanitary plumbing and drainage pipe sizing however we believe that its application can be justified should it prove to be accurate for water pipe sizing, and accurate assumptions can be made for drainage. This would be achieved by applying updated inputs which reflect developments in soil and wastewater fixtures, an understanding of human behaviour through data collection and observations, and the influence of both of these factors on water supply and plumbing fixture use within buildings.

Accurately assessing probability in water and plumbing use is a complex task. Common existing methods adopted in Australian Standards, British Standards and the Institute of Plumbing Design Guide have been tried and tested over many decades and have generally proved to work however, we do not believe these have been pushed to their limits. As fixture flow rates are reduced and human behaviour within buildings changes, they are likely to become increasing over conservative. Using developing digital technologies can help bridge this knowledge gap and this data is becoming increasingly available in the plumbing industry.

Flow velocities within sanitary plumbing and drainage is often considered to be a key requirement to maintain a free-flowing drainage network on the basis that it will remove sediment and solids within the network. However, we think maximum solid transport distances should also be considered as solids in sanitary plumbing systems account for the majority of blockage concerns. When designers are applying an alternative approach or even validating and existing method, this should certainly be a consideration.

Plumbing research conducted on this topic is wide and varied coming from all regions of the globe **-** some of it is conclusive, much of it is conflicting. What we do know is drainage systems relying on gravity and airflow to achieve successful operation are dynamic and unpredictable, and in many cases this behaviour cannot be reduced to mathematical equations. Thus, finding a so-called optimal design point between over sizing or under sizing or even optimising a system's performance is very complex without simulation or physical testing. This report focuses on the information relevant to improving drainage sizing methods and the impacts this might have on hydraulic performance and transient airflows. The report also tests conflicting information to formulate an opinion with the aim of limiting risk and increasing confidence in adopting an alternative method for pipe sizing.

With a view to adopting a more robust performance based method for sizing sanitary plumbing and drainage in the 2025 Plumbing Code of Australia, based on our research, we conclude that adopting a modified method of the British Standards 12056.2, International Plumbing Code Design and adopting the Colebrook White equation for horizontal drainage using filling capacity and velocity as limiting factors, is a sensible benchmark to be used at the hydraulic designer / engineer's discretion where a design falls outside the limitations of AS/NZS 3500.2.

Although adopting a new way of sizing carries risks, particularly in its early phases, we hope this report outlines some key considerations for further analysis of these methods. As with existing methods, the designer should consider transient airflow, filling capacity limits, self-cleansing velocities and solid transport travel distances, and how these might affect the system when applying this approach. As an alternative and more accurate method for future sizing approaches we believe that a modified Wistort's method has a lot of potential and acknowledge this might not be able to be achieved through testing and further analysis in the short term.

Key Findings and Recommendations

A summary of all the key findings and recommendations within this report is provided below. For ease of future reference, all key findings are provided with the prefix 'KF'- and recommendations are provided with the prefix 'R'-. All items are also separated into their respective categories that they appear in within the report. A more detailed breakdown and explanation of the following items can be found in Sections 4.6, 5.7 and 6.7.

KF - 1: Key findings relating to discharge and fixture units and the proposed sanitary discharge estimation method.

KF - 1.1: The derivation of the DU and respective K-Factors from *BS EN 12056-2:2000* (B.S. Institute, 2000) is unknown.

KF - 1.2: K-Factors can be expanded under specific assumptions.

KF - 1.3: The origin of the FU is well documented, however its into Australian Standards is unknown.

KF - 1.4: New, statistical based methods such as the Modified Wistort's Method have been tested for calculations involving peak potable water demand.

KF - 1.5: Our analysis in Appendix A.1 has determined that the Modified Wistort's method is a viable means of determining peak discharge flow rate, provided that accurate discharge fixture flow rates and probability of use (discharge) values can be obtained.

KF - 1.6: Attempts to derive a simplified estimation expression similar to the DU expression based on the Wistort's Method has been unsuccessful.

KF - 2: Key findings relating to sanitary drainage design and the proposed sanitary drainage calculation method.

KF - 2.7: The relationship between pipe flow rate and filling capacity can be expressed as follows:

$$Q = -4A\sqrt{2gmS_0}\log_{10}\left(\frac{k}{14.8m} + \frac{0.315\nu}{m\sqrt{2gmS_0}}\right)$$

KF - 2.8: The Colebrook-White expression stated in KF – 2.1 is already present in *AS 2200-2006* (Standards Australia, 2006) and offers a large degree of flexibility should any design constraints vary in the long term, yet it is also relatively easy to use with the presence of design charts.

KF - 2.9: Drainage charts by Butler and Pinkerton (Butler & Pinkerton, 1987) and *AS 2200-2006* (Standards Australia, 2006) are equally viable to facilitate sanitary drainage design.

KF - 2.10: The research conducted and supplemented with the discussion with Heriot-Watt University supports the implementation of the *BS EN 12056.2:2000* (B.S. Institute, 2000) method of sanitary drainage design into the *NCC 2025 Volume 3 - PCA*, albeit with additional clarifications and adaptations to better suit the Australian Standards.

KF - 3: Key findings relating to sanitary plumbing design and the complexities of vertical drainage.

KF - 3.11: The research conducted, and supplemented with the discussion with Heriot-Watt University, supports the implementation of the *BS EN 12056.2:2000* (B.S. Institute, 2000) branch, stack and vent sizing method into the *NCC 2025 Plumbing Code of Australia* within some limitations.

KF - 3.12: The theoretical backing of the branch sizing method provided by *BS EN 12056.2:2000* (B.S. Institute, 2000) cannot be determined and our analysis rules out the possibility of sizing guidelines based on the Colebrook-White expression listed in KF – 2.1.

KF - 3.13: A mathematical expression for branch pipe flow in sanitary plumbing systems could not be found.

KF - 3.14: Guidance on pipe filling capacities, velocity restrictions and pipe gradients for sanitary plumbing systems are absent in *BS EN 12056-2:2000* (B.S. Institute, 2000) and *AS/NZS 3500.2:2021* (Standards Australia, 2021).

KF - 3.15: Current codes typically size stacks assuming steady state annular flows occupying a certain percentage of the cross-sectional area of the stack (Lansing, 2020) which dates back to Hunter's work in 1923 (U.S. Department of Commerce, 1923).

KF - 3.16: The now superseded *BS 5572* (B.S. Institute, 1994) was noted to size stack flow rates based on the following formula and assumed they operated at 25% fill capacity, however, it is unknown whether a similar equation was within *BS EN 12056-2:2000* (B.S. Institute, 2000):

$$Q_{r=\frac{1}{4}} = 3.15D^{\frac{8}{3}}$$

KF - 3.17: The now superseded *BS 5572:1994* (B.S. Institute, 1994) which limited stack suction pressures to $\pm 375N/m^2$ was supported by (Swaffield, 2010) and was considered to be a more refined approach.

KF - 3.18: Experimental testing and simulations show that in addition to flow volume, the airflow depends on various other factors such as the length of the stack, the number and location of discharge entry points along the stack, and the number and type of fixtures connected to the system.

R - 1: Recommendations for discharge and fixture units and the proposed sanitary discharge estimation method.

R - 1.1: Existing DU should not be directly updated with more modern fixture discharge flowrates given the unknowns of its origins.

R - 1.2: Further testing and application of collected usage data (refer to Section 4.5.1 and 4.5.2) should be conducted to realise the potential for the Modified Wistort's Method to be adapted for use in peak sanitary drainage estimation.

R - 1.3: In the short term, the *BS EN 12056-2:2000* (B.S. Institute, 2000) DU and K-Factor approach should be adopted as a viable Verification Method for the *NCC Plumbing Code of Australia 2025* revision.

R - 1.4: Further testing using multiple different building types within the NCC to obtain a greater understanding of the differences between a BS Verification Method system design and a AS system design.

R - 2: Recommendations for sanitary drainage design and the proposed sanitary drainage calculation method.

R - 2.1: Adopt the Colebrook-White equation present in *AS 2200-2006* (Standards Australia, 2006), shown in KF – 2.1, into the *NCC 2025 Volume Three – Plumbing Code of Australia* (Australian Building Codes Board, 2022) as a Verification Method for sizing drainage capacities of sewerage pipework.

R - 2.2: A filling capacity between 50% and 70% should be used.

R - 2.3: A minimum velocity of 0.7m/s should be achieved at least once per day during the daily peak design flow.

R - 2.4: The sanitary drainage system should not exceed a velocity of 2.0m/s during daily peak design flow.

R - 2.5: Minimum and maximum pipe grades should be designed such that the minimum and maximum velocities specified in R – 2.3 and R – 2.4 are not exceeded.

R - 2.6: A pipe roughness value of 1.5mm should be the default design value for sanitary systems.

R - 2.7: The kinematic viscosity of water at 20°C ($v = 1.01 \times 10^{-6}$) should the default design value.

R - 2.8: Further research and reviews should be conducted to minimise any unforeseen consequences with adopting the *BS EN 12056.2:2000* (B.S Institute, 2000) method for sizing sanitary drains to the Australian Plumbing Industry. Suggestions are documented in Appendix A.9.2.

R - 3: Recommendations for sanitary plumbing design and the complexities of vertical drainage.

R - 3.1: An in-depth comparative assessment between *BS EN 12056.2:2000* (B.S. Institute, 2000) and *AS3500.2:2021* (Standards Australia, 2021) should be conducted to better understand the implications of adopting this method for the Australian Plumbing Industry and determine whether there are design guidance items provided in *AS3500.2:2021* (Standards Australia, 2021) that could be adopted by the *BS EN 12056.2:2000* (B.S. Institute, 2000). Items for consideration have been provided in Section 6.7.

R - 3.2: The *BS EN 12056.2:2000* (B.S. Institute, 2000) method for stack and vent sizing should be refined with guidelines to ensure that under sizing systems is mitigated as a first priority over any attempts to optimise the standard to avoid oversizing drainage systems.

R - 3.3: Guidance developed from further academic and experimental research should be provided on stack height and appropriate system configuration for tall buildings if *BS EN 12056.2:2000* (B.S. Institute, 2000) is to be adopted

For the *Draft NCC 2022 Volume Three – Plumbing Code of Australia*, our recommended changes are in green as follows:

- C1V1 Clause 2 – Fix formula:

$$Q_{Total} = K\sqrt{\sum DU} + Q_{Other}$$

- Table C1V1a – Expanded frequency factors as shown below in Table 1:

Table 1: Expanded frequency factor table for Draft NCC 2022 Volume 3 Table C1V1a

Fixture Usage Profile	NCC Building Classes	Frequency Factor (K)	Time Between Fixture Use (s)
Intermittent use: e.g., dwelling, guesthouse, apartment buildings or offices	1, 2, ~~3, or~~ 4, or 5	0.4 – 0.6	1900 – 800
Frequent use: e.g., medium use public facilities for hospital, school, restaurant, retail, or hotel	3, ~~5,~~ 6, 7, 8, 9a, or 9c	0.6 – 0.8	800 – 450
Congested use: e.g., high use public facilities for events with concentrated fixture use	9b	0.8 – 1.2	450 – 200
~~Special use: e.g., laboratory~~	~~Not applicable~~	~~1.2~~	

- C1V1a Explanatory Information – Addition of explanatory text below:

  When using these frequency factor figures, the designer should use their own judgement to consider the appropriate factor for the design based on estimated time between fixture use.

- Table C1V1b – DU expansion and omittance of System 3 (full bore flow design) shown below in Table 2:

Table 2: Expanded and modified DU table for Draft NCC 2022 Volume 3 Table C1V1b

Fixture ~~Usage~~	**System 1 DU (50% filling degree)**	**System 2 DU (70% filling degree)**	~~**System 3**~~
Basin	0.5	0.3	~~0.3~~
Bath (without shower)	0.8	0.6	
Bath (with shower)	0.8	0.5	
Bidet	0.5	0.3	
Dishwashing Machine (domestic)	0.8	0.6	~~0.2~~
Shower (single)	0.6	0.4	~~0.4~~
Sink (single and double)	0.8	0.6	~~1.3~~
Urinal (wall-hung)	0.8	0.5	~~0.4~~
Urinal (stall or each 600mm length of slab)	0.2	0.2	
Washing Machine up to 6 kg	0.8	0.6	~~0.6~~
Water Closet (4l cistern)	Not Permitted	1.8	
Water Closet (6l cistern)	2.0	1.8	~~1.2~~
Floor Waste Gully (80mm or 100mm)	Sum of DU from connected fixtures	Sum of DU from connected fixtures	

- C1V1b Explanatory Information – Adjustment as per green text below:

  System types referred to in Table C1V1b are as follows:

  - *System 1 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 50%.*
  - *System 2 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 70%.*
  - ~~*System 3 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 100%.*~~
  - *System 1 and 2 are similar to the fully vented modified system ~~and System 3 is similar to the single stack system detailed in AS/NZS 3500.2.~~*
  - *Filling degree is defined as the ratio between the height of the fluid in a pipe at design flow (h), and the internal diameter of the pipe (D), or h/D.*

- C1V4 System 3 Branch Design – To be removed in its entirety

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1. Introduction

Arup has been engaged by the Australian Building Codes Board (ABCB) to assist in further progressing previous work commissioned by the ABCB around the development or adoption of an industry accepted performance-based method for calculating sanitary drainage and plumbing pipe sizes within the future *National Construction Code, Volume 3 Plumbing Code of Australia 2025*. This report summarises Arup's work on Phase 1 of this project on behalf of the ABCB.

It is widely accepted in the Hydraulic and Plumbing Engineering Industry that the current methodology for calculating domestic water supply pipework and sanitary plumbing and drainage pipework under *PCA Volume 3* and *AS/NZS 3500* is outdated and does not reflect the real-world operating conditions of plumbing systems today.

The current calculation methods which are historically based on the Hunter Method use a common loading unit or fixture discharge unit for sizing domestic water services or sanitary plumbing respectively. Whilst this certainly has its merits, it is inaccurate to assume that a common unit could be applied to the same fixture which is in two distinct operating conditions. For example, a wash hand basin located in an office building would experience different usage frequencies than that of a wash hand basin located in a theatre or stadium.

This research project conducted by Arup and indeed previous work within the industry, assesses current Sanitary Plumbing and Drainage Pipe sizing methods with a view to optimise and enhance a common method for the industry to more accurately size plumbing and drainage pipework through a performance-based approach which respects the advancements in plumbing technology and building occupancy use.

This report intends to capture Arup's review of three prior independent pieces of work on this subject commissioned by the Australian Building Codes Board, being the *Fixture Unit Rating Systems Discussion Paper* by (GHD, 2015), *Sanitary Plumbing and Pipe Sizing* by (Lucid Consulting Australia, 2019) and *Sanitary Plumbing and Drainage Pipe Sizing Verification Methods* by (Lucid Consulting Australia, 2020), and our own review of further work and literature available within the industry which is relevant to the topic.

We hope the literature review with applied engineering principles will lead to the development of a proposed methodology to calculate sanitary plumbing and drainage system pipe sizes which is:

- Accurate, easy to use and adaptable
- Reduces uncertainties in design and has scientific backing behind values and formulas used in calculations
- Proposes an alternative method to the current deemed to satisfy approach which offers benefits to the designer through a rationalised or optimised outcome
- A method to allow a discharge or fixture unit to be adapted to allow for future development in fixtures and fittings

Finally, this report intends to capture current gaps in technology, knowledge or information which may limit the development of this work and to propose a plan for further research and investigation to ultimately achieve the end goal of a published performance-based method for adoption in the *National Construction Code, Volume 3 Plumbing Code of Australia 2025*.

1.1 Terms and Abbreviations

Term	Description
Australian Building Codes Board (ABCB)	The organisation responsible for preparing the National Construction Code and Plumbing Code of Australia, and the end client of this report.
Australian Standard (AS)	See reference list for Australian Standards referenced in this report
Australian / New Zealand Standard (AS/NZS)	See reference list for Australian / New Zealand Standards referenced in this report
Average flush volume	Average volume of water used in a flushing appliance calculated by taking one full flush discharge volume and four reduced flush discharge volumes
Arrestor	Apparatus designed to intercept and retain silt, sand, oil, grease, sludge or other substances that are prohibited to charge to the sewer or drainage system
Backflow	Flow in a direction contrary to the normal or intended direction of flow
Basin (WHB)	Fixture for holding water for ablutionary purposes
Bath (B)	Fixture for containing water in which the human body may be immersed for ablutionary or treatment purposes
British Standard (BS)	See reference list for British Standards referenced in this report
British / European Standard (BS/EN)	See reference list for British / European Standards referenced in this report
Capacity	Volume calculated of effective water level or wetted area of pipework
Channel	Open graded passage for the conveyance of liquids
Designer	The plumbing or hydraulic practitioner designing the sanitary plumbing and drainage system
Deemed to Satisfy (DTS)	Compliant with the prescriptive requirements of the referenced standard I.e., Plumbing Code of Australia, BS 12056.2 or AS/NZS 3500.2
Discharge capacity	Volume of water discharged from a fixture appliance
Drain	Pipework installed above or below ground including all fittings, intended to convey sewer, waste water or trade waste water under gravity conditions

Fitting	Item placed in a pipeline for jointing, connecting or changing the direction or internal diameter of the pipeline
Branch Drain	Section of drain the is intended to receive the discharge of fixture discharge pipe which has a lower fixture unit loading and which may be of a smaller nominal size than the main drainage at its point of connection,
Main Drain	Main conduit of a drainage system to which branches are connected
Frequency factor	Coefficient based on probability of fixture use applied to calculated drainage flow rate to adjust final sum to consider likelihood of probable use
Fully vented system	Sanitary plumbing system with provision for separate ventilation of every fixture trap connected other than trap of each floor waste gully
Fully vented modified system	Sanitary plumbing system where traps of any group of two or more fixtures of floor waste gully discharging to the same branch pipe are vented in a common by one or more group vents
Discharge Unit (DU)	Typically used in British Standard BS EN 12056.2 - Unit of measure based on the rate of discharge, timer of operation and frequency of use of a fixture that express the hydraulic load imposed by that fixture on the sanitary plumbing installation
Loading Unit (LU)	Typically used in Australian Standards AS/NZS3500 - Weighted factor applied to a fixture or appliance, used for the estimation of simultaneous water usage rates
Fixture Unit (FU)	Typically used in Australian Standards AS3500 - Unit of measure based on the rate of discharge, timer of operation and frequency of use of a fixture that express the hydraulic load imposed by that fixture on the sanitary plumbing installation
Sanitary drainage system	Horizontal in-ground or elevated drainage which is not an offset part of a sanitary plumbing system.
Sanitary plumbing system	A network of vertical pipes using the stack principals of either single stack, single stack modified, fully vented or fully vented modified, including any horizontal offsets as part of the stack.
Sink (SK)	Waste water fixture containing one or more bowls to temporarily retain water for cleaning purposes and for receiving domestic, culinary, laboratory or industrial waste water
Water Closet (WC)	Sanitary fixture consisting of water closet cistern and water closet pan.
Water closest cistern	Flushing cistern to be installed with a water closet pan which incorporate and control valve to control

	water level and a flushing valve to discharge water into the water closet pan
Water closet pan	Accepting bowl to be installed with a water closet cistern or flush valve which incorporate a trap seal for accepting discharge from water closet cistern
Water seal depth	Vertical distance measured between the dip and crown weir of a trap
Waste water	Waste water discharged from waste water fixtures
Waste water fixture	Sanitary appliance for acceptance of waste water typically shower, wash hand basin, kitchen sink, laundry sink
Soil water	Soiled waste water discharged from water closet or urinal
Soil fixture	Sanitary fixture for use in soil applications typically water closet or urinal
Stack	Vertical pipe included offset that extends through more than one floor level using
Vent / Vent pipe	Pipe used for carrying air within sanitary plumbing and drainage systems
Verification Method	Performance based compliance pathway under the Plumbing Code of Australia

1.2 Symbols

Symbols	Definitions
°	degree(s)
°C	degree(s) Celsius
µm	micrometre
kg	kilogram(s)
kg/m	kilogram(s) per metre
Km	Kilometre(s)
kPa	Kilopascal(s)
L	Litre(s)
L/min	Litre(s) per minute
L/sec	Litre(s) per second
M	Metre(s)
m/s2	Metre(s) per second
m2	Square metre(s)
min	Minute(s)

mm	Millimetre(s)
Pa	Pascal(s)
Pa/m	Pascal(s) per metre
Q	Flow volume
%	Percentage
>	Greater than
<	Less than
≤	Less than or equal to
≥	Equal to or more than

Further symbols used within specific calculations are referenced as part of a calculation explanation throughout the body of this report.

1.3 Project Stakeholders

1.3.1 ABCB Team

The Australian Building Codes Board Team who lead the collaboration of this research project is as follows.

Role	Name	Phone	Email
Project Manager	Neil Rech	02 6243 7980	neil.rech@abcb.gov.au
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1.3.2 Arup Research Team

The research conducted by Arup as part of this project was led by the following members of the Arup Public Health, Hydraulic and Plumbing team.

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2. Scope and Limitations

2.1 History of ABCB research

Previous research commissioned by the Australian Building Codes Board as part of the Sanitary Plumbing and Drainage Pipe Sizing project is summarised in the following reports:

- Fixture Unit Rating Systems – Discussion Paper (GHD, 2015)
- Sanitary Plumbing and Drainage Pipe Sizing – British and European Standards Review (Lucid Consulting Australia, 2019)
- Sanitary Plumbing and Drainage Pipe Sizing Verification Methods (Lucid Consulting Australia, 2020)
- Draft National Construction Code Volume 3 – Plumbing Code of Australia 2022 (Australian Building Codes Board, 2022)

We have reviewed these reports, our opinion and commentary on their findings can be found in Section 3 Literature Review.

2.2 Scope of this paper

2.2.1 Objectives

The ultimate objective of the Sanitary Plumbing and Drainage Pipe Sizing project as set out by the Australian Building Codes Board is to update the *National Construction Code, Volume Three, the Plumbing Code of Australia*.

To help achieve this goal this current phase consists of two primary stages each defined by the Australian Building Codes Board with a set of key objectives outlined below.

2.2.2 Stage 1

1. Review of the previous work conducted by the ABCB for sanitary drainage pipe sizing (see above).
2. Review and replace the discharge units with the appropriate flow rates (L/s) from each plumbing fixture based on the information provided by the ABCB upon engagement.
3. Note: It is assumed that the difference between the discharge units and the observed flow rates is a result of changes in fixture use and efficiency since the inception of the discharge unit. There may also have been a safety factor built into the discharge unit resulting in an overestimation.
4. Review and update the frequency factors (the probability of fixture use) for all appropriate classes of buildings. This is a key feature of this pipe sizing methodology. Consideration should be given to the number of fixtures provided in correlation with the number of bedrooms where appropriate (such as multiunit residential buildings). Where possible, Verification Methods in Section C of NCC Volume Three 2022 – Preview (Australian Building Codes Board, 2022) should be expanded where the frequency of use data provides for an accurate estimation of the different use of fixtures in different building types. Data on frequency of fixture use may be available from the ABCB Office to assist in this investigation. Consideration should be given to the *Peak Water Demand Study* (Buchberger, et al., 2017).
5. Review the sizing methodology and calculations in the Verification Methods of Section C of NCC Volume Three 2022 – Preview (Australian Building Codes Board, 2022).
6. Consider the appropriateness of the filling capacities of different system types.

7. Consider the grades of pipes for each appropriate size as outlined in *AS/NZS 3500.2:2021* (Standards Australia, 2021), noting that the Verification Method utilised for pipe sizing should limit any changes to current installation practices where possible.

8. Produce staging plan to address the objectives of Phase 2.

2.2.3 Stage 2

1. Develop an overview of the appropriate hydraulic capacities of different sanitary pipe sizes that can be utilised. An outline of the appropriate hydraulic capacity for each pipe size is required to ensure that the pipe size selected is appropriate for the hydraulic capacity determined by the Verification Method.

2. Note: Hydraulic capacities of different pipe sizes, grades and materials are provided in Australian Standards such *as AS/NZS 3500.2:2021* (Standards Australia, 2021) and *AS 2200:2006* (Standards Australia, 2006).

3. Provide recommendations of any required safety factors which should be considered or investigated further to ensure that the risk of system failure is appropriately addressed.

4. Provide recommendations on ventilation requirements to ensure that use of the revised sanitary plumbing and drainage pipe sizing methodology does not create a hydraulic imbalance in the system.

5. Identify any consequential changes required to the design and installation practices to facilitate the use of this alternative pipe sizing methodology.

2.2.4 Outcomes

The research conducted by Arup as part of this report took place between June 2022 and August 2022. The above Stage 1 and Stage 2 objectives have evolved through the undertaking of this report, an expanded and modified set of Stage 2 objectives is outlined in the Stage 2 Plan within the appendix of this report.

2.2.5 Clarifications

This report is subject to the following disclaimers.

- As part of the research conducted to inform this report, we have sourced literature which was freely available on the subject matter at the time of writing. We do not claim to have reviewed all resources relevant to the subject matter.

- No physical installation, physical performance testing, mock ups or surveying has been completed by Arup as part of this report.

- Our research and analysis is largely based on available information and known mathematical equations. We have used excel based spreadsheets as part of our testing and comparison of different methods using the formulas outlined in this report. No complex computer simulations or modelling have been completed by Arup as part of this report.

- This report intends to review existing information and provide opinion on performance-based sizing methods for sanitary plumbing and drainage flow rates and pipe sizing only, and intends to inform scope for future testing, analysis and further development.

- This report is intended to be reviewed by the Australian Building Codes Board and Hydraulic Industry working group which includes other qualified and reputable hydraulic consultants, external industry experts and licensed plumbing contractors prior to incorporation into any future codes or standards as a performance-based design framework. We accept no responsibility for any outcomes as a result of using this method.

2.3 Disclaimers

This report is subject to the following disclaimers:

- This report contains work completed by Arup as part of Phase 1 of the Sanitary Plumbing and Drainage Pipe Sizing Project. All information contained within this report has been prepared by Arup in accordance with instructions from the Australian Building Codes Board and taking into account our client's particular instructions and requirements and addresses their priorities at the time. This report is not intended for, and Arup has no liability for, any third-party use or reliance on this report. Arup is not responsible for updating this report should any information, opinions and recommendation no longer be valid in the future.
- In preparing this Sanitary Plumbing and Drainage Pipe Sizing research report we are relying on information contained in reports supplied by GHD and Lucid Consulting Australia who have been appointed directly by the Australian Building Codes Board. We have relied in particular on the accuracy and completeness of those reports and accept no liability for any error or omission in those reports which has resulted in an error or omission within this report.
- Arup is not responsible for the accurateness of any 3rd party material, technical data or information referenced within this report including design standards, guidelines, research papers and testing data.
- The work undertaken by Arup in connection with preparing this report is subject to the terms of the agreement between Arup and the Australian Building Codes Board including scope limitations set out in this report.
- This report is designed to provide information in regard to the subject matter covered. The views expressed in this publication are those of the author(s). The publisher / editor / author does not accept any responsibility for the contents or any loss or damage which might occur as a result of following or using data or advice given in this report.
- The sizing methods and formulas recommended in this report are for guidance only. It is the responsibility of the engineer / designer applying these formulas to satisfy themselves of the accurateness and appropriateness of using these methods and formulas. Arup is not responsible for the use of these methods and formulas by others.

3. Literature Review

3.1 Review of Discussion Paper by GHD

The report produced by GHD published in 2015, *Fixture Unit Rating Systems Discussion Paper* (GHD, 2015), provided a comprehensive literature search to identify the origins of the Fixture Unit (FU) system within *AS/NZS 3500.2:2003 Amendment 3*, and provided expansive commentary on the most relevant research happening outside of Australia at time of writing (GHD, 2015). GHD also provided a list of potential future research items. This section includes commentary on any key items within the report and highlights any areas of concern.

During GHD's investigation into the background of the FU, they identified Hunter's definition of a FU from BMS 65 (Hunter, 1940) and proceeded to provide an in-depth breakdown into the derivation of Hunter's method. The report covered the probability principle behind Hunter's FU, his curves, and also provided an example to breakdown how the method works. There was however, no detailed explanation into how Hunter determined the number of operational fixtures that would not be exceeded 99% of the time.

Further into the report, GHD provided a broad historical chronology of the main Water Authorities around Australia and attempted to discover the origins of the FU within Australia. They were able to locate the first authority reference to a FU in NSW by the Metropolitan Water Sewerage and Drainage Board in 1966 however, the reference to fixture units for water supply systems in buildings could not be found, nor was any information regarding the adaptation of Hunter's FU within Australia. The first recognised technical text was reported to be in 1990 with the publication of the *AS 3500.1:1990*.

GHD later investigated the application of the FU method in countries outside of Australia and identified that South Africa has been looking into the application of fuzzy logic in their designs. The Monte Carlo method of computational modelling was also noted to be implemented in determining water demand within buildings however, the application of either of these methods have rarely been extended into sanitary drainage design.

GHD also reported on the issues with the existing DTS design method raised by the Australian plumbing industry based on their consultation with industry members and research into published literature. Whist we were unable to identify the industry members consulted, we generally agree with the problems and concerns raised. We would however like to add to the comment regarding the effects of more recent pipe materials with lower friction coefficients, that in our opinion, whilst true immediately after installation, the effect of biofilm will significantly affect the pipe roughness over time.

A summary of potential amendments which could be applied to the existing FU rating method within *AS/NZS 3500.2:2003 Amendment 3* was suggested by GHD however, of the seven suggested amendments, we believe that only one is reasonably viable. This involves reworking the minimum required pipe gradients to reflect the lower flow volumes experienced within plumbing networks and to ensure self-cleaning velocities can occur. Increasing the minimum gradients required would have a significant impact on new and existing designs when modification works occur and does not address the core issue of inaccurate pipe sizing. Sizing pipes accurately would provide a solid foundation to solve almost all the issues outlined in the report regarding the FU method. The suggested amendment of adjusting flush volumes to reflect contemporary values is unlikely to achieve this as the inherent problems with FU are still present. The more involved solution of overhauling the base unit suggested by GHD, but dismissed as having little benefit, may be the solution in our opinion. We believe that by completely changing the base unit, a new method for determining peak sanitary flows will inevitably be required. This new method may then allow the other potential amendments such as fixture use frequencies and probabilities to be resolved simultaneously.

A list of potential future research opportunities was also provided by GHD. We do not have any additional comments for these items however, we would like to highlight the suggestions of seeking real time records from different building types, and the use of simulation modelling programs to test different scenarios where appropriate. GHD also provided some comments regarding items that should be excluded from future research of which we generally agree with.

3.2 Review of British and European Standards Review by Lucid Consulting

The report, *ABCB Sanitary Plumbing & Drainage Pipe Sizing*, by Lucid Consulting Australia (Lucid) (Lucid Consulting Australia, 2019), provides a relatively thorough review of the main body of the European Standards, *BS EN 12056-2:2000* (B.S. Institute, 2000) and *BS EN 752:2017* (B.S. Institute, 2022). We generally agree with their findings however, we do have further commentary on their report which is detailed below.

One of our key concerns with the Lucid standards review report is their method of Fixture Unit (FU) conversion provided in Section 2.3. The report suggests that a FU to flowrate conversion can be obtained from *AS/NZS 3500.2:2021* (Standards Australia, 2021), however we could not determine where within the standard these values were obtained from. Table 6.3(B) of *AS/NZS 3500.2:2021* (Standards Australia, 2021) does provide a fixture unit rating to flow conversion for continuous flows however, this does not align with the statement by Lucid that a single fixture unit for a basin equates to an equivalent flowrate of 0.03 l/s. Literature by (Swaffield, 2010) titled *Transient Airflow in Building Drainage Systems* provides an equation for the conversion of continuous flowrates in the Australian Standards however, the values are in line with Table 6.3(B) as opposed to the values provided by Lucid (refer to Appendix A.4).

We agree with the observations made relating to the standards *BS EN 752:2017* (B.S. Institute, 2022) detailed within the report however, we would also like to highlight *BS EN 16933-2:2017* (B.S. Institute, 2018) referenced within. *BS EN 16933-2:2017* (B.S. Institute, 2018) was referenced as the method for the design of flows within foul drains and sewers, the hydraulic capacity of pipelines, and the self-cleaning conditions. Although the standard is designed for use in drainage design outside of buildings, it should also largely apply to the *AS/NZS 3500.2:2021* (Standards Australia, 2021) definition of "Sanitary Drainage." A modified Colebrook-White and Manning's formulae is recommended for hydraulic capacity and flows were assumed to be turbulent within drains and sewers. Further discussion on the modified Colebrook-White equation is available in Section 5.1.

Section 4.2.2 of this Lucid report compares, in principle and at high level, the system configurations of *BS EN 12056-2:2000* with systems configurations of *AS/NZS 3500.2:2021* (Standards Australia, 2021) however we believe that a more detailed technical and numerical comparison should have been conducted to adequately support their comparisons. For instance, we were unable to identify whether the National Annex of the *BS EN 12056-2:2000* was considered in their review. Although the National Annex is classified as an informative item within the standard, it provides crucial explanatory information and guidelines into System III designs used within the UK. The nuances to a System III design such as trap seal requirements or connection zones to a discharge stack are all provided within this Annex and thus, should have been thoroughly reviewed. It is noted however, that a brief commentary regarding National Annexes is provided within Lucid's subsequent report on verification methods.

From a calculation perspective, we disagree with their comparison method of DU and FU within Section 4.3.4 of their report. The report attempts to compare a converted FU with the unaltered DU, yet it is later mentioned that the DU cannot be used as a direct comparison to the discharge rate of sanitary appliances. In order for their comparison to be valid, their calculated DU must be applied to its respective wastewater flow rate equation which applies a usage constant to the square-root of the DU. i.e.:

$$Q_{Total} = K \times \sqrt{\sum DU} + Q_{Other}$$

A more realistic value for a system of 30 sinks, as stated in the report, within a congested use case (K = 1) such as a stadium would result in a flowrate value of 6.2 l/s which is similar to the 6.3 l/s calculated by Lucid for *AS/NZS 3500.2:2021* (Standards Australia, 2021). As mentioned above, we have uncertainties regarding Lucid's derivation of their FU flow rate conversion, thus, this comparison provided by Lucid should be adopted with caution. An alternative FU to DU flowrate comparison has been provided in Appendix A.1 for a residential tower and office building.

On the contrary, we support the comparison method and calculations used in Section 4.2.12 of their report whereby a System Type I configuration from *BS EN 12056-2:2000* (B.S. Institute, 2000) for both primary and secondary ventilated stack, was compared an equivalent *AS/NZS 3500.2:2021* (Standards Australia, 2021) design. The comparison concluded that both systems are quite similar in configuration. We did not have any concerns with their comparison, but we would like to propose that a comparison with sanitary designs with offsets included be conducted to assess its impact on the system. This will involve testing various configurations for different building types or stack systems.

An important observation by Lucid in their report, identified that Discharge Units (DU) in *BS EN 12056-2:2000* (B.S. Institute, 2000) are used for the purpose of calculation and are not related to discharge rates of sanitary fixtures within product standards. *BS EN 12056-2:2000* (B.S. Institute, 2000) confirms this in Section 6.2.2. The presence of a ‘l/s’ unit value for DU within *BS EN 12056-2:2000* (B.S. Institute, 2000) is thus somewhat misleading as it implies a relationship to discharge rates. This observation plays a vital role in our justification for the avoidance of using DU and for the development of a more accurate FU, DU, or alternative design approach in Chapter 4.

We noted that in Table 5 in Section 4.2.8 of the Lucid report, NCC Class 7 type buildings (carparks) were not associated with any of the usage factors. Understandably, if these were public fixtures or dedicated cleaner’s fixtures, the usage factor could vary significantly. Whilst the comparisons provided in the report for the remainder of the NCC building types appear to be accurate, we believe a more detailed breakdown for the various building classes should be performed, provided data is available to support this.

The report concludes with recommendations for further research and testing. Of the items proposed, we concur that additional, more in-depth testing between *BS EN 16933-2:2017* (B.S. Institute, 2018) and *AS/NZS 3500.2:2021* (Standards Australia, 2021) should be conducted using a number of differing, real world examples.

3.3 Review of Proposed Verification Methods by Lucid Consulting

Lucid Consulting Australia (Lucid) conducted a subsequent report following their standards comparison report from 2019 and proposed six verification methods for inclusion in a future iteration of the PCA. This report is titled *Sanitary Plumbing and Drainage Pipe Sizing Verification Methods* (Lucid Consulting Australia, 2020). Based on our comparison we believe the report was well presented and concise, and we generally agree with the comments provided within the discussion section, particularly around items raised from feedback provided by internal Lucid engineers. We do however have a number of comments regarding the Verification Methods (VM) they proposed.

We do not have any particular concerns regarding their introduction and summary of the work and we agree with the approach outlined in this Lucid report on how the VM should be approached. At its core, a VM should encourage designers to use suitable performance-based solutions to achieve compliance and should avoid the limitations with a DTS approach. The VM should also importantly, minimise any changes to installation methods prescribed within a deemed to satisfy system design. The main pathway to ensuring this, is to be very clear on what the overarching requirements are within the NCC. Commentary and suggestions addressing this item will be provided within this report where relevant.

Section 2.1 of this VM report identified that peak flowrates immediately downstream of a plumbing fixture are effectively equal to the supply flowrate of the fixture, however, we do not believe this is always true, as flowrates can also be influenced by outlet size, head of water above the outlet and the geometry of the accepting fixture. This section also re-emphasises a key finding by the GHD discussion paper (GHD, 2015) which concluded that the principles behind the statistical approach of the existing drainage flowrate design remains valid, and work should be done to update the input data to reflect modern fixture flowrates and usage profiles. Alternative statistical methods proposed such as the DRAINET model by Heriot-Watt University and use of Fuzzy Logic or Monte Carlo simulations were also suggested. Where possible, suggestions for the use of these alternative statistical methods will be scoped out for future stages of this research.

Section 2.2 of the Lucid VM report provides a brief mention to the two more commonly used approaches. These are the Colebrook-White and Manning equations. A brief analysis into both these equations is provided in Appendix A.2.6 of this report, and a summary of pipe filling capacities and suggested pipe filling degree is provided in Appendix A.3 and A.2.5 respectively. We would however, like to challenge the claim where maximum flowrate within a pipe occurs at a filling degree of 83% as numerical analysis conducted by (Swaffield, 2015) in the text *Transient Free Surface Flows in Building Drainage Systems*, concluded that maximum flowrate within a pipe using the Colebrook-White approach occurs at a pipe filling capacity of 95% whereas maximum velocity occurs at 81%. Reference to design charts for flowrate estimation in

AS2200-2016 (Standards Australia, 2006) was also made. A comparison of design charts such as the ones provided by (Butler & Pinkerton, 1987) in their text *Gravity Flow Pipe Design Charts* is provided in Section 5.6.

Section 2.5 on waste stranding provides insight into the scenarios where pipework may be designed with slopes that are too steep. The two referenced papers state that higher filling degrees due to smaller pipework and lower gradients may increase solid transportation due to the increase in hydrostatic force. The referenced (Swaffield, 2015) text also conducted simulations using their DRAINET model and supported the idea that smaller pipe sizes results in further transportation distances for solids at a similar flow rate however, there does not appear to be a trend suggesting steeper pipework will result in higher blockage risk (Swaffield, 2015). The text did however identify an anomaly when testing solid transports at a drain gradient of 1 in 40. Consultation with a university or research body will be required to determine the significance of this finding.

The Lucid VM report once again emphasised that fundamentally, DU are "*not related to the discharge rates of sanitary appliances quoted in product standards*", and the units of l/s are only given for "*purposes of calculation only*". This makes DU no more adaptable than FU from *AS/NZS 3500.2:2021* (Standards Australia, 2021) and since the derivation of the DU is not well documented, it may be of benefit to develop a method for the designer to derive their own FU as documentation on the derivation of this unit is more accessible. This is discussed further in Chapter 4.

We also agree with the statement that "*there is value in including VMs*" that use "*elements of BS EN 12056-2:2000*", however, we believe that the proposed VM's have integrated more than just elements of *BS EN 12056-2:2000* (B.S. Institute, 2000) which will significantly hinder the adaptability of the VM. Furthermore, incorporating the sizing of wastewater flowrates, branches, stacks and AAV's directly from an equivalent standard without referencing the fundamental mathematics or research behind the stated design values heavily impacts the ability for designers to develop different performance-based solutions accurately. The report has summarised similarities and differences between the two standards and provided *BS EN 12056-2:2000* (B.S. Institute, 2000) design methodologies for major elements of sanitary and plumbing design in a fairly well manner, however, there has been very little work performed on determining where, why, or how the BS decided to use certain values, tables or figures.

The Lucid VM report makes numerous assumptions upon the ability for the *BS EN 12056-2:2000* (B.S. Institute, 2000) standards to be applied in Australia. Extensive testing and verification based on numerous real-world examples must be conducted rather than basing the VM off a key assumption that "*principles behind BS are equally valid in Australia*" and hence will "*not result in any negative consequences*." Furthermore, the risks associated with this assumption will not necessarily outweigh the benefits of providing a VM that will ultimately provide a similar design outcome to a DTS system. Internal Lucid reviews also concur with this perspective and have noted that the proposed VM does not provide any significant differences in stack and drainage outcomes.

We do not have any further significant commentary of their proposed CV2.1 on the "Determination of sanitary plumbing and sanitary drainage wastewater flowrates." It was adapted quite well from BS EN 12056-2:2000 (B.S. Institute, 2000).

Whilst we do not believe there is significant benefit in the designer using one of three different system classes with marginally different DU, there is notable benefit nonetheless with the introduction of a frequency usage factor. We also believe that FU and K-Factors should be revised and developed based on recorded real-world data however, this is further discussed in Chapter 4.

CV2.2, CV2.3 and CV2.4 for Systems I, II and III respectively appear to be generally well adapted from *BS EN 12056-2:2000* (B.S. Institute, 2000). An aspect that we support for adoption is for the clarification on when there are no limits to length of pipes or number of 90-degree bends within a discharge branch. Alternatively, a direct transcription of the table from *BS EN 12056-2:2000* (B.S. Institute, 2000) would also be valuable and may provide more clarity to the wording within subclauses a, b, and c. One area that would benefit from additional research and clarification involves the tables for branch discharge capacity transcribed from *BS EN 12056-2:2000* (B.S. Institute, 2000). From initial review, it appears that the provided flowrates do not correlate with Colebrook-White results. For example, in the System I (50% pipe filling capacity) branch capacity table (Table CV2.3) shows a branch capacity of 3.75 l/s. In order to get that flow according to Colebrook-White, a DN100mm pipe at 70% filling capacity and over 2% slope is required to achieve this flow, yet the table suggests a gradient greater than 0.5% is sufficient. If these tables are to be incorporated, understanding how their values are obtained must first be understood as factors such as internal pipe diameters may skew design parameters.

One concern regarding the implementation of System Class III designs is that the methodology for designing branches is significantly more complex than the other two classes. Within the existing NCC Volume 3 (Australian Building Codes Board, 2019), there are already limitations to liquid to air ratios within sanitary drainage pipework, with the upper limit specified at 0.65 to 0.35. The proposed VM already suggests the filling degree to be increased to 70%. Since System III is a design for full bore (100% filling degree) discharge, it should be removed as a VM unless wording is changed within the NCC to accommodate full bore sanitary plumbing and drainage designs.

Another common design strategy within CV2.2 to CV2.5 is for the sizing of group vents to be designed in accordance with *AS/NZS 3500.2:2021* (Standards Australia, 2021). We have concerns with interchanging standards for VM design due to complications with installation and compliance, and uncertainties with system performance that may arise with this approach. We do however agree that the decision that utilising *AS/NZS 3500.2:2021* (Standards Australia, 2021) standards for group vent design is the more appropriate approach and we believe it will provide a better result in terms of hydraulic performance due to the larger vent diameters required by the Australian Standard. As discussed further in Chapter 6, our research has led us to understand that larger vent stacks only serve to provide better drainage performance by reducing pressure transients and friction within the 'dry part' of the drainage system.

With CV2.6, we largely agree with the VM proposed by Lucid as we believe the use of the modified Colebrook-White equation to estimate pipe drainage capacities will provide the most wholistic view on pipe drainage capacities under free surface flows. The integration of charts is also a good idea as it allows for rapid verification by the designer on drainage capacity based on various common pipe sizes and slopes. We would however, like to propose that in addition to specifying a filling degree between 50% and 70%, the absolute theoretical pipe limits should also be provided with a disclaimer or explanatory note explaining how to this number was obtained. A discussion into horizontal pipe filling capacities is outlined in Section 5.2. We also believe a similar approach should be made for maximum and minimum pipe velocities. This is discussed further in Section 5.3.

Regarding the chosen Colebrook-White roughness coefficient by Lucid of 1.0mm to account for biofilm and a kinematic viscosity equivalent to clean water at 20℃, further testing and research into the viability and validity of these assumptions is made in Appendix A.2.8. The summary of our findings and recommended values to be used within the modified Colebrook-White equation is available in Section 5.5.

There also appears to be slight discrepancies within Tables CV2.9 and CV2.10 of the Lucid VM Report to the tables within *BS EN 12056-2:2000* (B.S. Institute, 2000). The tables by Lucid were reported to have been recalculated using Colebrook-White using parameters set in their VM with equivalent Australian internal pipe diameters, and then de-rated using Chart 13 from *AS 2200:2006* (Standards Australia, 2006). We have conducted a comparison in Appendix A.2.1 and A.2.2 and observed errors to be between 2.5% - 14.6%. We believe the discrepancy may have a result of using different internal diameters as well as differing methods using a derating chart as opposed to calculating the values based on pipe filling capacities.

The Lucid VM report also raises a very important note regarding limitations of VM using Colebrook-White's equation as a method for determining pipe capacity. The calculation method is based on straight, uniform pipe lengths, and thus, factors such as bends, junctions, incorrect installation, and pipework deterioration will reduce the theoretical capacity of the pipe. We believe further research needs to be conducted to determine a method to determine the effects of these reduction elements. This may involve introducing a table to describe the percentage reduction to pipe velocities, or even a modification to the Colebrook-White equation, however, this will allow for more accurate results to be obtained through the VM and pipe-filling safety factors will become less arbitrary.

Reviews are essential to validating outcomes. We believe Lucid has achieved this through their internal review which provides significant commentary around the proposed VMs. Additional commentary from industry bodies or experts would have also been beneficial. Overall, our views are in line with the comments provided by internal Lucid engineers on the proposed VMs. Some of the key items include:

- The benefits associated with the development of a VM that provide flowrates from the existing FU by *AS/NZS 3500.2:2021* (Standards Australia, 2021) (or through the use of the DU VM), allows for better communication between sewer authorities or wastewater treatment plant designers.

- Issue with the recurring lack of guidance on which system design column to use and the unresolved problems with deriving DU for fixtures not already provided in DU tables.

- CV2.2 to CV2.4 do not present any significant beneficial outcomes over *AS/NZS 3500.2:2021* (Standards Australia, 2021) and Lucid engineers indicated that they could not envisage applying these VMs unless in exceptional circumstances due to the minor benefits received for the additional risks associated with a performance solution. It was also noted to provide minor additional flexibility despite the presence of three different System classes. We believe that instead of multiple VM's with minor flexibility, one single method is all that should be offered provided it has sufficient flexibility for the designer to comfortably adjust any parameters.

Lucid engineers also suggest the integration of RVAS systems into VMs. Alternatively, we believe the best approach for the integration of RVAS or equivalent systems, in the interest of future proofing and avoiding manufacturer bias, is to provide limitations and guidance to allow its use without impacting conventional parts of the system. I.e., Instead of creating a VM that allows for RVASS or equivalent systems, we should create a VM that that allows manufactures to easily follow and justify the ability of their product to be a performance solution based on fundamental governing principles and equations. Furthermore, due to the potential for aerator junction designs to change based on proprietary designs from manufacturers, specifying a type of junction with certain performance characteristics may not be the most efficient approach. Alternatively, a requirement for the minimum performance required by the entire sanitary plumbing and drainage system within a building should be specified, rather than specifying requirements for RVAS systems. It will then be incumbent on the manufacturers to develop a product that would be suitable for the system and explain the impacts it may have on the rest of the system. This will also open up the possibilities for different drainage solutions to be developed and improved.

Lucid claimed that due to the similar system design resulting from VM CV2.2 and CV2.3 when compared with an equivalent *AS/NZS 3500.2:2021* (Standards Australia, 2021) system, a major justification for the implementation of this VM is the potential to reduce cost of system designs. We disagree with this perspective as design decisions revolving around sanitary drainage should not be influenced by cost but rather by performance, noting that cost and material reduction benefits are of course beneficial.

Section 5.2 of the Lucid VM report stated additional investigations into performance characteristics of installed systems within Australia are required. Specifically, they call for an investigation into the frequency of pipe blockage factors in Australia and their causes to provide valuable information for further improvements to the PCA. They also suggest investigations into frequency and causes of ventilation uses, resultant air pressures and resultant filling degrees for *AS/NZS 3500.2:2021* (Standards Australia, 2021) and *BS EN 12056-2:2000* (B.S. Institute, 2000) systems. We support this recommendation and the benefits of such investigations.

We also agree with recommendations by Lucid that suggest the need to conduct a detailed investigation into the effects of aerator junction on the capacity of a sanitary plumbing stack, and the necessity for providing guidance into how VM's are supposed to be properly applied. Regarding the provision of education material to designers via the Australian Building Code Board website, additional items such as simple web-based calculators, or pro-forma owned by industry bodies should be made available. Training courses run by Hydraulic Industry Bodies would also be beneficial.

Lucid also proposed that a possible further step to quantifying probability performance requirements would be to develop a VM that allows designers to "size pipework using a first principles formula that takes inputs of fixture flowrates and fixture usage characteristics, similar to the draft Modified Wistort's VM". We believe that this would be the ultimate objective of this research study.

3.4 Review of National Construction Code (NCC) Volume 3 2022

A draft of *NCC Volume 3 2022* (Australian Building Codes Board, 2022) has been provided for our review. Since a significant portion of the newly proposed VM was already incorporated from the Lucid VM report reviewed above in Section 3.3, we will avoid duplication of comments by providing commentary only on items that differ from the Lucid VM report.

The requirement for a trap seal to not experience an air pressure difference greater than 375Pa is reported to date back to the origins of Hunter's work in 1924 and also appeared in the 1994 UK *BS 5572* (B.S. Institute, 1994) standard however, we have limited understanding of the effects, if any, on DTS system designs. Sanitary venting and vertical stack design as reported by Swaffield in *Transient Airflow in Building Drainage Systems* (Swaffield, 2010), also mentions this methodology however the mathematical calculation relating to this design parameter is yet to be identified. An investigation into this design parameter to determine the fundamental mathematical principles for its origin is presented in Chapter 6.

We also note what we believe to be a transcription error with the DU to flowrate conversion equation first shown in C1V1 Clause 2. Q_{Total} should be calculated with the Q_{Other} term being added separate from the square root function. E.g.,

$$Q_{Total} = K \times \sqrt{\sum DU} + Q_{Other}$$

Our commentary from Section 3.3 regarding the omission of NCC Class 7 buildings from the frequency factor tables have already been addressed in the *NCC Volume 3 2022* (Australian Building Codes Board, 2022). We would however, also like to propose that NCC Class 3 buildings be categorised as a frequent fixture use building.

Regarding discharge unit tables, there are no additional comments regarding the frequency factor and discharge unit tables other than those already provided in the VM report review in Section 3.3 involving the omission of System III full-bore flow design.

Minimum and maximum pipe velocities, and liquid to air ratios require additional research and verification as mentioned in the VM report review provided in Section 3.3. There are no further commentary on these items.

4. Discharge Unit Modification

4.1 Reviewing Discharge Units (DU) and Expanding BS EN 12056-2 Frequency Factors (K)

Further to our literature review of the previous work conducted by ABCB in Chapter 3 we noted the following key observations:

- Discharge Units (DU) do not equate to fixture flow rates. As highlighted within *BS EN 12056-2:2000* (B.S. Institute, 2000), DU are not discharge flow rates of sanitary fixtures and are only provided for the purpose of calculation, thus, we don't believe it would correct to update an original DU by replacing it with modern observed discharge rates.
- Conclusive information on how DU were derived cannot be found. From our review of the previous work conducted by Lucid and GHD, and from our own independent investigations, we cannot identify how the original DU within *BS EN 12056-2:2000* (B.S. Institute, 2000) were derived. Without this knowledge, it is not possible to develop a like-for-like replacement of the existing DU and state with any degree of certainty that it would work the same.
- Conclusive information on how K-factors were derived cannot be found. *CIBSE Guide G* (CIBSE, 2019) and *Plumbing Engineering Services Guide* (Whitehead, 2002) references the low, medium, and high water use demands which appear to be associated with the K-factors within *BS EN 12056-2:2000* (B.S. Institute, 2000). It was stated that the time between fixture uses for each case was 1200, 600 and 300 seconds respectively, however, no direct mathematical relationship between K-factors and time intervals were provided.

Due to the concerns above, we believe that simply updating *BS EN 12056-2:2000* (B.S. Institute, 2000) with modern observed flow rates would not result in a sound outcome as the calculation would no longer be mathematically valid. The DU to flowrate formula is shown below:

$$Q_{Total} = K \times \sqrt{\sum DU} + Q_{Other}$$

As the flow rate is the square root of a discharge unit multiplied by a K-factor, which is assumed to be dimensionless, it is not mathematically sound for DU to have a dimension of $\frac{Volume}{Time}$.

From results of dimensional analysis, it was determined that the only way to obtain a calculated result Q with the dimension $\frac{Volume}{Time}$ from a DU within a square root function with the dimension $\frac{Volume}{Time}$, is to ensure that the DU is multiplied by another volume and inverse time factor. I.e.,

Since:

$$Q_{Total} = \frac{Volume}{Time} = \frac{Length^3}{Time}$$

For:

$$Q_{Total} = K \times \sqrt{\sum DU}$$

If:

$$DU = \frac{Volume}{Time}$$

Then:

$$K = \frac{Volume^{0.5}}{Time^{0.5}}$$

From our investigation, we suspect K may be proportional to the inverse of time between fixture uses which would account for the inverse time dimension, however, we were unable to identify where a volume term could have originated from. We were also unable to identify any means to introduce a relevant volume term to provide a dimensionally correct answer. The difficulty with obtaining another volume term further reinforces the idea that DU within *BS EN 12056-2:2000* (B.S. Institute, 2000) cannot be considered as a flowrate.

A potential solution would be to ignore dimensional analysis altogether. This however would assume that the DU, whilst not strictly a flowrate, is a sufficiently close approximation to the actual discharged flow. We however do not recommend pursuing this method as not only does it not resolve the initial uncertainties with the DU method, but also further introduces new uncertainties that are difficult to test and validate.

An alternative hypothesis is that the DU shown in *BS EN 12056-2:2000* (B.S. Institute, 2000) is actually in the form of $\frac{Volume^2}{Time^2}$ and the 'K-Factor' is indeed a dimensionless term. The probability of a fixture being used is also a dimensionless term developed through the ratio of the duration of time that a fixture is busy and, the duration of time that the fixture is observed. If we consider the latter term as the duration of time between fixture uses, we can consider the K-Factor having a dimension equivalent to $\frac{Time}{Time}$. In this form, we gain the possibility to relate the fixture usage intervals detailed within the *Plumbing Engineering Services Design Guide* (Whitehead, 2002) to the K-Factor and thus, further expand it.

On this assumption, we presume that the K-factor is inversely proportional to the time between fixtures uses. E.g.:

$$K \propto \left(\frac{a}{T}\right)^b$$

Where:

$a, b =$ constants
$T =$ time between fixture uses

Based on the *Plumbing Engineering Services Guide* (Whitehead, 2002) and the *BS EN 12056-2:2000* (B.S. Institute, 2000), we further assume the relationship between fixture use intervals and K-Factors are as summarised below in Table 3.

Table 3: Potential fixture usage interval and K-Factor relationship

Time Between Fixture Use (second)	K-Factor
1200	0.5
600	0.7
300	1.0

From Table 3 above, we are able to propose the relationship between K-Factors and fixture usage intervals:

$$K = \left(\frac{300}{T}\right)^{0.5}$$

It is unknown if the constant 300 is related to anything, and despite the fraction form closely resembling a fixture usage probability:

$$p = \frac{duration\ of\ time\ that\ the\ fixture\ is\ busy}{duration\ of\ time\ that\ the\ fixture\ is\ observed}$$

It does not make sense for a typical fixture to be in operation for 300 seconds.

From the relationship above, we can determine the K-factors for a range of time intervals, in addition to those documented within *BS EN 12056-2:2000* (B.S. Institute, 2000), as shown below in Table 4.

Table 4: Table of Expanded K-Factors (values in green were used to extrapolate other k-factors)

Time Between Fixture Use (second)	K-Factor
3400	0.3
1900	0.4
1200	0.5
800	0.6
600	0.7
450	0.8
300	1.0
200	1.2

The K-Factors were rounded to the nearest 1 decimal place. The original K-Factor values and respective time between fixture uses are coloured in green. A K-Factor of 0.9 and 1.1 was not provided as we believed the time increment for the period between fixture uses were too small to be of value. For reference, a K-Factor of 0.9 and 1.1 would result in a time between fixture use of 350 seconds and 250 seconds respectively.

A curve was also fitted to the three data points and the trendline was exported to a graph in a red dotted line in Figure 1 below to illustrate the similarities between the mathematical relationship and the empirical in blue. The trendline provides evidence to support our assumption that the K-Factor within *BS EN 12056-2:2000* (B.S. Institute, 2000) is proportional to the time between fixtures uses due to the similarity represented between curves. It should be emphasised however that with only three data points to extract a trendline, it is not possible to state with complete certainty that this is the actual relationship between K-Factors and time between fixture uses. Extrapolating so far beyond the existing data points can also lead to significant errors as it assumes the trend continues indefinitely.

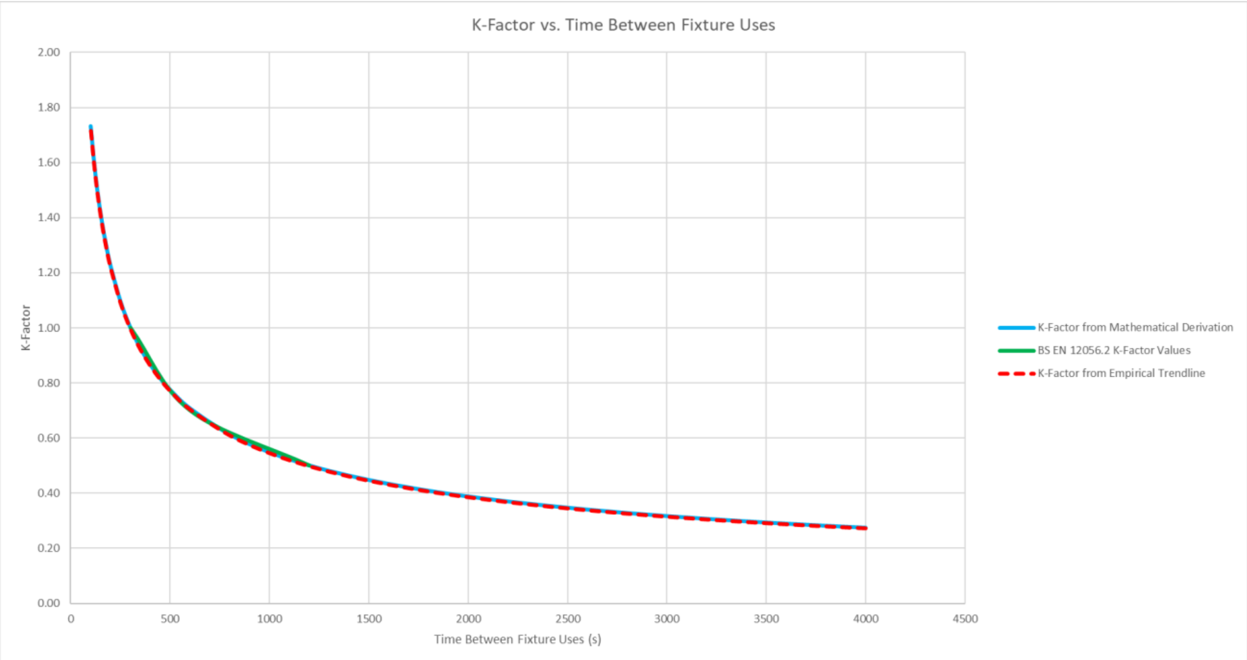

Figure 1: Graphical representation of the relationship between K-Factor and fixture usage intervals

4.2 Reviewing Fixture Units (FU)

In lieu of updating the DU, we considered the possibility of reusing the already existing FU in *AS/NZS 3500.2:2021* (Standards Australia, 2021). We sourced the *BMS 65* report (Hunter, 1940) and followed his method to try and derive the FU that the *AS/NZS 3500.2:2021* (Standards Australia, 2021) utilises.

In Hunter's report, it is explicitly stated that when applying the Hunter probability function, the values of 't,' 'T' and 'τ' is largely a 'matter of engineering judgement.' In the modern-day context, 't' and 'T', which is the average duration of flow for a given kind of fixture for one use, and the average time between successive operations of any given fixture of a particular time respectively, can be empirically sourced given the technology and data available. 'τ' however, which is a time that the event in question will occur for an aggregate of 1 second, is still a numerical value selected based on engineering judgement. Hunter's FU were based on $\tau = 100$ seconds, which was selected assuming this would provide satisfactory service 99 percent of the time.

Through this proposed probability function, we were able to obtain the relationship between the number of fixtures in the sample with the minimum of fixtures required to ensure the number of fixtures within that sample will be operating at a selected period of time. This relationship is unique to the probability of each fixture being used and can vary significantly depending on the number of fixtures in the sample and the probability of fixture usage. Since the curves were independent of each other, and on the basis that it is mathematically invalid to sum the equivalent flow rates required by each fixture from their respective curve, Hunter integrated a weighting factor ranging between 1 and 10 to each fixture based on the fixture with the largest load. This was based on the report '*Recommended Minimum Requirements for Plumbing'* (U.S. Department of Commerce, 1928), which uses fixture weights between 1 and 6, with 6 being designated to the fixture with the largest load. This resulted in two curves for less than approximately 1000 FU and one single curve for a system exceeding 1000 FU. Hunter noted that this allowed for "*reasonably satisfactory results, which are much simpler to apply*" (U.S. Department of Commerce, 1928). Hunter, however, did not detail his decision on the extension of the flush valve curve to 3000 FU seen in Figure 2, and using it as the reference curve for all other fixtures when FU exceeded 1000 FU despite both flush tanks and baths curves showing a steeper trend at larger demands at this point.

From our understanding of Hunter's method, we identified the following problems with providing a means to add or adjust the existing FU provided in *AS/NZS 3500.2:2021* (Standards Australia, 2021).

- The documentation on how the FU was originally adopted in Australia, its adaptation from Hunter's Method, probability of fixture usage and reasoning behind the use of a weighting factor between 0 to 6 could not be found.
- The engineering judgement required to select a viable 'τ,' whilst mathematically sound, may cause disputes or uncertainties unless it can be supported by strong scientific research or industry related evidence.
- Each fixture when represented as a FU is dependent not only on the reference fixture, but also on its probability of use and load for 99 percent of use cases. If the usage profile or discharge flow rate of the reference fixture changes, the FU of all the other fixtures will change and the entire table of FU will need to be recalibrated.
- FU was not developed with varying fixture usage profiles in mind. Depending on what the building is used for, there would be at least three usage categories: Low, Medium, and High. This means there will be at least three different demand curves for each fixture.

Due to the concerns above, we believe that updating FU in *AS/NZS 3500.2:2021* (Standards Australia, 2021) with modern observed flow rates is not possible, and arbitrarily assigning new FU values based on changes in fixture discharges over time and best engineering judgement would still ultimately result in a poor outcome. How the updated FU were obtained will need to be thoroughly documented to avoid the issues we currently experience with FU and a very strong case will need to be presented to justify every value that was selected based on engineering judgement.

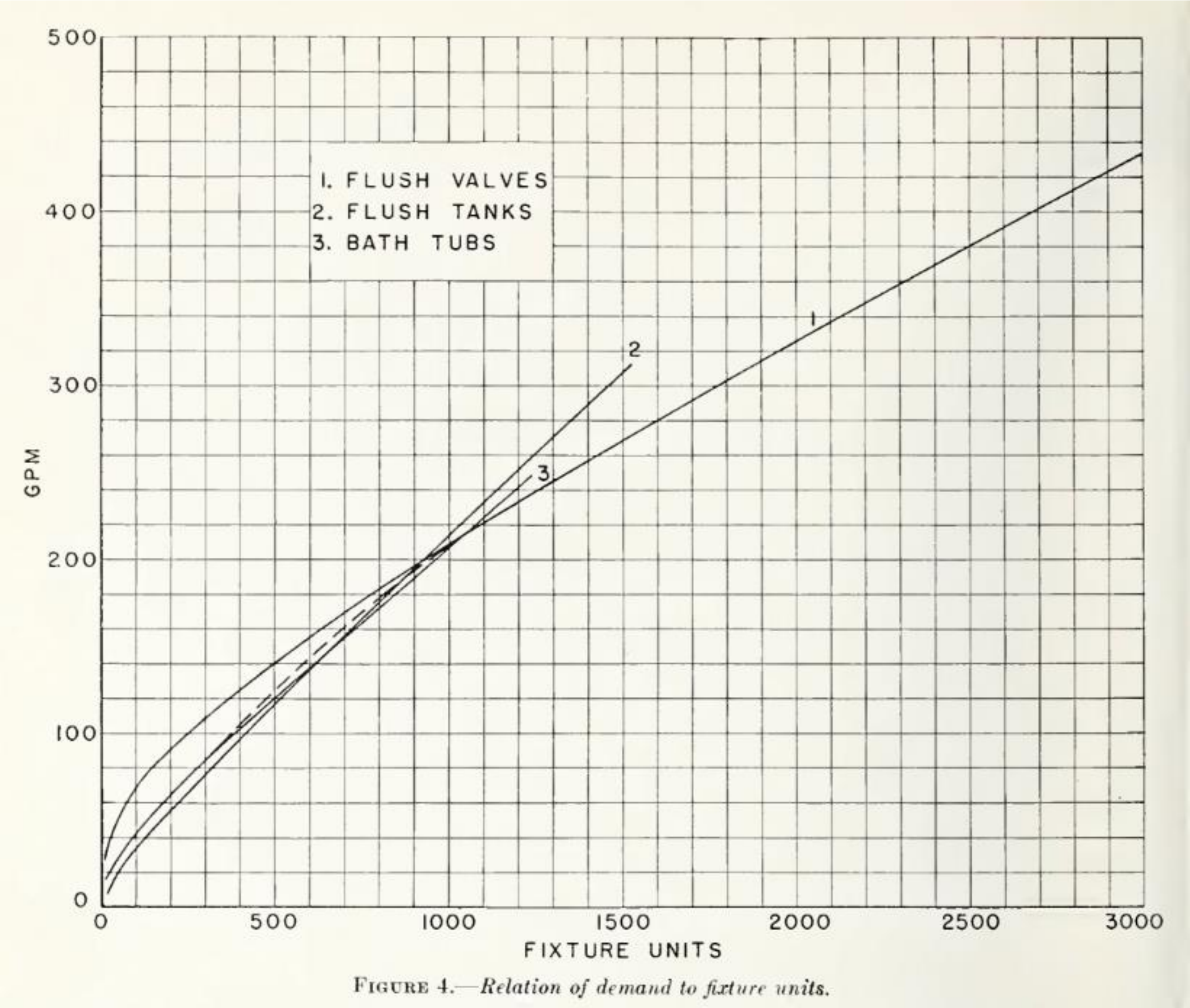

Figure 2: Fixture unit curves by Hunter for three different fixtures (Hunter, 1940)

If a table similar to that provided in *AS/NZS 3500.2:2021* (Standards Australia, 2021) for FU were to be adjusted to accommodate modern fixtures with added flexibility and resilience to changes in the future, an entirely new table will be required. This new table would need to be derived from first principles based on Hunter's method and eliminate any uncertainties with the original derivation of the *AS/NZS 3500.2:2021* (Standards Australia, 2021) FU. The derivation of the new table would need to be supplemented with extensive documentation detailing what and how data is obtained, and every engineering judgement will need to be thoroughly justified. This would allow designers and consultants in the future to avoid encountering any uncertainties with how the new FU were derived and allows them to adjust parameters more readily, as they deem appropriate. Additionally, fixture use time, time between fixture uses, flow rate and 'τ' for the reference fixture unit should also be provided. This would allow designers to approximate the usage probabilities of other fixtures based on the provided FU and allow them to provide their own FU based on the reference fixture. It should also be enough information for designers and researchers to provide their own FU for any new and innovative fixtures they develop.

Further additions to the proposed requirements to develop a more robust FU table would be the incorporation of different FU based on usage frequencies, not too dissimilar to how the *Plumbing Engineering Services Design Guide* (Whitehead, 2002) provides different loading units for simultaneous water demand based on frequency of use. Alternatively, a constant based on usage profiles similar to *BS EN 12056-2:2000* (B.S. Institute, 2000) can be incorporated to allow additional flexibility with design.

Despite the concerns that would be addressed by a revised FU table for sanitary drainage peak load calculations, ultimately, we recommend against pursuing this idea further. At its core, the Hunter method of probability, whilst can still be considered somewhat adequate, is extremely outdated. Significant research has been conducted in this field which incorporates computer simulations with experimental verification to provide much more accurate, adaptable, and robust methods for determining sanitary drainage demands. Whilst the current FU method provides a more simplistic method that involves minimal complex calculations to facilitate rapid approximations in conceptual designs and on-site modifications, we believe an approach different to *AS/NZS 3500.2:2021* (Standards Australia, 2021) FU should be adopted.

4.3 Reviewing Modified Wistort's Method

As briefly mentioned in Section 3.1, significant research into more accurately determining the water demand of buildings is ongoing within the hydraulic industry, with more recent studies incorporating Monte Carlo computer simulation models and fuzzy logic decision making systems.

Under the guidance of ABCB, the *Peak Water Demand Study* (Buchberger, et al., 2017) was considered in our investigation to source a more accurate, robust, and flexible method for estimating peak sewer discharge. Whilst the paper was focused on estimating peak water demands in buildings, we believe the findings made by the research group could be similarly applied to sanitary drainage demands. The method that was of particular interest was the Modified Wistort's Method due to its similarity to Hunter's method of probability distribution, and flexibility of inputs associated with this method.

The unmodified Wistort's method was originally proposed by Robert Wistort in 1994 and incorporated the normal approximation for binomial distribution to estimate peak loads on plumbing systems. The number of busy fixtures is considered to be a random variable with a binomial distribution having a mean 'np' and variance '$np(1-p)$', where 'n' was the number of fixtures and 'p' was the probability of a single fixture operating (Buchberger, et al., 2017). From the normal approximation, the 99th percentile demand in a building with K different fixture groups can be determined by the expression:

$$Q_{0.99} = \sum_{k=1}^{K} n_k p_k q_k + (z_{0.99}) \sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2}$$

Where:

$Q_{0.99} =$ 99th percentile demand
$n_k =$ number of fixtures within the fixture type k
$p_k =$ probability of a single fixture operating within fixture type k
$q_k =$ rate of busy fixture of type k
$(z_{0.99}) = 2.326$, or the z-score of the 99th percentile in a standard normal distribution

And:

$$p_k = \frac{duration\ of\ time\ that\ the\ fixture\ k\ is\ busy}{duration\ of\ time\ that\ the\ fixture\ k\ is\ observed}$$

Investigations conducted into this method by (Buchberger, et al., 2017) in their *Peak Water Demand Study* concluded that the expression above works best when the sum of the mean number of busy fixtures across K different fixture groups is greater or equal to 5. This term was called the Hunter Number and has the expression:

$$H(n,p) = \sum_{k=1}^{K} n_k p_k \geq 5$$

For fixtures with low probability of usage, such as those in residential units or single-family homes with $p = 0.02$, the number of fixtures required to satisfy this expression equates to 250. This makes Wistort's method unsuitable for estimating demands in these scenarios. The research group responsible for the *Peak Water Demand Study* (Buchberger, et al., 2017) then proposed a 'zero-truncated binominal distribution' to Wistort's expression:

$$Q_{0.99} = \frac{1}{1-P_0}\left(\sum_{k=1}^{K} n_k p_k q_k + [(1+P_0)z_{0.99}]\sqrt{\left[(1-P_0)\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2\right] - P_0\left(\sum_{k=1}^{K} n_k p_k q_k\right)^2}\right)$$

Where:

$$P_0 = \prod_{k=1}^{K}(1-p_k)^{n_k}$$

Through Monte Carlo computer models, they discovered that this modified Wistort's equation works well with $H(n,p) \geq 1.25$. For a fixture example above where $p = 0.02$, the number of fixtures required to satisfy this expression now equates to 63 (nearest whole fixture). Whilst this is still not ideal for single residential homes, it is still a significant improvement over the unmodified expression.

4.4 Attempt to Simplify Wistort's Method to Imitate the DU Method

Based on Wistort's work on normal approximation for binomial distribution as discussed above, and the desire to create a similar calculation method to *BS EN 12056-2:2000* (B.S. Institute, 2000) with one square root term and selectable frequency adjustment factor values, we attempted to develop a simplified approximation method for estimating fixture discharge. Whilst it is unknown whether *BS EN 12056-2:2000* (B.S. Institute, 2000) developed its characteristic DU equation via a statistical foundation, we believed that developing a similar equation by approximating an equation developed from a purely statistical method would allow for a more accurate, adaptable, and broadly applicable outcome. Ideally, a simplification of an even more accurate statistical method, such as Modified Wistort's Method, would be greatly preferred however the Wistort's method provided a less complex starting point to determine the viability of this task.

Through mathematical and computer based empirical testing, we were unfortunately unable to derive an approximation method that works as simply as the *BS EN 12056-2:2000* (B.S. Institute, 2000) peak fixture discharge flowrate. The results of our attempts were compared with the results of both Wistort's and Modified Wistort's expressions and was deemed to be far too inaccurate to be reasonably considered. As a result, we suggest that an academic researcher with a strong background in statistical manipulation or equivalent be consulted, should further development to this approach be made. In the interest of comprehensive documentation, our attempts to simplify Wistort's Method are presented in Appendix A.5.

4.5 Data Collection Method for Alternative Methods

4.5.1 Probability of Use

Values of probability of use for each fixture are required to utilise the Wistort's or Modified Wistort's Method of calculating sanitary drainage flow demand. (Wise & Swaffield, 2002) proposes that probabilities of use "*may be expressed in terms of the average time for which an outlet is in use in relation to the average interval between uses over some period during which there is a series of uses at random*." In effect:

$$p = \frac{t}{T} = \frac{average\ duration\ of\ time\ that\ a\ fixture\ outlet\ is\ used}{average\ time\ interval\ between\ outlet\ uses}$$

It should be noted that the probability of outlet use takes an equivalent form to the probability of supply use presented in Section 4.3. Maximum hourly probabilities of supply points for fixtures within small and large occupancy flats, hospital wards and office buildings provided by data from previous literature have been summarised by (Wise & Swaffield, 2002) as shown below in Figure 3.

Table 1.4 Examples of maximum hourly probabilities for water supply points

	Water supply point	Weekday		Saturday		Sunday	
		Maximum probability	Period (hours)	Maximum probability	Period (hours)	Maximum probability	Period (hours)
Flats							
Small, 1.5 occupants on average	WC	0.0155	7–8	0.0133	7–8	0.0116	10–11
	Washbasin (C)	0.0085	8–9	0.0142	14–15	0.0080	9–10
	Washbasin (H)	0.0038	8–9	0.0039	9–10	0.0037	8–9
	Sink (C)	0.0034	9–10	0.0055	8–9	0.0152	10–11
	Sink (H)	0.0154	17–18	0.0136	8–9	0.0179	10–11
	Bath (C)	0.0017	7–8	0.0041	14–15	0.0020	13–14
	Bath (H)	0.0059	16–17	0.0427	14–15	0.0042	13–14
Large, 3.2 occupants on average	WC	0.0501	7–8	0.0417	8–9	0.0443	10–11
	Washbasin (C)	0.0076	7–8	0.0050	9–10	0.0053	9–10
	Washbasin (H)	0.0108	7–8	0.0080	7–8	0.0085	9–10
	Sink (C)	0.0258	17–18	0.0329	10–11	0.0441	11–12
	Sink (H)	0.0342	18–19	0.0310	9–10	0.0415	10–11
	Bath (C)	0.0030	18–19	0.0038	9–10	0.0035	10–11
	Bath (H)	0.0068	22–23	0.0142	11–12	0.0125	14–15
Hospital ward	Washbasin (C)	0.031					
	Washbasin (H)	0.042					
Office building	WC (Men)	Av. interval between uses: 1200 s. Period: 9–12 h Probability based on 75 s inflow duration: 0.0625					
50 men, four WCs 50 women, six WCs	WC (Women)	Av. interval between uses: 600 s. Period: 11–12 h Probability based on 75 s inflow duration: 0.125					

Figure 3: Maximum hourly probabilities of supply points for fixtures within small and large occupancy flats, hospital wards and office buildings (Wise & Swaffield, 2002)

However, we note that the above probability values are for water supply. Probabilities of water supply and water discharge events will not be equal for cistern fed fixtures such as water closets, since cistern fill times differ significantly to flushing discharge times. Similarly, fixtures such as basins and sinks that can be plugged will have different discharge probabilities.

Probabilities of outflows from WC's, washbasins and sinks in flats and houses was determined by data collected by (Wise & Croft, 1954), as shown below in Figure 4 (Wise & Swaffield, 2002). It should be noted that the "*value for the washbasin covers occasions when it was filled and discharged but not occasions when the tap was run without the plug being inserted*" and the "*value for the sink included occasions when a bowl or bucket of water was emptied to waste*" (Wise & Swaffield, 2002).

Table 1.5 Maximum hourly probabilities for discharge in domestic use

	Duration of discharge, t(s)	Interval between discharges, T(s)	$p = t/T$
WC	5	1140	0.0044
Washbasin	10	1500	0.0067
Sink	25	1500	0.0167

Figure 4: Maximum hourly probabilities of discharge in domestic use (Wise & Swaffield, 2002)

(Wise & Swaffield, 2002) presents a method for converting between supply probabilities and discharge probabilities, though the use of the inflow and outflow times for each fixture. The process for conversion is summarised below in Figure 5, and is illustrated by the formula below:

$$p_{discharge} = \frac{t_{discharge}}{T} = p_{supply} \times \frac{t_{discharge}}{t_{supply}} = \frac{t_{supply}}{T} \times \frac{t_{discharge}}{t_{supply}}$$

This method is advantageous given that there is more data available regarding supply probabilities than discharge probabilities. Figure 5 below compares the discharge probabilities determined in an independent study (Figure 3), to the discharge probabilities derived from the supply probabilities and demonstrate reasonable agreement. This method demonstrates that if supply probabilities for each fixture type within each building class and occupancy level are known, and if the fixture inflow and outflow durations are obtained from manufacturer datasheets, the discharge probabilities can be determined.

Table 1.6 Conversion of supply probabilities to discharge probabilities

	WC	Washbasin
Supply probability	0.05	0.009
Duration of flow at an individual water supply point (s)	75	12
Duration of discharge from an appliance (s)	5	10
Conversion factor	5/75	10/12
Supply probability multiplied by conversion factor	0.0033	0.0075
Discharge probability (table 1.5)	0.0044	0.0067

Figure 5 Conversion of supply probabilities to discharge probabilities (Wise & Swaffield, 2002)

The following conclusions can be made:

- It is evident that the supply data provided in Figure 3 is not comprehensive with regards to all fixture types, building classes and occupancy levels. Whilst the *Peak Water Demand Study* (Buchberger, et al., 2017) provided probability of supply usage, the results are averaged over 1038 homes with varying occupancy levels. We think that this may skew the data and that separate probabilities of use should be developed for different occupancy levels.

- We note more data is required to be obtained as per the method presented in Figure 3 for a full set of building classes, typical fixtures and occupancy levels. As a minimum we recommend obtaining probability of use from water supply data which is collected and analysed for conversion to sanitary fixtures considering average time of filling for WC cisterns and plugged fixtures, as well as discharge times. This research could be conducted by manufacturers, research bodies or consultants within the industry subject to building monitoring and privacy approvals.

- It should also be clarified that fixtures such as basins, sinks and baths which can be plugged, should have their probabilities tested for these instances.

- We believe that this method of conversion from supply to discharge probability provides a reasonable estimate given that supply and discharge events are inherently linked at typically a 1:1 ratio i.e., for every supply event to a fixture it is expected that the following event will be a discharge event.

- There may be some fixtures for which it may be valid to conclude that their supply probabilities are equivalent to their discharge probabilities, specifically those fixtures without cisterns or plugs (e.g., showers). Further data is required to test this assumption.

4.5.2 Fixture Discharge Flow Rates

With regards to discharge flow rate values, we do not advise using the same values that would be provided in water demand investigations (Buchberger, et al., 2017). The key concern regarding the use of water demand flow rates as the discharge flow rate is primarily associated to toilets with cisterns, where the discharge during a flush would be significantly greater than the cistern refilling flow rate.

With regards to all other fixtures, the flowrate discharge into a sanitary system can vary based on whether a plug is used or not. Without a plug, the greatest discharge rate would be near equivalent to the discharge rate of water from the fixture itself however, if the fixture is plugged, the discharge down the fixture drain would be largely proportional to the outlet size and head of water above it. Toilets with flush valves would be an exception whereby the fixture flow rate is very similar to the discharge rate. To ensure robust sanitary drainage designs, we propose that all fixtures that can be plugged, shall have their wastewater flow rate to account for it. This method, however, will require a standardised method of measuring the waste flowrate from a fixture to be developed such that manufacturers and designers will be able to provide their own flowrates for use in sanitary plumbing and drainage design in the future.

We have been provided with discharge flow rates for various fixtures from Innovation Engineering which utilised simplified measurements of total volume divided by total time discharged to derive a discharge rate of l/s however, we would recommend that further testing is conducted to validate these values across a wide range of fixtures with more accurate measurements considering impact of head of water over the outlet.

4.6 Recommendations

The research within the chapter can be summarised as follows:

- The derivation of the DU and respective K-Factors from *BS EN 12056-2:2000* (B.S. Institute, 2000) is unknown.
- Existing DU should not be directly updated with more modern fixture discharge flowrates given the unknowns of its origins.
- K-Factors can be expanded under specific assumptions.
- The origin of the FU is well documented, however the adoption of FU into Australian Standards is unknown.
- New, statistical based methods such as Modified Wistort's Method have been tested for calculations involving peak potable water demand.
- We have conducted a study of an example residential tower and office building and compared the peak discharge flow rates calculated using *AS/NZS 3500.2:2021* (Standards Australia, 2021), *BS EN 12056-2:2000* (B.S. Institute, 2000), the Wistort's method and the Modified Wistort's Method in Appendix A.1. This analysis has determined that the Modified Wistort's method is (1) a comparable and viable means of determining peak discharge flow rate, provided that accurate discharge fixture flow rates and probability of use (discharge) values can be obtained, and (2) significantly influenced by these input values.
- We believe there is potential for the Modified Wistort's Method to be adapted for use in peak sanitary drainage estimation subject to further testing and application of collected usage data (refer to Section 4.5.1 and 4.5.2).
- Attempts to derive a simplified estimation expression similar to the DU expression based on the Wistort's Method has been unsuccessful.

From these findings, we propose that in the short term, the *BS EN 12056-2:2000* (B.S. Institute, 2000) DU and K-Factor approach be adopted as a viable Verification Method for the *NCC Plumbing Code of Australia 2025* revision. Further testing using multiple different building types within the NCC is recommended to provide a greater understanding of the differences between a BS Verification Method system design and a

DTS system design. We also support a long-term goal for the adaptation of the Modified Wistort's Method for use as an alternative Verification Method in sanitary plumbing and drainage systems. The Modified Wistort's Method provides a very strong statistical foundation whilst still allowing the potential for adaptation and modification in the future as fixture usage profiles and flowrates continue to evolve. This approach however will require further investigation into existing buildings to determine probability of fixture use within different types of building classes as per the NCC, and analysis to determine typical fixture discharge rates.

Our recommended changes to the *Draft NCC 2022 Volume Three – Plumbing Code of Australia* are presented in the Recommendations section of Chapters 5 and 6.

5. Sanitary Drainage Design

5.1 Relationship Between Pipe Flow, Velocity, and Filling Capacity

To determine a reasonably accurate method for estimating pipe filling capacities within sanitary drainage systems, we must revisit the fundamental equations defining free surface flows. Whilst the behaviour of wastewater within drainage systems can be quite complex to describe, particularly around junctions and offsets, building drainage networks can be characterised as predominately free surface in nature with the exception of surcharge conditions and siphonic systems (Swaffield, 2015). This generalisation allows the sanitary drainage system to be simplified to the Chezy equation. The Chezy equation is the basic expression defining steady uniform flow in free surface flows of channels and partially filled pipe flows. It is expressed as:

$$Q = A\sqrt{\frac{2g}{f}}\sqrt{mS_0} = AC\sqrt{mS_0}$$

The coefficient ‘C’ is typically termed the Chezy loss coefficient and significant research was conducted since its introduction in 1776 to define the value of ‘C’ for a range of channel conditions (Swaffield, 2015). Robert Manning then developed through experimentation, a representation for the coefficient ‘C’ where its value is dependent on the roughness coefficient ‘n.’ This expression then became generally known as the Manning’s equation:

$$Q = AC\sqrt{mS_0} = A\frac{m^{\frac{1}{6}}}{n}m^{\frac{3}{6}}S_0^{0.5} = A\frac{m^{0.667}}{n}S_0^{0.5}$$

Colebrook-White later developed an expression that allowed for the Chezy ‘C’ term to be inferred directly from the full-bore friction factor, and replaced the parameter with the hydraulic mean depth (Swaffield, 2015):

$$\frac{1}{\sqrt{f}} = -4\log_{10}\left(\frac{k}{14.8m} + \frac{0.315}{Re\sqrt{f}}\right)$$

Where:

f = friction factor
$m = \frac{A}{P}$ = hydraulic radius
A = flow cross section
P = wetted perimeter of the channel
$Re = \frac{\rho u m}{\mu}$ = Reynolds number
ρ = density of the fluid
u = mean velocity of the fluid
μ = dynamic viscosity of the fluid

By combining Colebrook-White’s expression with the Manning’s representation of the Chezy equation, and defining the Reynolds number in terms of hydraulic mean depth, an equation for determining flowrate at any depth, slope, pipe fill and pipe wall roughness can be obtained (Swaffield, 2015):

$$Q = -4A\sqrt{2gmS_0}\log_{10}\left(\frac{k}{14.8m} + \frac{0.315}{\frac{\rho}{\mu}m\sqrt{2gmS_0}}\right)$$

The equation above can be alternatively expressed with a kinematic viscosity term ν:

$$Q = -4A\sqrt{2gmS_0}\log_{10}\left(\frac{k}{14.8m} + \frac{0.315\nu}{m\sqrt{2gmS_0}}\right)$$

This modified Colebrook-White equation allows the velocity, and flow, within a gravity drained pipework to be equated to the pipe filling degree. Both European and Australian standards have adopted the use of this equation in varying forms, however the European standards have implemented this to a more significant degree. The *BS EN 752:2017* (B.S. Institute, 2022) references *BS EN 16933-2:2017* (B.S. Institute, 2018) to use a similar variation of the formula above for calculating pipe drainage capacities outside of homes. The filling capacities presented within *BS EN 12056-2:2000* (B.S. Institute, 2000) is assumed to be related to the modified Colebrook-White equation above and all commentary regarding the appropriateness of the filling capacities of different system types revolve around this equation. *AS 2200:2006* (Standards Australia, 2006) also provides a variation of this expression which forms the basis of its design charts for water supply and sewerage. There is however no reference to this standard within *AS/NZS 3500.2:2021* (Standards Australia, 2021).

5.2 Pipe Filling Capacities

As part of our research, we have identified various standards, technical documents and research papers that have provided a pipe filling capacity for sanitary drainage systems. An initial investigation by Northrop Consulting Engineers into various performance parameters of sanitary plumbing and drainage design has identified that "*liquid to air ratio in the order of 0.5-0.65 liquid to 0.35-0.5 air at a minimum velocity of 0.6-0.8m/s*" is sufficient to attain self-cleaning of the pipe (Cordina, 2017). The VM report conducted by Lucid (Lucid Consulting Australia, 2020) noted that the claim made by Northrop was "*based on ensuring self-cleaning… rather than being a limit on capacity*," and instead, proposed a filling degree of 70% to better align with *BS EN 12056-2:2000* (B.S. Institute, 2000). *BS EN 12056-2:2000* (B.S. Institute, 2000) however has filling capacity of 50%, 70% and 100% for their System I, System II, and System III designs respectively and we are unable to validate the reasoning behind these values.

Butler and Pinkerton's drainage design charts suggested a filling capacity of 75% and stated that at high filling capacities of 95% or greater, the consequences of minor flow fluctuations or surface disturbances can rapidly change gravity flow into pressurised flow (Butler & Pinkerton, 1987). This hydraulic instability was explained by the idea that at this filling depth, the relationship between flow rate and filling depth becomes non-unique for the same slope. Similarly, *BS EN 16933-2:2017* (B.S. Institute, 2018) requires underground drains and sewers to be sized at a maximum flow equal to 75% pipe filling capacity to allow for ventilation to occur in the non-wetted area. The Water Services Association of Australia (WSAA) also justifies their prescribed maximum pipe filling capacity of 70% in *WSA 02 2002-2.2* (Water Services Association of Australia, 2002) to ensure the efficiency of natural ventilation of a sewer.

Further, the research papers we sourced do not seem to provide any specific guidance or recommendations to filling capacities however, information has been provided on the theoretical maximum velocity and flow possible under gravity drainage is available. For circular pipes, it has been reported that the optimum flow depth for maximum velocity and flow occurs at 81% and 95% pipe filling capacity respectively (Swaffield, 2015). At full-bore flow, or 100% pipe filling capacity, the flowrate of a circular pipe would counter-intuitively be only 94% of the maximum flow rate achieved with a partially filled pipe. This was mathematically determined via the modified Colebrook-White equation shown in Appendix A.2.2 and the *Plumbing Engineering Services Design Guide* explains that this phenomenon is caused by the increased frictional resistance.

Our discussion with industry experts from Heriot-Watt University further confirmed our observations regarding the absence of filling capacity recommendations within the research literature. Heriot-Watt University noted that whilst research texts may refer to filling capacities within standards, recommended filling capacities will not be typically provided. Any mention of filling capacities are often strictly bounded to the experimental setup within the research paper and cannot be applied broadly as would be required within a standard. It was also noted that for most cases, filling capacities provided within standards are satisfactory and in practice, problems such as trap seal depletion or surge conditions may occur even with DTS designs.

Further research into pipe filling capacities concluded that greater pipe filling capacities resulted in better solid conveyance in sanitary pipes. This is also linked to self-cleansing velocities discussed in Section 5.3 in the sense that for the same flow, a smaller diameter pipe would generally be able to provide a higher filling degree and thus a higher drainage velocity which would promote solid conveyance within sanitary pipework.

We also conducted a mathematical examination to determine to differences in flow for 50%, 70% and 100% pipe filling capacities relative to the theoretical maximum. We have identified that the pipe filling capacity of 70% provides a factor of safety of 1.28 and a pipe filling capacity of 50% provides a factor of safety of 2.15 for pipe flow capacity. The raw data from the mathematical investigation is available in Appendix A.2.5.

From our analysis, we initially proposed that a pipe filling capacity of 70% would be the most optimal from a design and code implementation perspective. We were in agreeance with the Lucid Verification Method report that a pipe filling capacity of 70% should be adopted in lieu of the current recommended filling ratios provided in the *NCC Volume 3 2019* of 'between 1:1 and 0.65:0.35.' Internal reviewers for the Lucid Verification Method report however, had expressed concern regarding a filling degree of 70%. It was our opinion that at a 70% fill capacity, the safety factor of 1.28 would account for any abnormally high peak discharge within the system whilst still ensuring natural ventilation can occur. Furthermore, a 70% pipe fill design is based on the 99th percentile sewerage discharge and flows throughout the day will generally be significantly lower than this figure. We also believed that whilst using a 50% filling capacity provided a safety factor of 2.15 and enhanced pipework ventilation, the designer must also consider that lower flow velocities may result in higher instances of waste stranding, resulting in knock on impacts such as increased chances of pipework blockage. It was noted however, that depending on designers, the contrary could also be justified. Ultimately, if the designer can provide justification that the design will perform without negatively impacting or failing the performance requirements set out by the NCC and AS/NZS 3500.3, then their nominated pipe filling degree is viable. Furthermore, due to the present of System I designs, it would be contradictory to exclude 50% pipe filling capacities.

As a result, a pipe filling capacity between 50% to 70% was proposed as the recommended filling range. An explanatory note will be provided to explain that the designer should ultimately use their own judgement considering the configuration, velocity, self-cleaning and airflow requirements of their system. The Colebrook-White equation found in *AS 2200:2006* will also be referenced to provide means for future innovations to verify their system performance.

The development of reference tables documenting the flow rate and velocity for a 50% and 70% filling degree under the standard Australian pipe internal diameters and typical installation gradients are available in Appendix A.2.2.

5.3 Design Velocities

Similar to pipe filling capacities of Section 5.2, there appears to be very limited documentation as to the origins of minimum and maximum velocities within sanitary drainage networks. Whilst a range of minimum velocities to achieve self-cleaning is abundant within design literature, there is much less information available regarding maximum velocities. It is believed that the current NCC Volume 3 2019 Verification Method for sanitary drainage is based off the research conducted by Northrop Consulting Engineers which proposes a maximum velocity of 2.0m/s for probable use and 3.5m/s for surge conditions (Cordina, 2017). These values however were "*based on rules of thumb as found in the literature search*," however no references were provided for these specific values nor were we able to identify where these values were derived from. Further, the proposed 0.8m/s requirement was not referenced however we were able to find velocities ranging from 0.6m/s to 1.0m/s within design literature.

5.3.1 Minimum Velocity and Self-Cleansing

Throughout our investigation into minimum velocities of sewerage flow in sanitary drains, in most cases the literature would link minimum velocities to self-cleansing. A self-cleansing velocity is identified by *AZ/NZS 3500.0:2021* (Standards Australia, 2021) as the "*velocity of a flowing liquid in a pipe or channel, necessary to prevent the deposition of solids in suspension.*" *AZ/NZS 3500.2:2021* (Standards Australia, 2021) however, does not provide any guidance or requirement on minimum velocities within sanitary plumbing and drainage systems. *BS EN 16933-2:2017* (B.S. Institute, 2018) for wastewater drainage systems inside buildings also do not provide any guidance or requirement on minimum sanitary flow velocities.

For wastewater systems outside of buildings however, both the Australian Standards and the European Standards provide guidance for self-cleansing velocities. *WSA 02 2002-2.2* (Water Services Association of Australia, 2002) requires infrastructure scale systems to be designed to a minimum self-cleansing velocity of 0.7 m/s with minimum grades to be calculated based off this value and a Colebrook-White roughness of 1.5mm. *BS EN 752:2017* (B.S. Institute, 2022) refers to *BS EN 16933-2:2017* (B.S. Institute, 2018) for specifications on self-cleaning and specifies that for drains and sewers with DN less than 300mm, either a velocity of at least 0.7m/s that occurs daily, or a minimum gradient equal to the inverse of the pipe DN is sufficient. The National Annex section within *BS EN 16933-2:2017* (B.S. Institute, 2018) further explains that a self-cleaning velocity of 0.7m/s for foul drains and sewers with DN greater than 300mm is generally used. Whilst both standards agree on a minimum self-cleansing velocity, neither mentions where the 0.7m/s minimum flow velocity originated.

Industry guides on recommended minimum sanitary drain velocities to ensure self-cleansing are more varied. *CIBSE Guide G 2019* for example recommends a minimum velocity of 0.75m/s to achieve a self-cleansing velocity for pipework running 75% full (CIBSE, 2019). The *Plumbing Engineering Services Design Guide* also suggests a minimum self-cleansing velocity of 0.75m/s but claims that the idea of self-cleansing velocities in foul drains was originated from the early Victorian era when the manufacturing standards and quality of materials was much lower than it is today (Whitehead, 2002). *Health Aspects of Plumbing* by WHO challenges these recommendations and proposes that a minimum velocity of 0.6m/s will prevent solids building up to block the pipe (World Health Organization, 2006).

A mathematical analysis was also performed on the minimum grades of discharge pipes in sanitary plumbing systems specified in Table 6.6.1 of *AZ/NZS 3500.2:2021* (Standards Australia, 2021). We assumed a 50% pipe filling capacity, used the equivalent internal PVC diameter of each pipe DN, and input the values into the modified Colebrook-White equation in Section 5.1 to obtain our results in Table 5. Table 6.6.1 of *AZ/NZS 3500.2:2021* (Standards Australia, 2021) for sanitary plumbing systems was used in lieu of Table 3.4.1 for sanitary drainage systems as two additional smaller pipe sizes were available for comparison. These two pipe sizes have been highlighted below. The remainder of Table 6.6.1 is identical to Table 3.4.1 within *AZ/NZS 3500.2:2021* (Standards Australia, 2021).

Table 5: Minimum grades of drains as per *AS/NZS 3500.2:2021* and its probable equivalent drainage velocity

Minimum Grade of Drains		
Nominal Diameter (mm)	*Minimum Grade (%)*	*Velocity @ 50% Pipe Fill (m/s)*
40	2.50	0.55
50	2.50	0.68
65	2.50	0.79
80	1.65	0.74
100	1.65	0.90
125*	1.25	0.89
150	1.00	0.90
225	0.65	0.98
300	0.40	0.87

* DN125 for PVC pipework is not available as per AZ/NZS 3500.2:2021. DN125 for an HDPE pipe was used instead.

The results from the Colebrook-White formulation using the minimum pipe gradients above and their PVC pipe internal diameter for equivalent nominal diameters demonstrates that for all sanitary drainage pipe sizes, a minimum velocity of 0.7m/s will be achieved during peak flow conditions.

Based on the standards referenced above, the available technical guides, and numerical comparison with the DTS approach for sanitary drainage system design, it is of our opinion that a minimum design velocity of

0.7m/s should be proposed as the reference value within the sanitary drainage verification methods section of the NCC Volume 3. This selected value will sit in line with the current WSAA and BS EN standards for sanitary designs outside of buildings and will not contradict the current minimum grade requirements within *AZ/NZS 3500.2:2021* (Standards Australia, 2021). We believe the current verification method pathway within CV2.1 of the *NCC Volume 3 2019* is unnecessarily conservative and can contradict the existing DTS methodology depending on the pipe filling capacity selected. Furthermore, no literature could be found specifically referencing a 0.8m/s minimum velocity. We however recommend that further investigation is to be conducted into self-cleansing velocities and its relationship with travel distances of solids.

5.3.2 Maximum Velocity and Scouring

Unlike minimum required velocities of sanitary drainage systems, there is much less information justifying the specification of maximum drainage velocities. Maximum recommended velocities ranged between 2m/s to 3.6m/s depending on the technical document with justifications varying between rules of thumb and scour prevention. The investigation conducted by Northrop confirms the uncertainties with regards to maximum sanitary drainage velocities but notes that values ranging between 2m/s and 3.5m/s were identified within design manuals (Cordina, 2017). No references to specific pipe manuals were found within the report.

Health Aspects of Plumbing by WHO recommends a limit of 3m/s to prevent scouring and damage to pipes, however there was no further mention into where this value originated from (World Health Organization, 2006). The only other 3m/s limitation noted within the technical guide was within copper tubing design requirements for drinking water. WHO also reference's *Guideline on Health Aspects of Plumbing* for their chart on gradients required to produce the specified minimum and maximum velocities within drains however, no direct reference nor explanation was provided within this referenced document on how the values were derived (Taylor & Wood, 1982). WSAA also provides the similar guidance but for infrastructure scale sewerage designs. For example, WSAA states that reticulation sewers, which are typically sized between DN100 and DN300, are required to be designed to a pipe half-full velocity of 3m/s where practicable (Water Services Association of Australia, 2002). The *Plumbing Engineering Services Design Guide* on the other hand, states that there is no practical limit to maximum velocity but, claims that it is widely accepted that 3.6m/s should not be exceeded (Whitehead, 2002).

A numerical analysis was conducted using the modified Colebrook-White equation specified in Section 5.1 by recreating the 'capacities of drains' tables within Annex B of *BS EN 12056-2:2000* (B.S. Institute, 2000) with internal PVC pipe diameters specified in the Australian Standards. Results from 50%, 70% and 81% pipe fill are presented in Appendix A.3. The 81% filling capacity was selected for this comparison as it provides the maximum flow velocity within a circular pipe. Pipe slopes ranging between 0.5 to 5 percent were selected as it represents the typical pipe slopes utilised in sanitary design and construction. This allows the results to represent the absolute minimum pipe sizes at slopes below 5% that can reach the specified maximum velocities under gravitational flow conditions. A section of the results is provided below:

Table 6: 81% filling capacity reference table using Australian PVC-U internal pipe diameters

Slope (%)	DN65		DN80		DN100		DN150		DN225		DN300	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.99	0.40	1.67	0.46	3.68	0.56	10.08	0.72	33.23	0.97	56.67	1.11
1.0	1.40	0.57	2.38	0.65	5.23	0.80	14.32	1.03	47.14	1.38	80.35	1.57
1.5	1.72	0.70	2.92	0.80	6.42	0.98	17.57	1.26	57.81	1.69	98.52	1.93
2.0	1.99	0.81	3.37	0.93	7.42	1.13	20.31	1.46	66.81	1.95	113.85	2.23
2.5	2.23	0.91	3.78	1.04	8.30	1.27	22.72	1.63	74.73	2.19	127.35	2.49
3.0	2.45	1.00	4.14	1.14	9.10	1.39	24.90	1.79	81.90	2.40	139.55	2.73
3.5	2.65	1.08	4.48	1.23	9.84	1.50	26.91	1.93	88.49	2.59	150.77	2.95
4.0	2.83	1.15	4.79	1.32	10.52	1.61	28.78	2.06	94.62	2.77	161.22	3.15
4.5	3.00	1.22	5.08	1.40	11.16	1.71	30.53	2.19	100.38	2.94	171.03	3.34
5.0	3.17	1.29	5.36	1.48	11.77	1.80	32.19	2.31	105.83	3.09	180.31	3.52

As can be seen from Table 7, for pipe slopes between 0.5 and 5.0 percent, at 81% filling capacity, a velocity greater than 2m/s cannot be reached under gravitation flow until either a slope greater than 3.5% is achieved for a DN150 pipe, 2.0% for a DN225 pipe, or 1.5% for a DN300 pipe. For a velocity of 3.5m/s to be exceeded under gravitation flow conditions, a DN300 pipe is required to be set to a slope greater than 4.5%. At this velocity, the DN300 pipe would be discharging at 180l/s. The values have been colour coded in green and blue for 2m/s and 3.5m/s respectively for ease of reference. Additionally, a conversion of grades as a percentage to grades as a ratio is provided in Table 7 below.

Table 7: Pipe grades conversion table with rounding to nearest 0.05%

Conversion of Pipe Grades	
Percentage (%)	*Ratio (gradient)*
5.00	1 in 20
4.00	1 in 25
3.35	1 in 30
2.50	1 in 40
1.45	1 in 70

From Table 7 above, it becomes more evident on how significant the slopes will need to be for even a DN300 pipe in order to achieve a velocity of 2.0m/s. For all intents and purposes, we believe the set pipe velocity restriction of 2.0m/s for gravitational drainage within the NCC Volume 3 2019 is adequate with the reasoning behind such limitations being pipe scour prevention and noise reduction. A maximum velocity limit of 3.0m/s was considered with the intent to match the WSAA requirement however, due to the significantly larger pipe sizes involved with reticulation, branch and trunk sewer mains which more readily allows the development of faster flow velocities, in our opinion it is sensible to retain the current limit of 2.0m/s. Furthermore, this prescribed velocity limit should also ensure that any peak flows exceeding the 99th percentile design flow will not exceed the presumed scour velocity of 3.5m/s, promoting longevity within design.

With regards to the 3.5m/s requirement for surge condition, we believe the requirement is unnecessary and potentially misleading. The pressure transients within the sanitary system that would allow for a surge condition to results in a flow velocity of 3.5m/s would most likely also cause fixture traps to be broken and would also require the stack ventilation system to fail or reach capacity. Since fixture traps are designed to withstand pressure fluctuations within 375 Pa, it is more likely that fixture traps will fail before the surge pressure required to reach the maximum velocity of 3.5m/s is reached. Furthermore, we do not believe a sanitary drainage or plumbing system should be designed to account for surge conditions in general but rather design for peak flow rates.

Maximum capacity of drainage pipes is supposed to account for 99% of all flows with tolerance built-in to account for any additional unexpected flows. Any additional flows exceeding the 99th percentile design flow is expected to be very short and quickly attenuated downstream. In theory, unforeseen circumstances such as surcharge from the reticulation sewer outside the building should be accounted for through soffit requirements or reflux valves as per utility connection and legislation requirements and should not involve sanitary drainage velocities. Contrastingly, for rainwater drainage design, specifying a maximum surcharge velocity is perfectly valid from a design standpoint as there will be no trap seals to break and the pressure build up from a surcharging rainwater downpipe is much more likely to result in the velocities specified.

5.4 Pipe Gradients

Throughout our investigation into existing standards, technical guides and research literature, the minimum pipe gradients required for sanitary drainage were commonly related to minimum flow velocities required by the sanitary system to ensure self-cleansing. There was research conducted on travel distances of solids by Swaffield which provides additional insight into justification for minimum pipe gradients however, this research was limited to pipework immediately downstream from a low flush WC instead of the sanitary drainage system further downstream (Swaffield, 2015).

When comparing standard requirements for sanitary drainage pipework gradients between Australian and European, we noted that *BS EN 12056-2:2000* (B.S. Institute, 2000) only provides information for branch drains connecting to stacks. *BS EN 16933-2:2017* (B.S. Institute, 2018) however, provides clear recommendations for minimum grades with small diameter drains and sewers. Figure 6 below is extracted directly from Table NA.7 within the National Annex section of *BS EN 16933-2:2017* (B.S. Institute, 2018):

Peak flow [l/s][a]	Pipe size [mm]	Minimum gradient[b,c,d]
<1	75	1 in 40
	100	1 in 40
>1	75	1 in 80
	100	1 in 80[e]
	150	1 in 150[f,g]

[a] Peak flows should be based on probability flow calculation methods.

[b] These gradients have been empirically demonstrated on the basis of 6 l WC flush volumes. Further research is necessary to evaluate the recommended gradients for use in systems with very low WC flush volumes.

[c] Exceptionally, where the length of drain or sewer serving a small number of properties is very long, steeper gradients may be required.

[d] Where ground settlement is expected, steeper gradients are recommended.

[e] Minimum of one WC connected.

[f] Minimum of five WCs connected.

[g] Exceptionally, where a 150 mm diameter pipe is used to carry flows from fewer than five WCs, the minimum gradient should be 1 in 60.

Figure 6: Minimum recommended gradients for small diameter drains and sewers as per *BS EN 16933-2:2017* (B.S. Institute, 2018)

The recommended gradients provided by *BS EN 16933-2:2017* (B.S. Institute, 2018) differs to various degrees from Table 3.4.1 of *AZ/NZS 3500.2:2021* (Standards Australia, 2021) which provides more conservative values. It is believed that the values provided by *BS EN 16933-2:2017* (B.S. Institute, 2018) have been derived from the self-cleansing velocity requirement of 0.7m/s and the modified Colebrook-White equation however, we have not conducted a more thorough analysis to confirm this hypothesis. In the interests of maintaining clarity within the verification method, we recommend minimum gradients within sanitary drainage systems are to be designed such that the minimum self-cleansing velocity of 0.7m/s selected within Section 5.3 during peak daily flows is achieved.

We believe a similar approach should be followed for a maximum gradient within sanitary drainage systems whereby the maximum velocity should be designed such that the 99th percentile flow velocity does not exceed 2.0m/s.

5.5 Roughness Values and Kinematic Viscosity

Both an input for pipe roughness and fluid kinematic viscosity is required to utilize the modified Colebrook-White equation specified in *BS EN 16933-2:2017* (B.S. Institute, 2018) and *AZ 2200:2006* (Standards Australia, 2006). From our research, we noted that there is a general consensus on a recommended pipe roughness to design to however, there is much less guidance with regards to kinematic viscosity.

For roughness values, *BS EN 16933-2:2017* (B.S. Institute, 2018; B.S. Institute, 2022) suggests the use of 1.5mm for drains and sewers at design velocities between 0.76m/s and 1.0m/s due to the effects of biofilm. A roughness value of 0.6mm is proposed for drains designed to velocities greater than 1.0m/s. *WSA 02 2002-2.2*¸ also concurs with this approach and specifies a roughness coefficient of 1.5mm for calculations involving the design of minimum grades within pipework. It is also used when designing for maximum grades in external branch and trunk sewers. *CIBSE Guide G* (CIBSE, 2019) also suggests the use of 1.5mm for foul water pipework and proceeds to reference the *Gravity Flow Pipe Design Charts* (Butler & Pinkerton, 1987). From our investigation into technical standards and guides, a common consensus for a roughness value of 1.5mm for the design of sanitary drainage systems is observed.

We conducted a brief investigation into the effects of biofilm on pipe roughness to determine if there is research-based evidence to justify the selection of 1.5mm in sanitary pipework design. Research conducted in South Africa on biofilm growth and its impact on hydraulic pipelines identified Colebrook-White roughness value of 1.583mm for pipes DN 375 and smaller. The research paper noted that pipes under DN 375 without biofilm presence had pipe roughness values within the order of 0.60mm (Johannes van Vuuren, 2018). Contrastingly, a dissertation into the hydraulic effects of biofilms conducted in Colorado, USA proposed a predictive empirical equation for absolute pipe roughness based on pipe flow velocities (Michalos, 2016). For a pipe velocity of 0.7m/s the predicted roughness coefficient was noted to be 9.0mm, and 1.9mm for a velocity of 1.0m/s. It should be noted that whilst there is a strong linear trend in the recorded data when presented on a log-plot, there is significant scatter within the data thus, we do not advise designing to a roughness of 9.0mm.

Through our investigation we also recognised the relatively low sensitivity of pipe flowrate toward roughness. Within the *Gravity Flow Pipe Design Charts*, (Butler & Pinkerton, 1987) roughness values from 0.03mm to 15mm for a 143mm pipe at 1:50 (2%) grade and $\upsilon = 1.31 \times 10^{-6}$ m^{2}s^{-1} were analysed. Their assessment is shown below in Figure 7. This chart demonstrates that for a 10L/s flow which undergoes an increase in roughness from 0.6mm to 1.5mm, the filling degree would increase by approximately 10% and the velocity would decrease by approximately 10%. The effect of pipe roughness on velocity and flowrate on velocity and flow rate can be observed to relatively small the logarithmic relationship of roughness to velocity (Swaffield & Bridge, 1983).

Through the recommendations of standard and results from both research and technical documents, we are comfortable recommending sanitary drainage systems to be designed to a 1.5mm roughness. The designer may then choose to revise this value to reflect their design conditions more adequately.

Unlike roughness values, the documentation or justification of the kinematic viscosity specified within the referenced standards and design charts is much more limited. Our preliminary investigation into research papers yielded no conclusive results. Experiments conducted within research papers regarding various kinematic viscosities were typically very specific and thus, does not facilitate broader use cases as required within a Verification Method. A mathematical comparison was conducted in Appendix A.2.8 on the differences in pipe flow due to different kinematic viscosities of water. Kinematic viscosities of 1.76×10^{-6} m^{2}s^{-1} and 5.4×10^{-7} m^{2}s^{-1} which correspond to temperatures of 0 to 50°C were compared against each other and resulted in differences of between 0.3 and 2.2% for both velocity and flow rate values. Due to the complexities of identifying the kinematic viscosity of sewerage as it is expected to vary quite significantly depending on the waste discharged, and the relatively small differences to pipe flow expected to be attributed from kinematic viscosity, the default kinematic viscosity of water at 20°C of $\upsilon = 1.01 \times 10^{-6}$ m^{2}s^{-1} will be suggested instead. The designer may then choose to provide an alternative value that provides a better representation of their design conditions.

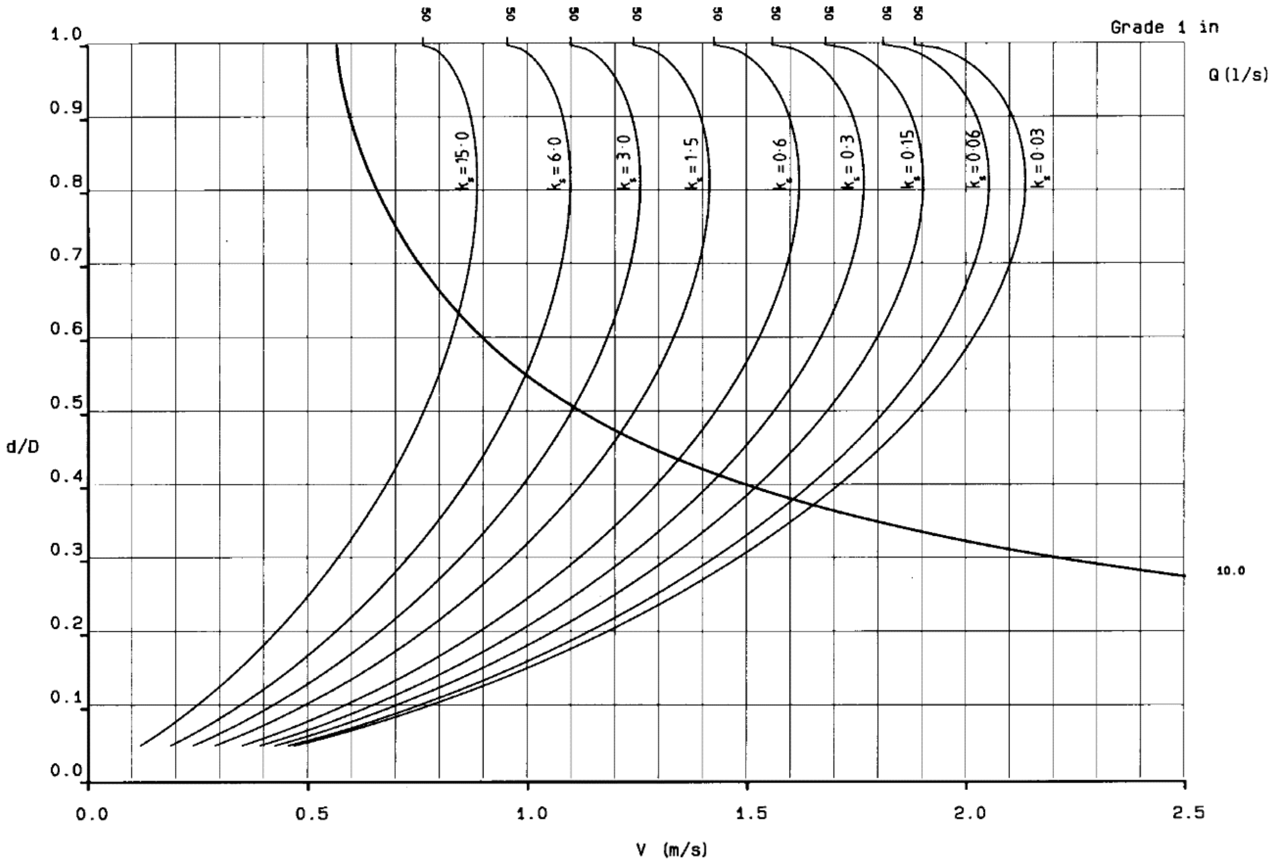

Figure 7: Sensitivity of flow rate and velocity to roughness (Butler & Pinkerton, 1987)

5.6 Sanitary Drainage System Design Charts

We believe the two most commonly referenced graphical methods for use in sanitary drainage system designs utilising the modified Colebrook-White equation in Section 5.1 are within *Gravity Flow Pipe Design Charts* (Butler & Pinkerton, 1987) and *AS2200-2006* (Standards Australia, 2006). Both graphical methods are visually quite different, each possessing their own benefits and disadvantages.

The *Gravity Flow Pipe Design Charts* (Butler & Pinkerton, 1987) which are referenced in the *Plumbing Engineering Services Design Guide* (Whitehead, 2002), represents the Colebrook-White expression by breaking down each chart to a specific pipe diameter and roughness (refer to Figure 8 below). The charts are based on a kinematic viscosity of water at 15°C and display a range of diameters from 100mm to 600mm. The pipe size increments are presumed to align with European DN pipe sizes. Roughness values are in increments of 0.06mm, 0.6mm, 1.5mm and 6.0mm. Whilst the design of these charts does not allow for more accurate design in bespoke pipe diameters and roughness coefficients, they provide an excellent graphical representation on the behaviour of fluid velocity with respect to pipe filling degree. It also provides an excellent visualisation on how velocities within pipes are non-unique as pipe filling degrees exceed 50% as well as illustrating how the maximum velocity achievable by a pipe at a set gradient occurs at approximately 81% filling capacity. Similarly, maximum flow occurs at approximately 95% filling capacity.

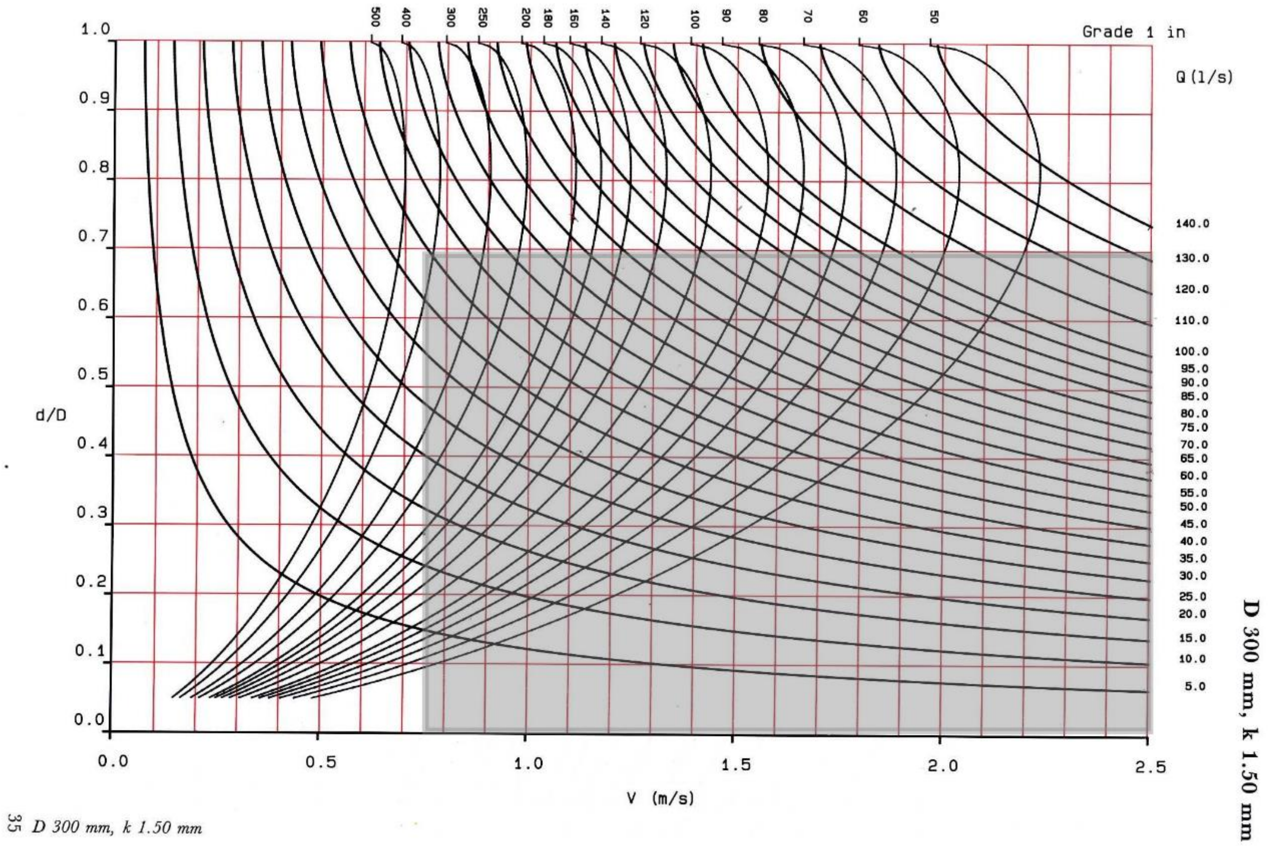

Figure 8: A design chart for a pipe size of 300mm with a roughness coefficient of 1.5mm (Butler & Pinkerton, 1987)

The *AS 2200-2006* (Standards Australia, 2006) design charts allow for a more refined sizing outcome compared to the *Gravity Flow Pipe Design Charts* as each chart within *AS 2200-2006* (Standards Australia, 2006) is broken down to differ by roughness coefficients only (see example below in Figure 9). Roughness coefficients range from 0.006mm to 6.0mm through a series of 11 increments and are based on the kinematic viscosity of water at 20°C. Unlike the Butler and Pinkerton charts (Butler & Pinkerton, 1987), the charts provided here are based on a full-bore pipe flow, i.e., a pipe filling degree of 100%. In order to obtain the corrected value for the design filling capacity, another chart is required to be used to find the proportional equivalent (see Figure 10). It should be noted that whilst initially, *AS2200-2006* (Standards Australia, 2006) will provide comparatively more accurate results, and more flexibility with design outcomes, the use of a derating chart can reintroduce slight deviations and inaccuracies to the actual calculated value. From a practical standpoint, these slight deviations should hold very little significance due to the inherent unpredictable nature of sanitary drainage and the accepted fact that these equations are merely generalised expressions of what is expected to occur majority of the time.

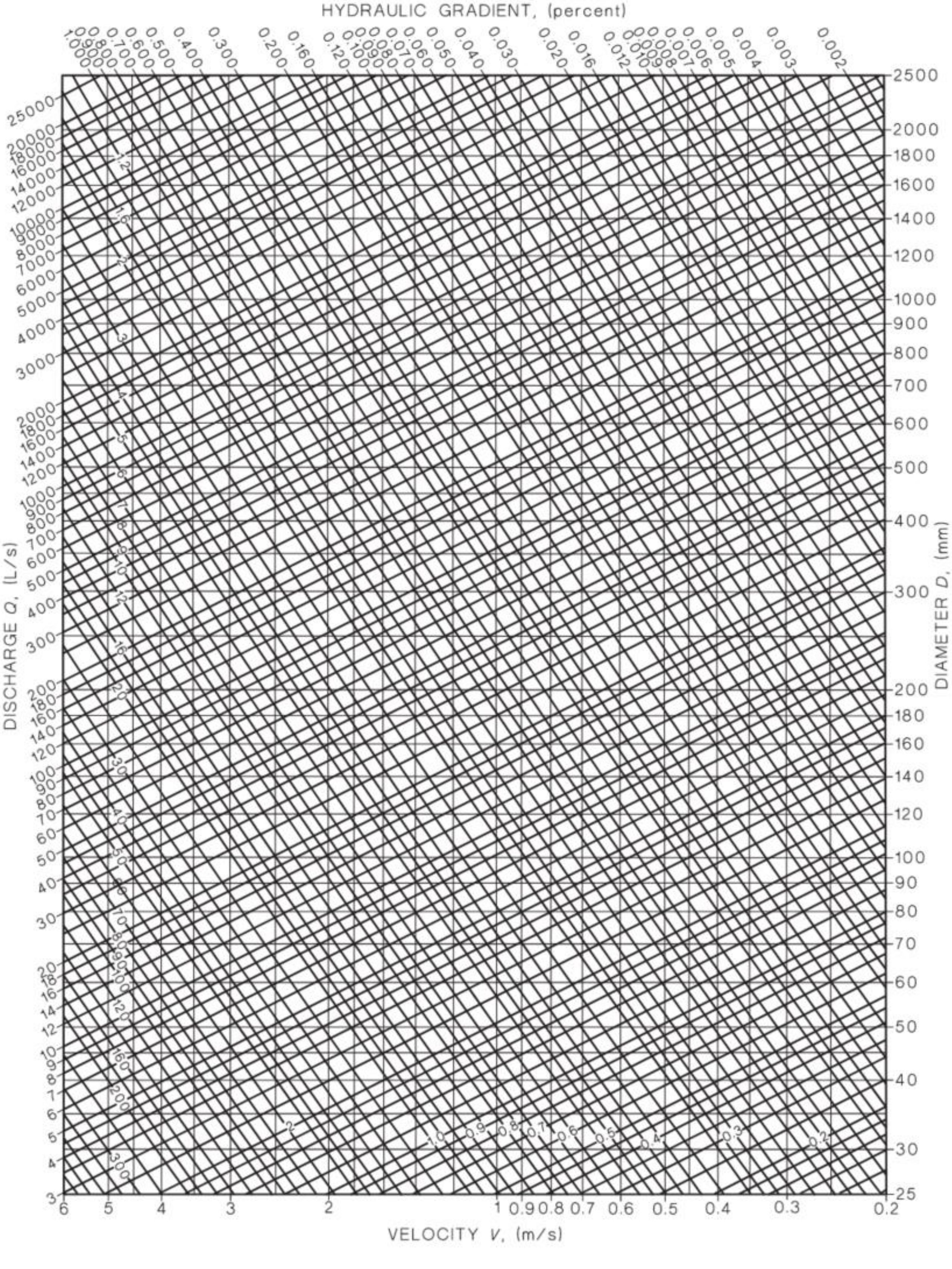

CHART 9 COLEBROOK-WHITE FORMULA WITH k = 1.50 mm

Figure 9: A design chart from *AS 2200-2006* for a roughness coefficient of 1.5mm at full bore flow (Standards Australia, 2006)

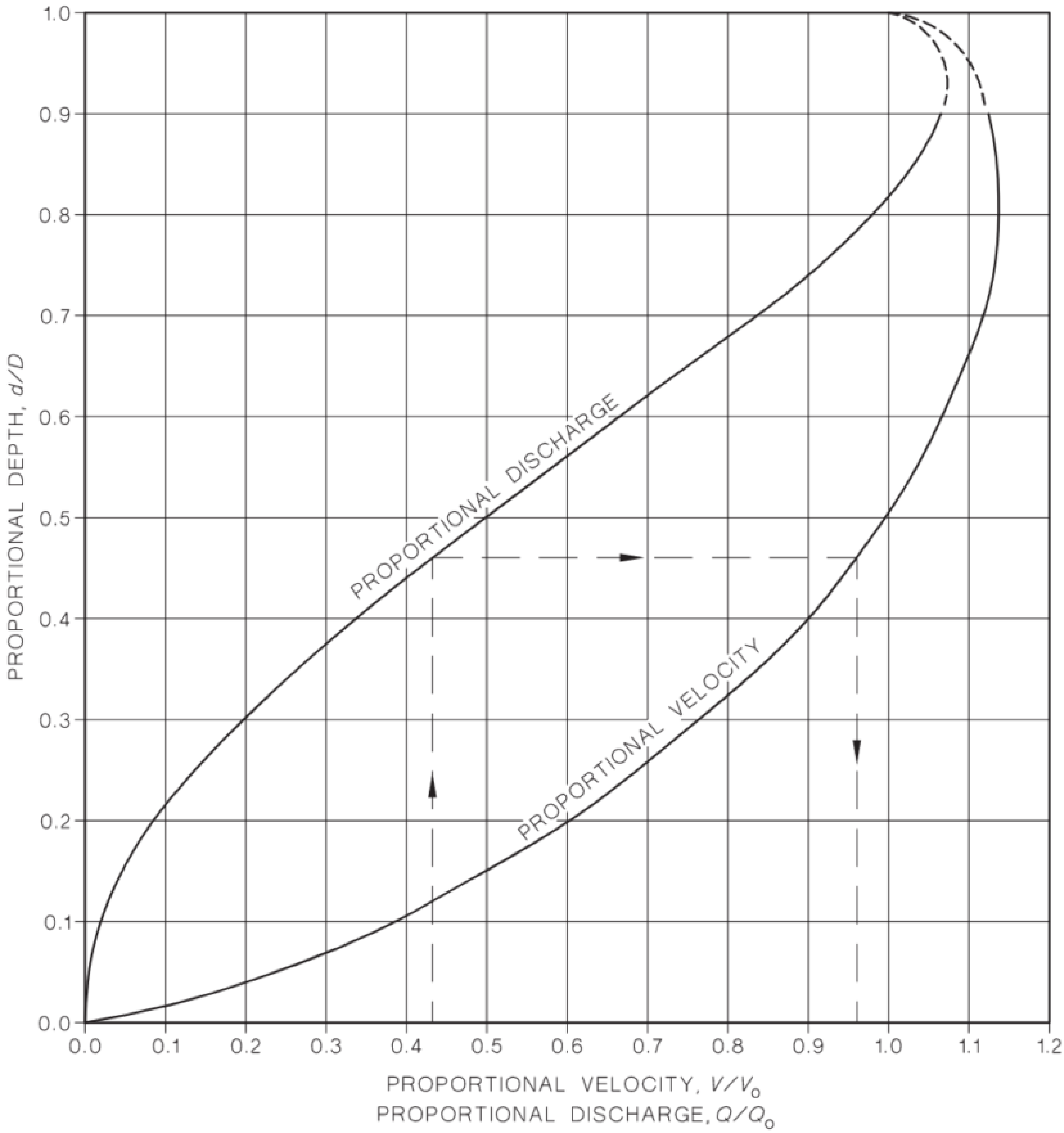

Figure 10: Chart provided in AS 2200-2006 to calculate non-full-bore flows (Standards Australia, 2006)

For ease of reference, the proportional values for the 50% and 70% pipe filling ratio are provided below in Table 8.

Table 8: Proportional velocity and flowrate values for 50% and 70% pipe filling ratios relative to the 100% filling ratio (Lucid Consulting Australia, 2020)

Filling Ratio (%)	Proportional Velocity (%)	Proportional Flowrate (%)
50	99.7	50
70	111.9	83.7

Ultimately, in our opinion the decision of which design charts to use will be based purely on the designer's preferences as both methods are equally valid and any differences between results are expected to be marginal.

5.7 Recommendations

Based on the research conducted in the paper on sanitary drainage and discussions with Heriot Watt University on recent work in this area, we largely support implementing the *BS EN 12056.2:2000* (B.S. Institute, 2000) method of sanitary drainage design into the *NCC 2025 Volume 3 - PCA*, albeit with additional clarifications and adaptations to better suit the Australian Standards.

The research within the chapter is summarised as follows:

- The relationship between pipe flow rate and filling capacity can be expressed as follows:
$$Q = -4A\sqrt{2gmS_0}\log_{10}\left(\frac{k}{14.8m} + \frac{0.315\nu}{m\sqrt{2gmS_0}}\right)$$
- The recommended pipe filling capacity is between 50% and 70%.
- The sanitary drainage system should be designed so that a minimum velocity of 0.7m/s is achieved at least once per day during the daily peak design flow.
- The sanitary drainage system should not exceed a velocity of 2.0m/s during daily peak design flow.
- Minimum and maximum pipe grades should be designed such that the minimum and maximum velocities specified above are not exceeded.
- A pipe roughness value of 1.5mm is the recommended design value for sanitary systems.
- The kinematic viscosity of water at 20°C ($\nu = 1.01 \times 10^{-6}$) is set as the default design value.
- Drainage charts by Butler and Pinkerton (Butler & Pinkerton, 1987) and *AS 2200-2006* (Standards Australia, 2006) are equally viable to facilitate sanitary drainage design.

From these findings, we propose that the Colebrook-White equation already present in *AS 2200-2006* (Standards Australia, 2006) to be adopted within the *NCC 2025 Volume Three – Plumbing Code of Australia* (Australian Building Codes Board, 2022) as a Verification Method for sizing drainage capacities of sewerage pipework. This methodology is already established within an existing Australian standard and in our opinion has a strong empirical background. The Colebrook-White expression offers a large degree of flexibility should any design constraints vary in the long term, yet it is also relatively easy to use with the presence of design charts.

It should be noted however, that whilst the *BS EN 12056.2:2000* (B.S Institute, 2000) method for sizing sanitary drains can be largely adopted as detailed below, further research and reviews must be conducted to minimise any unforeseen consequences with adopting this method for the Australian Plumbing Industry. These are detailed in Appendix A.9.2.

6. Sanitary Plumbing Design

6.1 Branch Design

Branch design within the context of sanitary plumbing refers to the pipe connecting sanitary appliances to a discharge stack or drain (B.S. Institute, 2000). Unlike sanitary drainage designs where there is a general consensus amongst standards, codes and technical design guides on the recommended methodology to follow during design, there is a significantly greater variance amongst sanitary plumbing system design. Within the European Standards, there are at least four distinct system design types with each country designated a specific system to design to (B.S. Institute, 2000). Within the Australian standards, a more refined design criteria is provided, with distinct design requirements for fully vented and single stack systems. A summary of the four systems provided within *BS EN 12056-2:2000* (B.S. Institute, 2000) is provided below in Table 9.

Table 9: Summary of key differences of systems within *BS EN 12056-2:2000* (Lucid Consulting Australia, 2020)

System	Use Locality	Key Design Characteristic
System I	Remainder of Europe	50% pipe filling degree
System II	Scandinavia	70% pipe filling degree
System III	UK	100% pipe filling degree
System IV	France	Separate soil and waste stacks

Further to the review of both DU and FU has already been conducted in Section 4, and the recommendations suggesting the adaptation of the *BS EN 12056-2:2000* (B.S. Institute, 2000) standard as a Verification Method for the short to immediate term, this section will provide supplementary commentary relating to sanitary plumbing branch design. The design guidelines for branch drainage within *BS EN 12056-2:2000* (B.S. Institute, 2000) is shown below in Figure 11 to Figure 14.

Unlike sanitary drainage designs where significantly more information is available to determine pipe flow relationships, we were unable to identify a mathematical expression specifically for sanitary branch pipe flow. Whilst sanitary drainage systems can utilise the Colebrook-White equation due to the assumptions relating to the attenuation of flows as it progresses far enough downstream of a fixture, branch design cannot rely on this assumption due to its close proximity to other fixtures and, significantly fewer fixtures upstream to generate a continuous flow. Furthermore, there is no parameter that allows the Colebrook-White equation to factor in vented and un-vented systems, thus further suggesting that a more complex and dynamic drainage relationship exists within branch systems.

As we were unable to identify an alternate expression to describe the relationship between flowrate, pipe filling capacity and slope driving the recommendations proposed by code, the Colebrook-White equation has been employed to determine the magnitude to which the code recommendations deviate from steady state assumptions made by the Colebrook-White Equation.

Table 4 — Hydraulic capacity (Q_{max}) and nominal diameter (DN)

Q_{max}	System I	System II	System III	System IV
l/s	DN	DN	DN	DN
0,40	*	30		30
0,50	40	40		40
0,80	50	*		*
1,00	60	50	see	50
1,50	70	60	Table 6	60
2,00	80**	70**		70**
2,25	90***	80****		80****
2,50	100	90		100

* Not permitted.

** No WC's.

*** Not more than two WC's and a total change in directions of not more than 90°.

**** Not more than one WC.

Figure 11: Hydraulic capacity (Qmax) and nominal diameter (DN) for Unventilated discharge branches *BS EN 12056-2:2000* (B.S. Institute, 2000)

Table 5 — Limitations

Limitations	System I	System II	System III	System IV
Maximum length (*L*) of pipe	4,0 m	10,0 m		10,0 m
Maximum number of 90° bends	3*	1*	see	3*
Maximum drop (*H*) (45° or more inclination)	1,0 m	**6,0 m DN > 70 **3,0 m DN = 70	Table 6	1,0 m
Minimum gradient	1 %	1,5 %		1 %

* Connection bend not included.

** If DN < 100 mm and a WC is connected to the branch no other appliances can be connected more than 1 m above the connection to a ventilated system.

Figure 12: Unventilated discharge branch Limitations *BS EN 12056-2:2000* (B.S. Institute, 2000)

Table 7 — Hydraulic capacity (Q_{max}) and nominal diameter (DN)

Q_{max}	System I	System II	System III	System IV
l/s	DN	DN	DN	DN
	Branch/Vent	Branch/Vent	Branch/Vent	Branch/Vent
0,60	*	30/30		30/30
0,75	50/40	40/30		40/30
1,50	60/40	50/30		50/30
2,25	70/50	60/30	see	60/30
3,00	80/50**	70/40**	Table 6	70/40**
3,40	90/60***	80/40****		80/40****
3,75	100/60	90/50		90/50

* Not permitted.

** No WC's.

*** Not more than two WC's and a total change in directions of not more than 90°.

**** Not more than one WC.

Figure 13: Hydraulic capacity (Qmax) and nominal diameter (DN) for Ventilated discharge branches *BS EN 12056-2:2000* (B.S. Institute, 2000)

Table 8 — Limitations

Limitations	System I	System II	System III	System IV
Maximum length (*L*) of pipe	10,0 m	No Limit		10,0 m
Maximum number of 90° bends*	No Limit	No Limit	see	No Limit
Maximum drop (*H*) (45° or more inclination)	3,0 m	3,0 m	Table 9	3,0 m
Minimum gradient	0,5 %	1,5 %		0,5 %
* Connection bend not included.				

Figure 14: Ventilated discharge branches Limitations *BS EN 12056-2:2000* (B.S. Institute, 2000)

6.1.1 Pipe Filling Capacities

Our initial testing to determine whether the Colebrook-White equation could be incorporated into sanitary branch design involved attempts to determine the slope required to achieve the specified flowrates based on the pipe fill capacity of the system and specified minimum gradients. The results were inconclusive (Table 10 and Table 11) as the calculations suggests that for flowrates of the magnitude specified within *BS EN 12056-2:2000* (B.S. Institute, 2000), the minimum pipe gradient for each respective DN would need to be far greater than the specified minimum of 1% for unvented and 0.5% for vented systems (see Figure 12 and Figure 14 below). This analysis has been based on values of flow rate and velocity calculated using Colebrook White for BS internal diameters with 50% filling capacity (see Table 12 below).

Table 10: Slope required as per Colebrook-White formulation based on specified unvented System I branch hydraulic capacity (B.S. Institute, 2000)

BS EN DN (mm)	BS EN 12056 Qmax – Unvented (L/s)	Slope Required (%)
40	0.50	> 5.0
50	0.80	> 5.0
60	1.00	~3.0
70	1.50	2.0-2.5
80	2.00	~2.5
100	2.50	~1.0

Table 11: Slope required as per Colebrook-White formulation based on specified vented System I branch hydraulic capacity (B.S. Institute, 2000).

BS EN DN (mm)	BS EN 12056 Qmax – Vented (L/s)	Slope Required (%)
50	0.75	> 5.0
60	1.50	> 5.0
70	2.25	4.5-5.0
80	3.00	> 5.0
100	3.75	2.0-2.5

Table 12: Flow Rate and Velocity Values for BS internal diameters with 50% filling capacity

Slope (%)	DN40		DN50		DN60		DN70		DN80		DN100		DN150		DN225	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.106	0.233	0.213	0.281	0.411	0.333	0.694	0.382	0.904	0.409	1.755	0.485	5.388	0.644	13.654	0.811
1.0	0.151	0.333	0.305	0.401	0.585	0.475	0.988	0.544	1.286	0.582	2.496	0.690	7.653	0.914	19.378	1.152
1.5	0.186	0.410	0.375	0.493	0.720	0.584	1.214	0.669	1.580	0.715	3.065	0.847	9.392	1.122	23.771	1.413
2.0	0.216	0.475	0.434	0.571	0.833	0.676	1.405	0.774	1.828	0.828	3.544	0.979	10.858	1.297	27.475	1.633
2.5	0.241	0.532	0.486	0.639	0.933	0.757	1.573	0.866	2.047	0.927	3.967	1.096	12.149	1.451	30.738	1.827
3.0	0.265	0.584	0.533	0.701	1.023	0.830	1.725	0.950	2.244	1.016	4.349	1.202	13.317	1.591	33.688	2.002
3.5	0.287	0.631	0.576	0.758	1.106	0.898	1.864	1.027	2.426	1.098	4.700	1.299	14.391	1.719	36.401	2.163
4.0	0.307	0.675	0.617	0.811	1.183	0.960	1.994	1.098	2.595	1.175	5.027	1.389	15.391	1.839	38.926	2.313
4.5	0.325	0.717	0.655	0.861	1.255	1.019	2.116	1.166	2.753	1.246	5.334	1.474	16.329	1.951	41.298	2.454
5.0	0.343	0.756	0.691	0.908	1.324	1.075	2.232	1.229	2.904	1.314	5.625	1.554	17.217	2.057	43.542	2.588

Table 10 and Table 11 above show comparison of a select number of pipe sizes using a System I (50% pipe filling capacity) design however, similarly calculations involving System II (75% pipe filling capacity) designs were also unable to provide conclusive results. Since *BS EN 12056-2:2000* (B.S. Institute, 2000) explicitly states that System I and System II branch discharge pipes are designed to 50% and 70% pipe filling degrees, the evidence suggests that the code recommendations are not based on Colebrook-White formulation. It is suspected that a more complex relationship exists between pipe filling capacity and branch discharge flowrate.

6.1.2 Design Velocities and Pipe Gradients

Similar to pipe filling capacities for branches sanitary plumbing systems, there is also very little information regarding design velocities and pipe gradients. Neither *BS EN 12056-2:2000* (B.S. Institute, 2000) nor *AS/NZS 3500.2:2021* (Standards Australia, 2021) provide any commentary on minimum or maximum flow velocities. Evidence from the pipe filling capacity analysis above already suggests that the Colebrook-White expression is not employed by the standard to determine pipe flow in branch drainage design. A further mathematical test involving the Colebrook-White equation was conducted to determine whether the various branch sizes of different system types was set based on a maximum velocity, however, this was also unsuccessful (see Table 13 and Table 14 below). Therefore, we are unable to identify any trends and the velocities required to reach each specified velocity in a System I type design appeared quite sporadic.

Table 13: Velocity required as per Colebrook-White formulation based on specified un-vented System I branch hydraulic capacity (B.S. Institute, 2000)

BS EN DN (mm)	BS EN 12056 Qmax – Unvented (L/s)	Velocity Required (m/s)
40	0.50	> 0.76
50	0.80	> 0.91
60	1.00	~0.83
70	1.50	~0.77-0.87
80	2.00	~0.93
100	2.50	~0.69

Table 14: Velocity required as per Colebrook-White formulation based on specified vented System I branch hydraulic capacity (B.S. Institute, 2000)

BS EN DN (mm)	BS EN 12056 Qmax – Vented (L/s)	Velocity Required (m/s)
50	0.75	> 0.91
60	1.50	> 1.1
70	2.25	> 1.2
80	3.00	> 1.3
100	3.75	> ~1.0

From the results above, we were unable to determine whether a consistent relationship between the specified maximum flowrates for System I and velocity exists; however, we can conclude that if a relationship exists, it is different to that predicted by the Colebrook White expression.

It should be noted that System III of *BS EN 12056-2:2000* (B.S. Institute, 2000) possesses a significantly more detailed table on the limitations for vented and un-vented branch discharge pipe designs by breaking down design parameters into appliance categories. The System III approach attempts to address a large range of fixtures and their typical design configurations, however, it still provides significantly less flexibility than System I, II and IV as there is no guidance for fixtures not included within the table.

We note that Table 6.6.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021) (Figure 15 below) provides minimum grades for branch discharge pipes and these grades are larger than those recommended by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000), as shown in Figure 11 to Figure 14 (0.5%-1.5% versus 2.5%). We recommend that further investigation is conducted to determine the implications of recommending lower minimum grades. We also recommend a comparison between maximum branch lengths recommended by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000) and Appendix B.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021).

Table 6.6.1 — Minimum grades of discharge pipes

Size of graded section of pipe DN	Minimum grade %
40	2.50
50	2.50
65	2.50
80	1.65
100	1.65
125	1.25
150	1.00
225	0.65
300	0.40
NOTE Appendix C provides a table for conversion of grades as a percentage to grades as a ratio.	

Figure 15: Table 6.6.1 Minimum Grades of Discharge Pipes *AS/NZS 3500.2:2021* (Standards Australia, 2021)

From the findings discussed above, we are not able to determine the theoretical basis underpinning the recommendations for branch sizing provided by *BS EN 12056-2:2000* (B.S. Institute, 2000) nor *AS/NZS 3500.2:2021* (Standards Australia, 2021). Further research should be conducted to determine whether there is a theoretical basis for these recommendations. We would also recommend a review of recommended minimum grades and maximum length of branch drainage provided by *BS EN 12056-2:2000* (B.S. Institute, 2000) (see Figure 12 and Figure 14) in light of more recent research regarding maximum travel distances of solids when subjected to low flow WC flushes. An example of this research is testing conducted by (Swaffield, 2015), as shown below in Figure 16. We suspect that higher pipe grades or shorter branch lengths may need to be recommended to account for lower flush volumes transporting the solids.

Table 7.1 Summary of simulation results for 6 litre/4 litre flush volume w.c.

Pipe diameter (mm)	*Pipe gradient*	*Max travel distance (m)*
100	1/40	56
100	1/60	44
100	1/80	28
100	1/100	19
75	1/40	125
75	1/60	75
75	1/80	47
75	1/100	18

Table 7.2 Summary of simulation results for 4 litre/2.6 litre flush volume

Pipe diameter	*Pipe gradient*	*Max travel distance (m)*
100	1/40	40
100	1/60	25
100	1/80	15
100	1/100	10
75	1/40	82
75	1/60	45
75	1/80	30
75	1/100	55

Figure 16: Simulation results of maximum solid travel distances for varying flush volumes, pipe diameter and gradients

6.2 Objectives of Stack and Vent Sizing

In our opinion, Swaffield and Thancanamootoo (Swaffield & Thancanamootoo, 1991) accurately summarise the aims of stack and vent sizing: "*The presence of individual trap seals of 50-75 mm depth connected to the stack by the horizontal pipe network on each floor imposes limits upon the maximum stack flow. The vertical transport of water and waste and the connection to a horizontal collection drain must not generate pressure fluctuations, positive or negative, capable of either destroying these trap seals or forcing foul air through them. Similarly, the design of the stack must be capable of accepting the whole building downflow with minimal risk of back-up in the lower floors.*"

As per the summary of Swaffield and Thancanamootoo, the following section will refer to sizing methodology of stacks and vents within drainage systems to ensure that suction pressures within the network are minimised such that trap seals are maintained. Section 15 of *AS3500.2:2021* (Standards Australia, 2021), which outlines testing methods of sanitary drainage installations makes reference to maintaining a minimum trap seal depth of 25 mm under "*normal operating conditions". BS EN 12056-2:2000* (B.S. Institute, 2000) makes a similar comment in Section NG.3.2 which details performance tests of drainage systems and states that "*a minimum of 25 mm of water seal should be retained in every trap*" following fixture discharge, with each test being repeated "*at least three times*". Testing regimes of self-siphonage for trap seal depths within *BS EN 12056-2:2000* (B.S. Institute, 2000) involves testing trap seal depths post (1) individual fixture discharges and (2) a combination of fixtures discharge simultaneously. Similar recommendations are made within C1P6 of the (Australian Building Codes Board, 2022), noting that "*at pressures of up to* $\pm 375Pa$, *water trap seals will not be reduced to depths less than 70mm for trap seals in pressurised rooms and 25mm for all other applications*".

Hence, we believe it is appropriate set the design criteria for stack and vent sizing to be such that a minimum trap seal depth of 25mm is achieved for all traps within the system for a probable simultaneous discharge event within the system. Consequently, discussions in this report relating to (1) “over-designed” or (2) “under-designed” stack or venting systems will be in reference to respective system designs that have (1) all trap seal depths substantially above the minimum trap depth or (2) deplete one or more traps within system below the minimum 25mm depth. However, we note the following caveat to the above definitions for apparent “over-designed” systems, if a decrease in one standard pipe size to a stack or vent or other drainage pipe in the vicinity then results in trap seals being depleted below a minimum of 25mm, then we would consider that system to be adequately design, as opposed to “over-designed”.

6.3 Stack Sizing

Generally current codes size stacks assuming steady state annular flows occupying a certain percentage of the cross-sectional area of the stack (Lansing, 2020). This sizing methodology dates back to Hunter’s work in 1923 (U.S. Department of Commerce, 1923), which led to the characterisation of flow within partially filled vertical pipes and determined that it varies with filling degree of the stack. Experimental observations of a 3-inch (75mm) stack determined that for low flow rates, the water adhered to the wall of the stack. However, Hunter observed the initiation of slug formation in the stack when the stack filling degree was increased from 25% to 33% full. It was Hunter’s position that intermittent slug formation plays a role in rapid pressure oscillations within drainage system (U.S. Department of Commerce, 1923; Wyly & Eaton, 1961). Hunter’s recommendation was that “*where terminal velocity exists, a stack should not be loaded to such an¼tent that more than 1/4 to 1/3 of the cross section of the stack is filled with water*” (Wyly & Eaton, 1961).

Hunter also defined a “*fitting capacity*” and used this as a measure of the effective capacity of the stack. This fitting capacity was defined as the “*rate of flow in gallons per minute at which the water just begins to build up in the stack above the inlet branch of the fitting when no water is flowing down the stack from a higher level*” (Wyly & Eaton, 1961). Experimental testing was conducted on 2-inch (50mm) and 3-inch (75mm) stacks for one inlet of varying inlet types, and some with inlets at two levels. A comparison of the results of one and two inlets demonstrated an increased capacity using two inlets, indicating that stack capacity may increase with the number of inlets.

This experimental work led to the following formula of stack capacity based on fitting capacity (Wyly & Eaton, 1961):

$$Q = kD^2$$

Where:

- Q is maximum flow rate $(gallons/min)$
- D is the diameter of the stack $(inches)$
- $k = 22.5$ for 45° Y inlets; and
- $k = 11.25$ for sanitary-tee inlets

A summary of stack capacities provided by Hunter’s experimental work and the above formula is shown below in Figure 17.

TABLE 1. *Practical carrying capacities of stacks* [a]

(Hunter)

Diameter of stack	Practical carrying capacity	
	Sanitary-tee fittings	Y or Y-and-⅛-bend fittings
in.	*gpm*	*gpm*
2	[b] 45	[b] 90
3	[b] 100	[b] 200
4	180	360
5	280	560
6	405	810
8	720	1, 440

[a] For water introduced at one elevation only, through double-branch fittings.
[b] Carrying capacities for the 2- and 3-in. stacks were determined by experiment. The values for larger diameters were computed from eq (1).

Figure 17: Practical Carrying Capacities of Stacks based on by Hunter (Wyly & Eaton, 1961)

The later work by Wyly and Eaton at the National Bureau of Standards (Wyly & Eaton, 1961) built upon Hunter's work and supported the method of determining stack loading by specifying a maximum cross-sectional area that the flow could occupy at terminal velocity. They note that this formula is "*intended as an upper limit to flow capacity where stack height is sufficient to ensure that stack capacity will not be governed by the capacities of the horizontal branches or by the capacities of the fittings at the junctions between the stack and the horizontal branches*" (Wyly & Eaton, 1961). The formula shown below is for a cast iron pipe and has been adapted by (Wise & Swaffield, 2002) into metric units. This formula for flow capacity within stacks was based on their derivation of terminal velocity from the Manning empirical formula for pipe friction coupled with the continuity equation (Wise & Swaffield, 2002):

$$Q = 31.9r^{\frac{5}{3}}D^{\frac{8}{3}}$$

Where:

- Q is maximum flow rate (m^3/s)
- D is the diameter of the stack (m)
- r is the fraction of cross-section occupied by the water flow

(Wyly & Eaton, 1961) also supported that stack loading should be limited to cross-sectional areas between 1/3 and 1/4, based off the research findings of Hunter (U.S. Department of Commerce, 1923) as well as (Dawson & Kalinske, 1939). By substituting in $r = 1/6$ and $1/4$ respectively into the above expression, the following equations are developed for flows through stacks $(m^3 s^{-1})$ (Wise & Swaffield, 2002):

$$Q_{r=\frac{1}{6}} = 1.6D^{\frac{8}{3}}$$

$$Q_{r=\frac{1}{4}} = 3.15D^{\frac{8}{3}}$$

(Wise & Swaffield, 2002) note that the above expression for the 25% full capacity served the now superseded *BS 5572* (B.S. Institute, 1994). (Lansing, 2020) cites (Wise & Swaffield, 2002), stating that for *BS EN 12056-2:2000* (B.S. Institute, 2000) "*The stack loadings for square entries reflect the 1/6th cross-sectional loading whereas the swept connections are arbitrarily higher*". We are unable to ascertain the above conclusion of cross-sectional areas used in stack loadings within *BS EN 12056-2:2000* (B.S. Institute, 2000) from reference to (Wise & Swaffield, 2002). It is noted that a larger allowable cross-sectional area for swept junctions may be justifiable, since swept connections limit the disruption of the annular flow in the stack, as reported by (Wyly & Eaton, 1961). It is also worth noting that the maximum flow rate specified for stacks in System I to IV of *BS EN 12056-2:2000* (B.S. Institute, 2000) is the same, implying that the same cross-sectional loading is consistent for all system types (see Figure 19 and Figure 20).

We also noted that a more comprehensive formula for steady state annular flow within stacks can be derived using the Colebrook-White Equation assuming a smooth stack (Wise & Swaffield, 2002):

$$\frac{Q_w}{4\pi D t}\sqrt{\frac{1}{2gt}} = -\log_{10}\left(\frac{k}{14.8t} + \frac{0.31375v}{t}\sqrt{\frac{1}{2gt}}\right)$$

The maximum flow rates obtained using the Colebrook-White equation versus the equations for flows through stacks ($r = 1/6$ and $1/4$) are slightly higher as reflected below in Figure 18. Figure 18 demonstrates that marginally higher flow capacities can be achieved using the Colebrook-White equation, partly due to smooth stack assumptions.

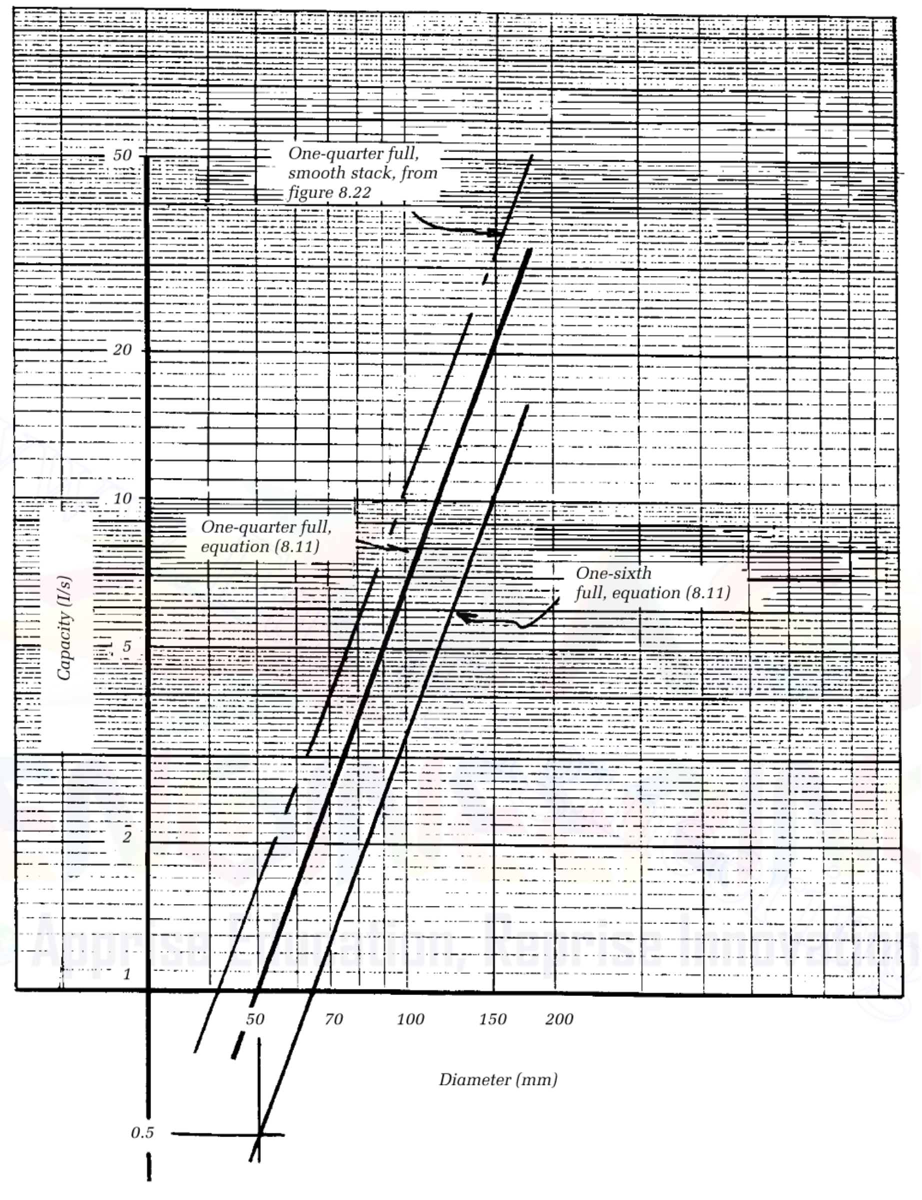

Figure 5.12 Relationships between stack diameter and capacity

Figure 18: Stack Capacity versus diameter considering $Q = 31.9r^{\frac{5}{3}}D^{\frac{8}{3}}$ (referenced as Equation 8.11) for 1/6 and 1/4 filling and the Colebrook-White equation (referenced as Figure 8.22) for 1/4 filling (Wise & Swaffield, 2002)

Further validation is required to determine the steady state annular flow formula and filling capacity used to determine the stack capacities listed within *BS EN 12056*:2000 (B.S. Institute, 2000) for square and swept entries of primary and secondary ventilated discharge stacks shown below in Figure 19 and Figure 20. We recommend further investigating the degree of variation in maximum allowable flows when using Colebrook-White as opposed to the formula developed by (Wyly & Eaton, 1961), as alluded to by Figure 18. Once the above validation has been conducted, we recommend conducting further research into whether there is an academic basis to the varied filling degrees for different entry and venting configurations. Whilst Hunter (U.S. Department of Commerce, 1923) accounted for fittings by developing stack capacities that were limited by the capacities of the fittings, we note this is a different approach to that of the maximum cross-sectional area loading method implemented by codes. Finally, an in-depth comparison between the National Annexes of *EN 12056:2000* from other European countries and *AS3500.2:2021* (Standards Australia, 2021) is recommended to understand the difference in installation configurations which may impact the design outcome when interchanging sizing methods. A high-level side-by-side comparison between the UK National Annex and *AS3500.2:2021* (Standards Australia, 2021) have been provided in Appendix A.8.

Table 11 — Hydraulic capacity (Q_{max}) and nominal diameter (DN)

Stack and stack vent	System I, II, III, IV Q_{max} (l/s)	
DN	Square entries	Swept entries
60	0,5	0,7
70	1,5	2,0
80*	2,0	2,6
90	2,7	3,5
100**	4,0	5,2
125	5,8	7,6
150	9,5	12,4
200	16,0	21,0

* Minimum size where WC's are connected in system II.
** Minimum size where WC's are connected in system I, III, IV.

Figure 19: Table within *BS EN 12056-2:2000* for hydraulic capacity (Qmax) and nominal diameter (DN) in primary ventilated discharge stacks (B.S. Institute, 2000)

Table 12 — Hydraulic capacity (Q_{max}) and nominal diameter (DN)

Stack and stack vent	Secondary vent	System I, II, III, IV Q_{max} (l/s)	
DN	DN	Square entries	Swept entries
60	50	0,7	0,9
70	50	2,0	2,6
80*	50	2,6	3,4
90	50	3,5	4,6
100**	50	5,6	7,3
125	70	7,6	10,0
150	80	12.4	18,3
200	100	21,0	27,3

* Minimum size where WC's are connected in system II.
** Minimum size where WC's are connected in system I, III, IV.

Figure 20: Table within *BS EN 12056-2:2000* for hydraulic capacity (Qmax) and nominal diameter (DN) in secondary ventilated discharge stacks (B.S. Institute, 2000)

6.4 Vent Sizing

Hunter (U.S. Department of Commerce, 1923) suggested the following formula is used to calculate the size of vents:

$$(y - a)(x - b) = c$$

Where:

- y is the volume rate of water flow in gallons per minute divided by 7.5 (Hunter at that time having conceived of the "fixture unit" as a volume rate of discharge equal to 7.5 gpm)
- x is the length of vent stack (main vent) in feet
- and a, b, and c are constants.

The values of the above constants were determined from Hunter’s experiment work and is shown below in Figure 21.

TABLE 2. *Computed constants for use in venting equation*

(Hunter)

Diameter of both drainage stack and vent stack	Values of constants		
	a	b	c
in.			
3	6	33	5,780
4	8	27	11,400
5	10	20	20,280
6	12	16	31,240
8	16	12	81,040

Figure 21: Computed constants for Hunter’s Vent Equation (U.S. Department of Commerce, 1923)

(Wyly & Eaton, 1961) understood that air movement within drainage systems was generated by the friction between the water flow down the stack and the enclosed air core. Assuming annular flow at terminal velocity, the air velocity at the air-water boundary would approach the velocity of the water. However, they were aware that is assumption did not hold and that “*general considerations indicate that the velocity gradient in the water section is much steeper than that in the air core*” (Wyly & Eaton, 1961). Hence, they assumed that the mean velocity of the air core within a stack does not exceed 1.5 times the mean water flow terminal velocity. This value of 1.5 is arbitrarily given noting that the data available does not provide this relationship with adequate precision. This assumed relationship between airflow and water downflow can be expressed as (Wyly & Eaton, 1961):

$$Q_a = \frac{A_a V_a}{A_w V_w} \times Q_w = \frac{1 - r_s}{r_s} \times \frac{V_a}{V_w} Q_w$$

Where:

Q_a is the airflow flow rate (gpm)

Q_w is the water flow rate (gpm)

V_a is the airflow velocity ($gmp/inch^2$)

V_w is the water velocity ($gmp/inch^2$)

A_a is the cross-sectional area of the stack occupied by airflow ($inch^2$)

A_w is the cross-sectional area of the stack occupied by water down flow ($inch^2$)

r_s is the fraction of cross-sectional area at terminal velocity that is occupied by water downflow

Substituting $Q_w = 27.8(r_s)^{\frac{5}{3}}(D)^{\frac{8}{3}}$ (this is the imperial version of Manning empirical formula provided in Section 6.2) into the above formula gives:

$$Q_a = 27.8r_s^{\frac{2}{3}}(1 - r_s) \times \frac{V_a}{V_w}(D)^{\frac{8}{3}}$$

Where:

D is the diameter of the pipe (inches)

Using the assumption by Wyly and Eaton (Wyly & Eaton, 1961) that:

$$\frac{V_a}{V_w} = 1.5$$

The relation relating airflow and water flow becomes:

$$Q_a = 41.7r_s^{\frac{2}{3}}(1 - r_s)(D)^{\frac{8}{3}}$$

(Lansing, 2020) stated that this method is currently being used as the basis of recommendations within *BS EN 12056.2:2000* (B.S. Institute, 2000) however further research is required to outline the translation of the above water-to-air relation, and the venting guidelines within the code. Examples of venting requirements in *BS EN 12056.2:2000* (B.S. Institute, 2000) is referenced below in Figure 19 and Figure 20. It is not clarified whether this is the approach used to size branch vents in addition to stack and secondary vents.

(Lansing, 2020) also noted that the now superseded *BS 5572:1994* (B.S. Institute, 1994) considered stack suction pressures. This approach, which limits water downflow to ensure that maximum suction pressures are not exceeded as opposed to assuming a fixed ratio between air and water velocities, is supported by (Swaffield, 2010) as "*a more refined approach as it recognises that the pressure level within a system depends upon the resistance to airflow provided by the design itself*." The *BS 5572:1994* (B.S. Institute, 1994) standard sets the maximum suction pressure within a drainage system to be $375N/m^2$.

The basis of the maximum suction pressure set at $375\ N/m^2$ can be traced back to the work of (Wise, 1954), who specified a ± 1inch pressure range for the design of stacks and vents as an attempt to account for self-siphonage and induced siphonage of trap seals, with some allowance for evaporation. This was followed by (Lillywhite & Wise, 1969) who recommended a minimum 25mm (1 inch) trap-seal reduction subjected to a design pressure drop of 0.375kPa (equivalent to $375\ N/m^2$) based on experimentation conducted in multistorey buildings. The conclusions of (Lillywhite & Wise, 1969) is explained in (Wise & Swaffield, 2002), noting that the trap loss experienced by a full trap of "*uniform bore and curvature*" is typically "*half of the suction when the drop in pressure is less than or equal to the trap depth*"; i.e. for a $500\ N/m^2$ (equivalent to a 50 mm water gauge) suction pressure the trap loss is approximately 25mm. It is noted that the above does not however hold true for WC's, which experience trap seal losses greater than half the suction pressure; i.e. for a $500\ N/m^2$ (equivalent to a 50 mm water gauge) suction pressure the WC trap loss is approximately 32.5mm. (Wise & Swaffield, 2002) also notes that suction pressures greater than trap seal depths result in much larger losses. Assuming a 50mm depth WC trap, a $375\ N/m^2$ (37.5 mm water gauge) maximum suction pressure still allows for 25mm trap seal retention post appliance discharge, to allow for evaporation. Hence, a general $\pm 375\ N/m^2$ maximum pressure variation is specified.

The consequence of this finding was that the previously held assumption that a $250\ N/m^2$ suction pressure was approximately equivalent to a 25mm trap-seal retention, was found to be an underestimation (Wyly & Orloski, 1978).

Further investigation is required to understand how (Lillywhite & Wise, 1969) derived a vent sizing calculation method by designing for a maximum suction pressure of $\pm 375\ N/m^2$. This is relevant as (Wise & Swaffield, 2002) stated the above methodology forms the basis of *BS 5572:1994* (B.S. Institute, 1994) vent sizing tables. Furthermore, (Swaffield, 2010) commented that determining stack capacities based on designing a system such that a maximum suction pressure of $\pm 375\ N/m^2$ is not exceeded, is a more "*refined*" approach. He also noted that this method involved "*an iterative solution rather than a code 'look-up table*'" and determined that "*there is no simple relationship between airflow and applied water* *downflow*". Given that (Swaffield, 2010) identified the iterative nature of this method, it is suspected that (Lillywhite & Wise, 1969) have made steady state assumptions to develop a set of recommendations which can be implemented into code.

The relevant question then becomes how the approximate maximum suction pressure methodology developed by (Lillywhite & Wise, 1969) and implemented in *BS 5572:1994* (B.S. Institute, 1994) compares to the method presented in (Wyly & Eaton, 1961) assuming fixed ratio between air and water velocities. It is not immediately evident which method is more appropriate for implementation.

As a comparison, (Swaffield, 2010) references the work of (White, 2008), noting that for a 125mm stack, *BS 5572:1994* (B.S. Institute, 1994) recommends a 32mm vent stack, *BS EN 12056.2:2000* (B.S. Institute, 2000) recommends a 50mm vent and the ASPE code recommended a 125 mm vent. (Swaffield, 2010) comment that "*Neither code yields any real guidance on how to design to a set maximum suction pressure in the stack*". The above comparison suggests that *BS 5572:1994* (B.S. Institute, 1994) was a less conservative sizing method, followed by the current *BS EN 12056.2:2000* (B.S. Institute, 2000), and lastly the ASPE code, which is significantly oversized in comparison to the British standards. However, to compare vent sizing between these standards, the maximum flow rates through a 125mm stack specified by each code needs to be known. As a comparison, *AS3500.2:2021* (Standards Australia, 2021) recommends a range of vent sizes from 65-125mm for a 125mm stack, depending on developed lengths of vents and fixture unit loading on the stack (see Figure 22 below).

Table 8.5.3.5 — Size of relief vents and stack vents

Size of stack	Maximum fixture units connected	Maximum developed lengths of vents, m							
		Required vent size, DN							
DN		32	40	50	65	80	100	125	150
40	16	6	15						
50	20	8	15	46					
50	36	6	10	30					
65	20		12	40	110				
65	56		7	24	80	170			
80	20		8	27	70	110			
80	80			12	20				
100	150			9	25	70	280		
100	300			8	22	60	216		
100	500			6	19	50	197		
125	300				9	22	95	280	
125	750				7	19	72	230	
125	1 100				6	14	62	190	
150	700				4	9	37	155	300
150	1 300					7	30	130	250
150	2 400					6	24	100	200
225	1 700							16	62
225	4 000							14	43
225	7 000							6	31

Figure 22: Size of relief vents and stack vents *AS/NZS 3500.2:2021* (Standards Australia, 2021)

The above discussion of the theory and assumptions used to inform the stack and vent sizing reflected in codes will be further discussed in Section 6.5 and 6.6 in relation to the findings of recent simulations which reveal the complexities surrounding building drainage design, and in particular, stack and vent sizing.

6.5 Complexities of Vertical Drainage and Venting

As alluded to in the previous section, the expression of (Wyly & Eaton, 1961) assumes a fixed ratio between the mean terminal annular water flow velocity and the mean entrained airflow velocity. In reality, the relationship between entrained airflow and annular water flow appears to be far more complex.

Experimental testing and simulations show that the airflow depends on various other factors in addition to flow volume. For example, the system configuration such as the length of the stack, the number and location of discharge entry points along the stack, and the number and type of fixtures connected to the system are all contributing factors (Lansing, 2020). The presence of junctions discharging into the stack results in local water flow decelerations. Whilst the effect of junctions on water flow may be localised, this results in the propagation of air pressure shockwaves throughout the system. The magnitude of these are variable and highly dependent on system configuration (Lansing, 2020). This phenomenon can be understood by the diagram developed by (Jack & Swaffield, 2009), shown below in Figure 23.

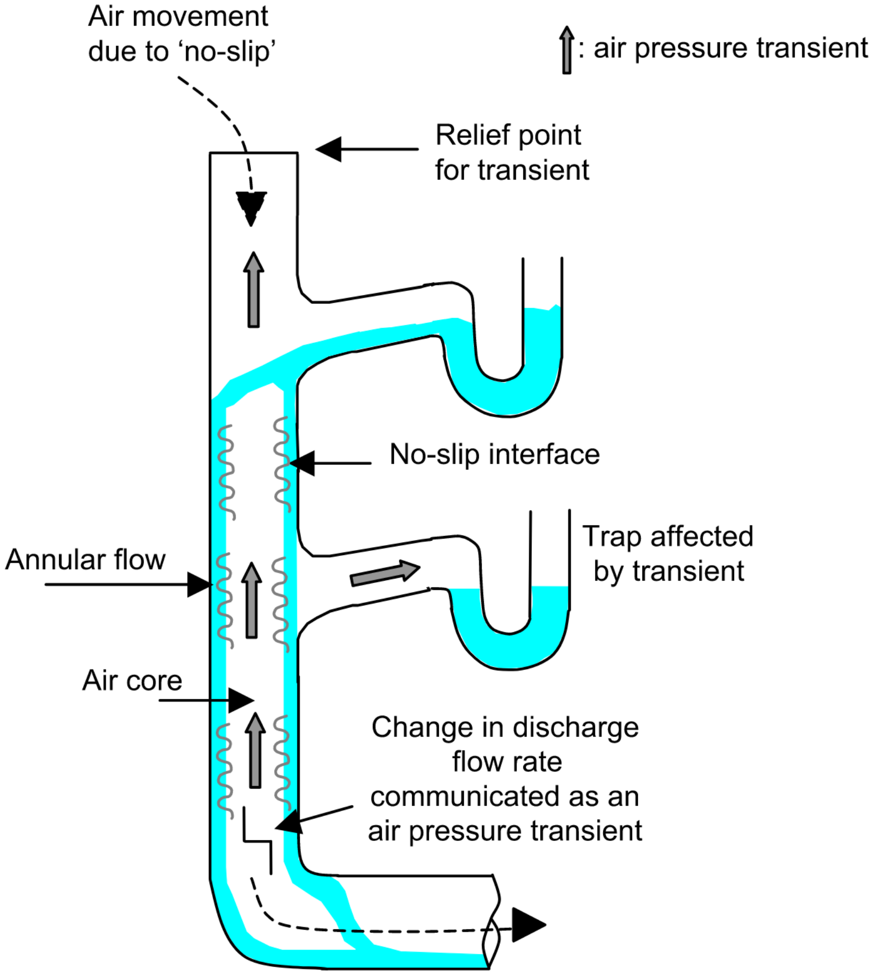

Figure 23: Annular flow within stacks and effects of flow rate changes on pressure transients (Jack & Swaffield, 2009)

The same commentary applies to the maximum cross-sectional area loading method currently used by *BS EN 12056.2:2000* (B.S. Institute, 2000) to size stacks, being that it does not consider or account for the dynamic nature of a drainage system. The assumption of steady state annular flow within stacks does not account for various factors that can influence the pressure regime within the drainage system. Much can be said about the shortfalls and flawed assumptions which underpin the current code recommendations to date (Swaffield, 2010). This includes oversimplifications of the system behaviour by assuming steady state flow, neglecting to account for the effect of pressure transients, and ignoring the steady state energy to relate water flow to air flow. However, more sophisticated simulations of drainage systems which can predict a system's pressure transient response, confirm that there is no unique relation between applied annular water downflow and entrained airflow, further advocating the complexity and dynamic nature of building drainage systems.

The above discussion however, does not negate the effectiveness of the various codes in providing generalised guidelines for sizing that have been implemented at a national and international scale. Whilst the codes do not directly address all the factors that influence the magnitude and propagation of pressure transients, (Jack & Swaffield, 2009) note that "*Generally, the effect of a reduction in flow volume is characterised by an overall reduction in the terminal water velocity within the stack, hence resulting in a corresponding reduction in air entrainment and system pressure*." As a result, the restriction of stack filling capacities below a certain proportion of the cross-sectional area, is a generalised means of minimising suction pressures within the drainage system. Instead, it highlights that sizing and configuring drainage systems in accordance with code requirements may result in under or oversizing of a system depending on the specific design situation. Additionally, the use of the code alone does not provide any insight into the instances when its guidelines lead to an over or under designed system, nor the magnitude with which it under or over designs a system. The use of simulations of system configurations according to code requirements allow for a better clarity on the two issues raised. Examples of the utility of simulations and experimental testing to better inform the codes are provided in Section 6.6 below.

It should also be noted that the above comment by (Jack & Swaffield, 2009) on reduced flow volume and the general consequent reduction in system pressure also alludes to the recent impact of low flow fixtures which has reduced the flows experienced within the system. (Jack & Swaffield, 2009) then proceeded to comment that "*It will be appreciated however, that reduced-volume appliance discharge profiles remain notably time-dependent, and the impact of transient pressures must therefore continue to be assessed in order to ensure trap seal integrity*." Hence, whilst it may be assumed that the codes generally result in over designed systems since they were based on fixtures with higher flows, we cannot make this blanket statement without visibility of the pressure regime resulting in code compliant systems.

6.6 The Role of Simulations and Experimental testing in the Development of Code

We understand that current code sizing methods may result in under or oversizing of vertical stacks, depending on the system configuration. Current research within the drainage field is focused on conducting simulations, which use fundamental St Venant equations of continuity and momentum to accurately simulate water flow and air pressure transients (Gormley, et al., 2021).

As an example, for tall buildings, a simulated single stack drainage system designed to *BS EN 12056-2:2000* (B.S. Institute, 2000) requirements demonstrated compromised system integrity. An AIRNET simulation by (Gormley, et al., 2021) determined that for 5.2 and 12.4L/s loadings for 100 and 150mm stacks respectively (as per *BS EN 12056-2:2000* (B.S. Institute, 2000)), the bottom trap of a 10-story 100mm single-stack system depleted to 19mm, and the middle trap of a 10-story 150mm single-stack system just fell short of code requirements, depleting to 24mm. A summary of the pressure profile, airflow and trap retention is shown below in Figure 24. Their simulation of a 20-story 150mm single-stack system also revealed that the bottom and middle traps were completely depleted (0mm). The above situations demonstrate a breach in system requirements specified by *BS EN 12056-2:2000* (B.S. Institute, 2000), as the code requires a minimum trap retention of 24mm. It should be noted that the fully vented and single-stack systems with AAV's were able to meet minimum trap seal retention depths for 10-story buildings. (Lansing, 2020) comments that calculations of maximum suction pressures by (Lillywhite & Wise, 1969) demonstrated that single stack systems can only serve up to 8 floors, which seems to be in line with the above research.

Whilst the research identified that single stack systems designed to *BS EN 12056-2:2000* (B.S. Institute, 2000) were under sized for tall buildings, it also reflects that fully-vented and single-stack with AAVs may be considered oversized for the design of a 10-story building. Note these systems were not tested for 20 story buildings since their trap depths are maintained well in excess of the minimum 25mm required for a 10-storey building. Regardless, we can only limit that view to the specific system configuration tested by (Gormley, et al., 2021) and we note that this apparent factor of safety provided by fully vented and active ventilation systems for 10 story buildings will diminish as the building height increases.

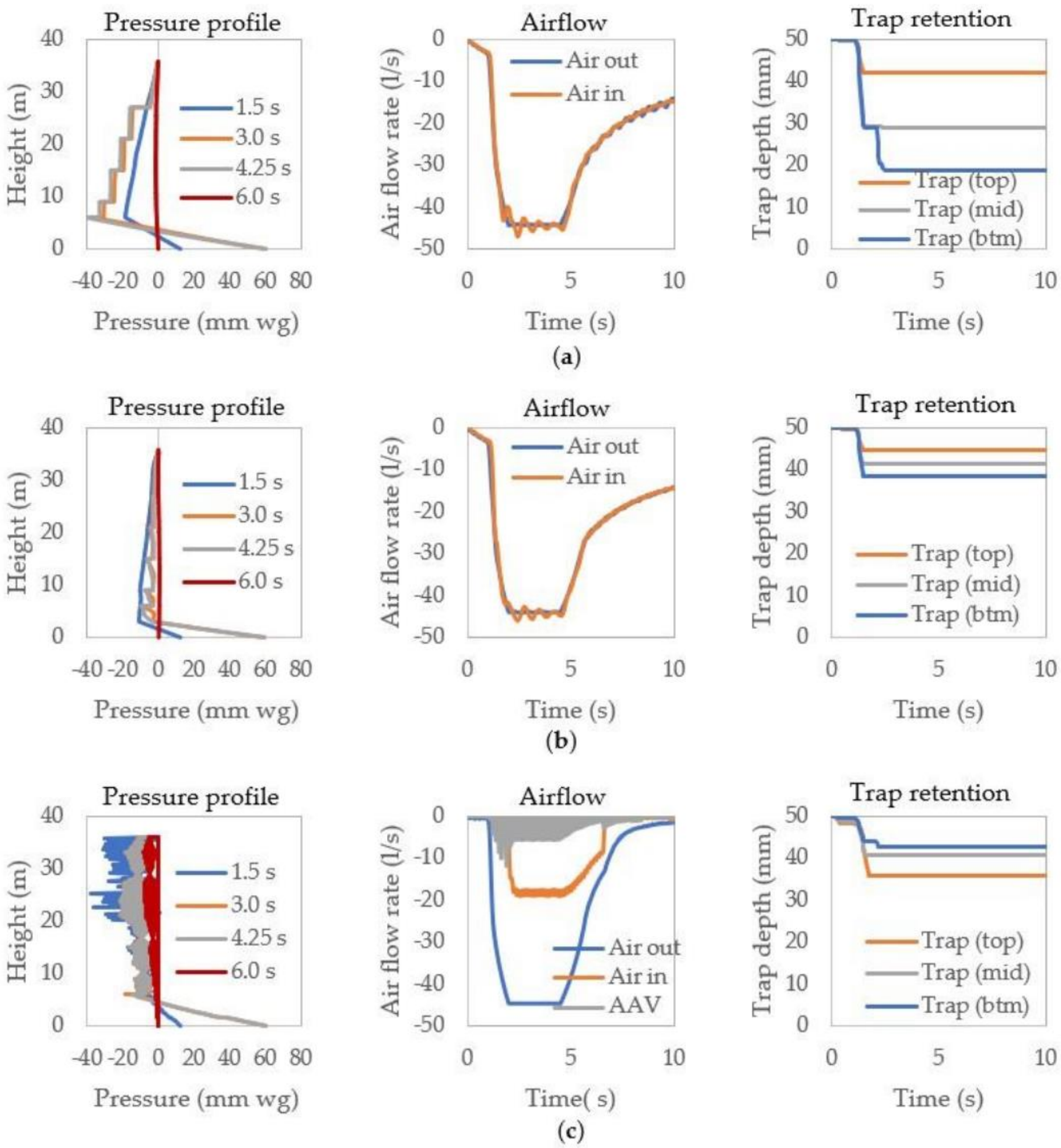

Figure 24: Simulated elements of operational performance for 10 story building with 100 mm dia. stack in system configurations: (a) single-stack; (b) fully-vented; and (c) single-stack with AAVs (Gormley, et al., 2021)

It is also worth noting that AIRNET simulations validated by experimental testing conducted by (Campbell, 2007) has determined the suction pressures of a two-storey building designed by *BS 5572:1994* (B.S. Institute, 1994) with a 2L/s discharge. It is demonstrated that considerably higher suction pressures in excess of $-375\ N/m^2$ were developed within the system when considering the effect of surfactants and at standard hot (55ÞC) and cold (18ÞC) temperatures as shown below in Figure 25 (Campbell, 2007). (Campbell, 2007) concludes this research by advising that if there is a "*temporary blockage due to a secondary concurrent discharge, traps may be depleted or lost*". Hence, we deem that this research highlights unconsidered factors of the code such as discharge temperature and the presence of surfactants, that seem to attenuate the perceived oversizing by the code, and potentially identify issues of under sizing in some circumstances. Whilst we note that the above study does not simulate a system to *BS EN 12056-2:2000* (B.S. Institute, 2000) requirements, but rather *BS 5572:1994* (B.S. Institute, 1994), we note that a similar trend of increasing suction pressures experienced would be identified.

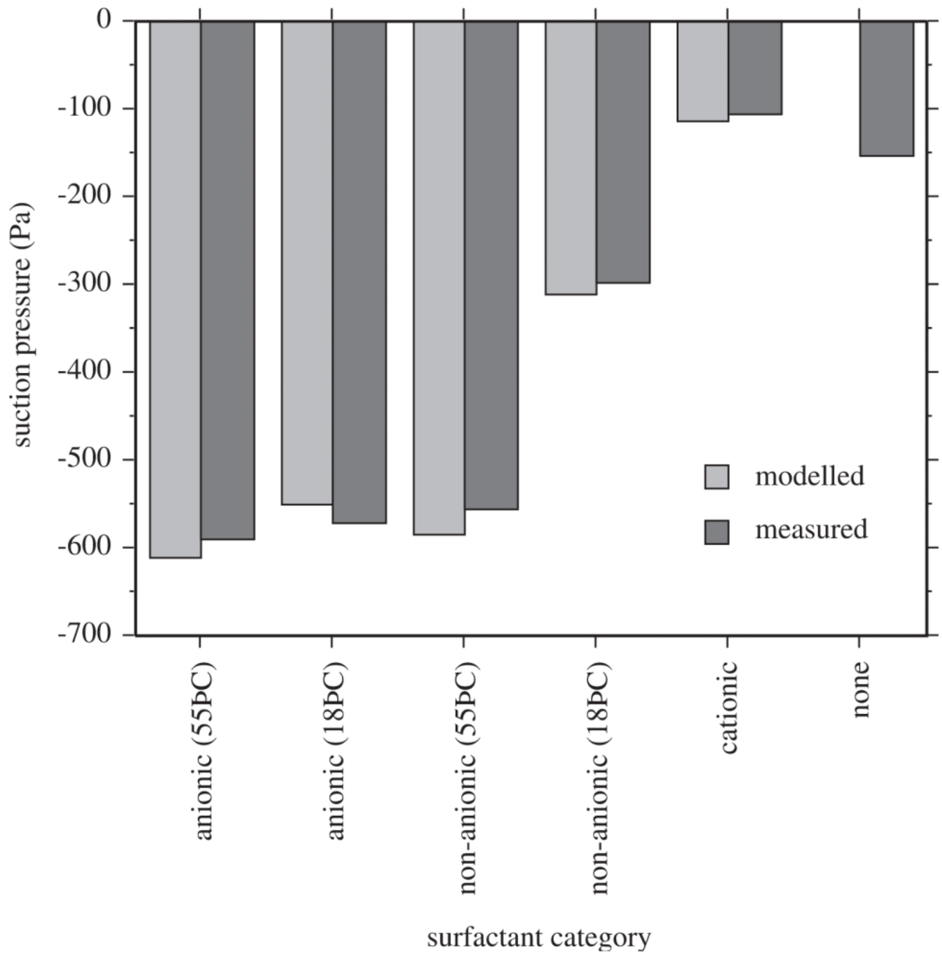

Figure 25: Summary of simulated versus measured air pressures for various detergent classes at set temperatures in 100mm x 5.8m tall glass stack with closed entry to simulate temporary blockage (Campbell, 2007)

In terms of venting recommendations that can be drawn from simulation studies, a study by (Swaffield & Thancanamootoo, 1991) recommends that "*Vent pipe and cross vents should be at least the same diameter as the main stack*". This view is also supported in (Swaffield, 2010), whose simulation work determines that for vents of equal diameter to stacks, only 33% of the air pressure transient wave is reflected at a three-pipe junction of a secondary-ventilated stack, as shown below in Figure 26. We understand that the results of limited studies should not be adopted into codes as "blanket rules", however we consider the results of the above studies to warrant investigation into whether further guidance around vent sizing in the form of consideration of developed vent lengths and stack loading detailed in *AS3500.2:2021* (Standards Australia, 2021) should be adopted in conjunction with *BS EN 12056-2:2000* (B.S. Institute, 2000).

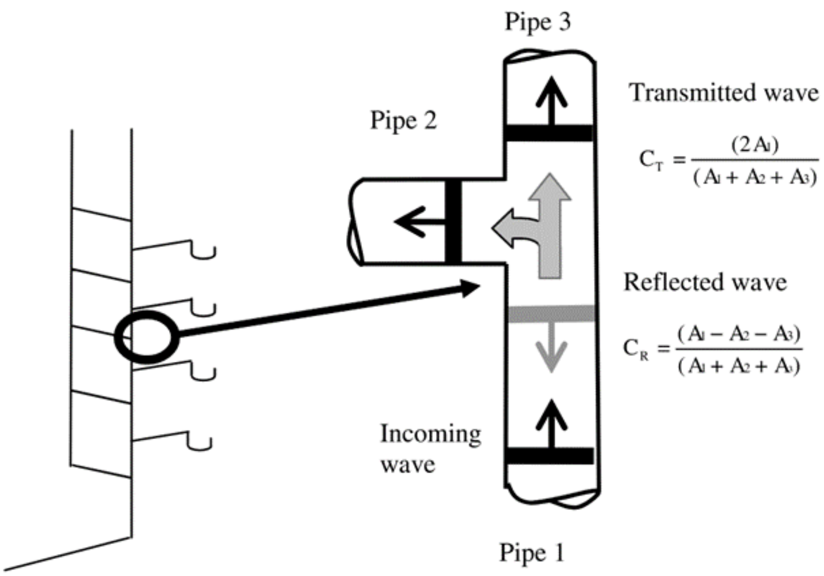

Figure 2.8 Typical three-pipe junction in a building drainage and vent system vertical stack; assume transient arrives from below along pipe 1, possibly due to a change in flow conditions further down the building

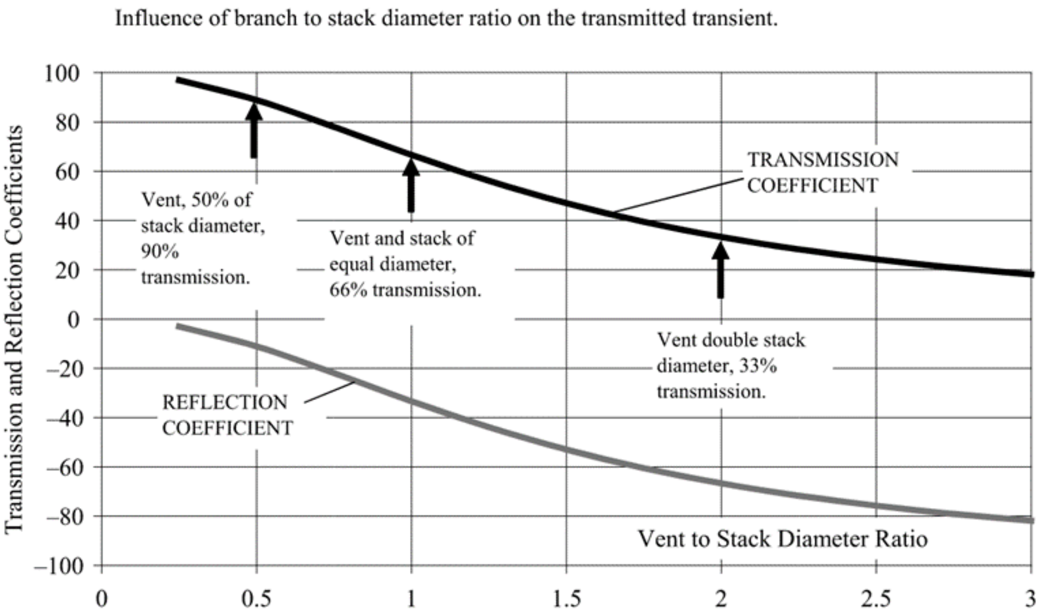

Figure 2.9 Reflection and transmission at a three-pipe junction expressed as % of the incoming wave, taken here as a positive low amplitude air pressure transient

Figure 26: Assessment of Reflection Coefficients at three-pipe junction of a secondary ventilated stack (Swaffield, 2010)

Whilst the results of AIRNET simulations and experimental testing are limited to the specific system configuration that is designed and should not be extrapolated, we note that the above research cited demonstrates the potential for some generalised recommendations to be made to address identified issues of non-compliance with the current code, particularly regarding recommendations around single stack configurations for tall buildings. If the results of simulation studies are to play a greater role in shaping code requirements, a number of simulations of varying parameters (e.g., stack heights, number and type of fixtures connected to stacks on each level) for a given system configuration (e.g., fully vented modified) should be conducted. This may facilitate the derivation of a set of guidelines for maximum allowable flow rates through stacks and corresponding vent sizing for a given set of bounded parameters or operating conditions, or at the very least serve to better gauge how current codes compare to more optimised designs.

6.7 Recommendations

Based on the research captured in this paper and discussions with Heriot-Watt University, we generally support implementing the *BS EN 12056.2:2000* (B.S. Institute, 2000) branch, stack and vent sizing method into the *NCC 2025 Plumbing Code of Australia* within some limitations. This seems to be a tried and tested method for sizing branches, stacks and vents within minimal risk of error. This method also has the benefit of a substantial literature base which is available to trace the origins of the theory underpinning the basis of the code when compared to *AS3500.2:2021* (Standards Australia, 2021). This is further supported by AIRNET testing conducted by research groups such as Heriot-Watt University, noting we are not aware of systems designed to *AS3500.2*:2021 (Standards Australia, 2021) having any validation by simulation such as AIRNET testing but are rather validated through industry feedback following installation which to date has not been measured or captured for analysis.

With the above said, we note that the theoretical backing of the branch sizing method provided by *BS EN 12056.2:2000* (B.S. Institute, 2000) cannot be determined, and that our analysis rules out the possibility of the sizing recommendations being based on the Colebrook-White expression. We suspect that there is an element of branch sizing guidelines driven by 'rules of thumb' developed by the industry over time given the complexities surrounding the unsteady discharge flow rates and associated ventilation that branch drainage experiences.

Prior to the adoption of the *BS EN 12056.2:2000* (B.S. Institute, 2000) method for the sizing of branches, stacks and vents, we recommend than an in-depth comparative assessment between *BS EN 12056.2:2000* (B.S. Institute, 2000) and *AS3500.2:2021* (Standards Australia, 2021) is conducted to better understand the implications of adopting this method for the Australian Plumbing Industry and, to determine whether there are design guidance items provided in *AS3500.2:2021* (Standards Australia, 2021) that could be adopted by the *BS EN 12056.2:2000* (B.S. Institute, 2000). We have not conducted this assessment, but in our research, we have identified the following points for consideration:

- Review recommended minimum grades and maximum length of branch drainage provided by *BS EN 12056-2:2000* (B.S. Institute, 2000) (see Figure 12 and Figure 14) in light of recent literature regarding maximum travel distances of solids subjected to low flow WC flushes; e.g. (Swaffield, 2015). We suspect that higher pipe grades or shorter branch lengths may need to be recommended to account for lower flush volumes transporting the solids.
- Impacts of adopting minimum grades specified by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000), which are lower than those specified by Table 6.6.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021).
- Review differences between maximum branch lengths recommended by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000) and Appendix B.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021).
- Impacts of adopting *AS3500.2:2021* (Standards Australia, 2021) relief vent sizing based on developed lengths and stack loading in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impacts of adopting *AS3500.2:2021* (Standards Australia, 2021) clearance zones at base of stacks and stack entry points in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impacts of using *AS3500.2:2021* (Standards Australia, 2021) stack, main drain and branch vent configurations with an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impact of adopting *AS3500.2:2021* (Standards Australia, 2021) drainage principles for either below ground drainage or elevated above ground drainage in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Header vents are not mentioned by *BS EN 12056.2:2000* (B.S. Institute, 2000). We note that *AS3500.2:2021* (Standards Australia, 2021) provides guidance on sizing header vents.

- As demonstrated by Figure 19 and Figure 20, *BS EN 12056.2:2000* (B.S. Institute, 2000) does not vary relief vent sizing based on the developed vent length as found in *AS3500.2:2021* (Standards Australia, 2021) (see Figure 27 below).

Table 8.5.3.5 — Size of relief vents and stack vents

Size of stack DN	Maximum fixture units connected	Maximum developed lengths of vents, m — Required vent size, DN							
		32	40	50	65	80	100	125	150
40	16	6	15						
50	20	8	15	46					
50	36	6	10	30					
65	20		12	40	110				
65	56		7	24	80	170			
80	20		8	27	70	110			
80	80			12	20				
100	150			9	25	70	280		
100	300			8	22	60	216		
100	500			6	19	50	197		
125	300				9	22	95	280	
125	750				7	19	72	230	
125	1 100				6	14	62	190	
150	700				4	9	37	155	300
150	1 300					7	30	130	250
150	2 400					6	24	100	200
225	1 700							16	62
225	4 000							14	43
225	7 000							6	31

Figure 27: *AS/NZS 3500.2:2021* sizing of relief and stack vents (Standards Australia, 2021)

We also note that the research presented in Section 6.6, raises concerns about whether design scenarios exist where the code may result in under or oversized stacks and vents. In our opinion the *BS EN 12056.2:2000* (B.S. Institute, 2000) method for stack and vent sizing could be refined with guidelines to ensure that under sizing systems is mitigated and thus providing more confidence in the design outcomes. We believe that this should be a priority over any attempts to optimise the standard to avoid over sizing drainage systems. The research of simulation models demonstrates that without consideration of pressure transients or the effects of water flow properties such as surfactants and temperature, we cannot have certainty about whether the code actually over sizes systems.

Our research demonstrates that if *BS EN 12056.2:2000* (B.S. Institute, 2000) is to be adopted, further design guidance needs to be provided on stack height and appropriate system configuration for tall buildings. For example, buildings over 8 storeys may require secondary ventilated stacks to be used instead of primary ventilated (single stack), or that the single stack is upsized. Further academic and experimental research is required into determining appropriate guidance on this matter. Recommendations by literature for minimum relief vent sizing should also be reviewed further and its incorporation into code tested and analysed.

For the *Draft NCC 2022 Volume Three – Plumbing Code of Australia*, our recommended changes are in green as follows:

- C1V1 Clause 2 – Fix formula:

$$Q_{Total} = K\sqrt{\sum DU} + Q_{Other}$$

- Table C1V1a – Expanded frequency factors as shown below in Table 15:

Table 15: Expanded frequency factor table for Draft NCC 2022 Volume 3 Table C1V1a

Fixture Usage Profile	NCC Building Classes	Frequency Factor (K)	Time Between Fixture Use (s)
Intermittent use: e.g., dwelling, guesthouse, apartment buildings or offices	1, 2, ~~3, or~~ 4, or 5	0.4 – 0.6	1900 – 800
Frequent use: e.g., medium use public facilities for hospital, school, restaurant, retail, or hotel	3, ~~5,~~ 6, 7, 8, 9a, or 9c	0.6 – 0.8	800 – 450
Congested use: e.g., high use public facilities for events with concentrated fixture use	9b	0.8 – 1.2	450 – 200
~~Special use: e.g., laboratory~~	~~Not applicable~~	~~1.2~~	

- C1V1a Explanatory Information – Addition of explanatory text below:

  When using these frequency factor figures, the designer should use their own judgement to consider the appropriate factor for the design based on estimated time between fixture use.

- Table C1V1b – DU expansion and omittance of System 3 (full bore flow design) shown below in Table 16:

Table 16: Expanded and modified DU table for Draft NCC 2022 Volume 3 Table C1V1b

Fixture ~~Usage~~	System 1 DU (50% filling degree)	System 2 DU (70% filling degree)	~~System 3~~
Basin	0.5	0.3	~~0.3~~
Bath (without shower)	0.8	0.6	
Bath (with shower)	0.8	0.5	
Bidet	0.5	0.3	
Dishwashing Machine (domestic)	0.8	0.6	~~0.2~~
Shower (single)	0.6	0.4	~~0.4~~
Sink (single and double)	0.8	0.6	~~1.3~~
Urinal (wall-hung)	0.8	0.5	~~0.4~~
Urinal (stall or each 600mm length of slab)	0.2	0.2	
Washing Machine up to 6 kg	0.8	0.6	~~0.6~~
Water Closet (4l cistern)	Not Permitted	1.8	

Water Closet (6l cistern)	2.0	1.8	~~1.2~~
Floor Waste Gully (80mm or 100mm)	Sum of DU from connected fixtures	Sum of DU from connected fixtures	

- C1V1b Explanatory Information – Adjustment as per green text below:

  System types referred to in Table C1V1b are as follows:

  - *System 1 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 50%.*
  - *System 2 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 70%.*
  - ~~*System 3 – A sanitary plumbing system where branch discharge pipes are designed with a filling degree of 100%.*~~
  - *System 1 and 2 are similar to the fully vented modified system* ~~*and System 3 is similar to the single stack system detailed in AS/NZS 3500.2.*~~
  - *Filling degree is defined as the ratio between the height of the fluid in a pipe at design flow (h), and the internal diameter of the pipe (D), or h/D.*

- C1V4 System 3 Branch Design – To be removed in its entirety

7. Bibliography

Ackers, J., Butler, D. & May, R., 1996. *Report 141. Design of Sewers to Control Sediment Problems.* London: CIRIA.

Anon., n.d. *Colebrook-White Equation.* [Online]
Available at: https://engineerexcel.com/colebrook-white-equation/
[Accessed 02 06 2022].

Australian Building Codes Board, 2019. *National Construction Code Volume Three - Plumbing Code of Australia,* s.l.: Australian Building Codes Board.

Australian Building Codes Board, 2022. *National Construction Code Volume Three - Plumbing Code of Australia - Draft,* s.l.: Australian Building Codes Board.

B.S Institute, 2000. *BS EN 12056-2:2000 Gravity drainage systems inside buildings - Part 2: Sanitary pipework, layout and calculation.* London: s.n.

B.S. Institute, 1994. *BS 5572:1994 Code of practice for sanitary pipework.* London: s.n.

B.S. Institute, 2000. *BS EN 12056-2:2000 Gravity drainage systems inside buildings - Part 2: Sanitary pipework, layout and calculation.* London: s.n.

B.S. Institute, 2018. *BS EN 16933-2:2017 Drain and sewer systems outside buildings - design.* London: s.n.

B.S. Institute, 2022. *BS EN 752:2017 Drain and sewer systems outside buildings - sewer system management.* London: B.S. Institution.

Buchberger, S. et al., 2017. *Peak Water Demand Study: Probability Estimates for Efficient Fixtures in Single and Multi-family Residential Buildings,* Illinois: The International Association of Plumbing & Mechanical Officials .

Butler, D. & Davies, J., 2000. *Urban Drainage.* New York: Spoon Press.

Butler, D., May, R. & Ackers, J., 2003. Self-Cleansing Sewer Design Based on Sediment Transport Principles. *Journal of Hydraulic Engineering,* pp. 276-282.

Butler, D. & Pinkerton, B. R. C., 1987. *Gravity flow pipe design charts.* London: Telford.

Campbell, D., 2007. Surfactant effects on air pressure transients in building drainage, waste and ventilation (DWV) systems. *Building and Environment,* p. 1989–1993.

CIBSE, 2019. *Guide G Public health and plumbing engineering,* London: The Chartered Institution of Building Services Engineers.

Cordina, A., 2017. *PCA Performance Parameters Health - Draft Report,* Australian Capital Territory: Northrop.

Dawson, F. M. & Kalinske, A. A., 1939. Report on the hydraulics and pneumatics of the plumbing drainage system. *Technical Bulletin 2 of the National Association of Master Plumbers of the United States.*

Fenton, J. D., 2010. Calculating Resistance to flow in open channels. *Alternative Hydraulics Paper,* 2(5).

GHD, 2015. *Fixture Unit Rating Systems Discussion Paper,* s.l.: s.n.

Gormley, M. et al., 2021. Building Drainage System Design for Tall Buildings: Current Limitations and Public Health Implications. *Buildings.*

Hobbs, I., Anda, M. & Bahri, P. A., 2019. Estimating peak water demand: Literature review of current standing and research challenges. *Results in Engineering,* Volume Volume 4.

Hunter, R. B., 1940. *BMS65 - Methods of Estimating Loads in Plumbing Systems,* Washington: National Bureau of Standards.

Jack, L. B. & Swaffield, J. A., 2009. Embedding sustainability in the design of water supply and drainage systems for buildings. *Renewable Energy,* Volume 34, p. 2061–2066.

Jenkins, A., 2017. *Hydraulics for Gravity Sewer Pipe: A Few Things to Consider.* [Online]
Available at: https://www.conteches.com/pipe-article/article/7/hydraulics-for-gravity-sewer-pipe-a-few-things-to-consider#:~:text=Many%20know%20that%20Polyvinyl%20Chloride,the%20pipe%20wall%20and%20joints.

Johannes van Vuuren, S., 2018. *Biofilm Growth and The Impact it has on the Hydraulic Capacity of Pipelines.* Las Vegas, s.n.

Lansing, J., 2020. *A Comparison of British and American Plumbing Engineering Standards and Practices,* Zurich: World Plumbing Council.

Lillywhite, M. S. T. & Wise, A. F. E., 1969. Towards a general Method for the Design of Drainage Systems in Large Buildings. *Building Research Establishment.*

Lucid Consulting Australia, 2019. *ABCB Sanitary Plumbing & Drainage Pipe Sizing,* s.l.: Lucid Consulting Australia.

Lucid Consulting Australia, 2020. *Sanitary Plumbing and Drainage Pipe Sizing Verification Methods (LCE19798-002),* Sydney: s.n.

Mahajan, B., 1981. Unsteady water depth measurement in a partially flled 7.6. *NBSIR 81-2249.*

McDermott, R., Strong, A. & Griffiths, P., 2019. Solid Transfer in Low Flow Sewers, the Distance Travelled So Far Is Not Enough. *Journal of Environmental Protection,* pp. 164-207 .

Michael, n.d. Building Drainage System Design for Tall Buildings: Current Limitations and Public Health Implications.

Michalos, C. T., 2016. *Hydraulic Effects of Biofilms on the Design and Operation of Wastewater Forcemains,* Colorado: Colorado State University.

Munthali, R. & Huang, X., 2021. A Review of Main Factors Leading to Air Pressure Fluctuations in Branch Drainage Pipes inside Buildings. *Journal of Building Construction and Planning Research,* pp. 66-76.

Nalluri, C. & Ghani, A. A., 1996. Design options for Self-Cleansing Storm Sewers. *Water Science & Technology* , pp. 215-220.

Qiongxian, K., 2020. Drainage Systems of High-Rise Buildings.

SPT, 2019. *ABCB Sanitary Plumbing & Drainage Pipe Sizing,* Sydney: Lucid Consulting Australia.

Standards Australia, 2006. *AS2200-2006 Design charts for water supply and sewerage.* s.l.:SAI Global.

Standards Australia, 2017. *AS/NZS 1260:2017 PVC-U pipes and fittings for drain, waste and vent applications.* s.l.:SAI Global.

Standards Australia, 2017. *AS/NZS 1477:2017 PVC pipes and fittings for pressure applications.* s.l.:s.n.

Standards Australia, 2021. *AS/NZS 3500.0:2021 Plumbing and Drainage Part 0: Glossary of terms.* s.l.:s.n.

Standards Australia, 2021. *AS/NZS 3500.2:2021 Plumbing and drainage Part 2: santary plumbing and drainage.* s.l.:s.n.

Standards Australia, 2021. *AS/NZS 3500.2:2021 Plumbing and drainage Part 2: santary plumbing and drainage.* s.l.:SAI Global.

Swaffield, J. A., 2010. *Transient Airflow in Building Drainage Systems.* London: Spon Press.

Swaffield, J. A., 2015. *Transient Free Surface Flows in Building Drainage Systems.* London: Routledge.

Swaffield, J. A. & Bridge, S., 1983. Applicability of the Colebrook-White Formula to Represent Frictional Losses in Partially Filled Unsteady Pipeflow. *JOURNAL OF RESEARCH of the National Bureau ol Standards,* 88(6).

Swaffield, J. A. & Marriott, B. S. T., 1997. Hospital Drainage Design: A Study of Solid Transport in Steep Gradient Discharge Pipes.

Swaffield, J. A., n.d. Multistorey Building Drainage Network Design An Application of Computer Based Unsteady Partially Filled Pipeflow Analysis.

Swaffield, J. A. & Thancanamootoo, A., 1991. Modelling Unsteady Annular Downflow in Vertical Building Drainage Stacks. *Building and Environment,,* 26(2), pp. 137-142.

Szyk, B., n.d. *Hydraulic Radius Calculator.* [Online]
Available at: https://www.omnicalculator.com/physics/hydraulic-radius
[Accessed 10 06 2022].

Taylor, F. & Wood, W., 1982. *Guidelines on health aspects of plumbing.* s.l.:International Reference Centre for Community Water Supply and Sanitation (IRC) .

U.S. Department of Commerce, 1923. *Recommended minimum requirements for plumbing in dwellings and similar buildings. Final Report of the Subcommittee on Plumbing of the Building Code Committee,* Washington: U.S. Department of Commerce,.

U.S. Department of Commerce, 1928. *Recommended Minimum Requirements for Plumbing,* Washington: National Bureau of Standards.

Vongvisessomjai, N., Tingsanchali, T. & Babel, M. S., 2010. Non-deposition design criteria for sewers with part-full flow. *Urban Water Journal,* p. 61–77.

Water Services Association of Australia, 2002. *WSA 02-2002 Sewerage Code of Australia - Part 1: Planning and Design.* s.l.:Water Services Association of Australia.

Whitehead, A., 2002. *Plumbing Engineering Services Design Guide.* s.l.:Institute of Plumbing.

White, P., 2008. A tall order. *CIBSE Journal Technical File,* p. 54–58.

Wise, A. F. E., 1954. The Royal Sanitary Institute Journal. *Design Factors for One-Pipe Drainage,* 74(4), pp. 231-241.

Wise, A. F. E. & Croft, J., 1954. Investigation of single-stack drainage for multi-storey flats. *Journal of the Royal Sanitary Institute,* pp. 797-826.

Wise, A. F. E. & Swaffield, J. A., 2002. *Water, Sanitary and Waste Services for Buildings.* London: Routledge.

World Health Organization, 2006. *Health Aspects of Plumbing.* s.l.:World Health Organization.

Wyly, R. & Eaton, H., 1961. *Monograph 31 - Capacities of Stacks in Sanitary Drainage Systems for Buildings,* Washington: National Bureau of Standards.

Wyly, R. S. & Eaton, H. N., 1961. *Capacities of Stacks in Sanitary Drainage Systems For Buildings.* s.l.:s.n.

Wyly, R. S. & Orloski, M. J., 1978. *Performance Criteria and Plumbing System Design,* Washington,: National Bureau of Standards.

Zeghadnia, L., Robert, J. L. & Achour, B., 2019. Explicitsolutionsforturbulentflowfrictionfactor:Areview,assessment. *Ain Shams Engineering Journal,* Volume 10, p. 243–252.

A.1 Comparison of Different Mathematical Methods

The current DTS method from *AS/NZS 3500.2:2021* (Standards Australia, 2021) has been compared with the *BS EN 12056-2:2000* (B.S. Institute, 2000) method, Wistort's Method and the Modified Wistort's method. All methods have been compared in terms of their total peak sanitary discharge flowrate for small, medium, and large sized examples.

Two sets of tests have been studied, one for a typical residential building and one for an office building. Each set has a fixture composition relative to each building type. Within each set, a small, medium, and large sized building will be provided for calculation comparison. In the interest of controlling variables to allow the test to remain practical, each set consists of a typical floor based off a realistic typical residential or office level, with the building size multiplied from this typical floor. E.g., a small building has 10no. of the typical floor, a medium building has 30no. of the typical floor, and a large building has 50no. of the typical floor.

We note that whilst we will only be testing an office building and residential tower, this same method can be applied to other building classes.

A.1.1 Simulated Residential Tower Model

A 10, 30 and 50 storey residential tower model has been assessed. For calculation purposes the tower consists of 1-, 2- and 3-bedroom apartments. The tower studied does not consist of any ground floor retail or laundry facilities and car parking has been ignored. Each typical floor of each residential tower is based off the apartment composition shown in Table 17.

Table 17: Distribution of typical apartment layouts on each floor

Apartment Layout	Number of Layouts Per Floor
1 Bedroom	2
2 Bedroom	4
3 Bedroom	1

Each apartment will consist of the following fixtures as shown in Table 18.

Table 18: Number and type of fixtures within each apartment, floor and simulated residential tower

Fixtures	1 Bedroom	2 Bedroom	3 Bedroom	Total No. of Fixtures per Floor	Total No. of Fixtures for 10 Storey	Total No. of Fixtures for 30 Storey	Total No. of Fixtures for 50 Storey
WHB	1	2	3	13	130	390	650
SHR	1	2	3	13	130	390	650
WC	1	2	3	13	130	390	650
KS	1	1	1	7	70	210	350
DW	1	1	1	7	70	210	350
LS	1	1	1	7	70	210	350
Total	*6*	*9*	*12*	*60*	*600*	*1800*	*3000*

A.1.2 Simulated Office Building Model

A 10, 30 and 50 storey office building has been assessed. The tower does consist of any ground floor retail or end of trip facilities and any car parking has been ignored. Each floor is based off a 1500sqm NLA with the following fixtures on each floor–

- 4 x WC's - men
- 6 x WC's - women
- 9 x WHB's

The total number and type of fixtures within the office tower model is summarised below in Table 19.

Table 19: Number and type of fixtures within the simulated office building

Fixtures	Total No. of Fixtures per Floor	Total No. of Fixtures for 10 Storey	Total No. of Fixtures for 30 Storey	Total No. of Fixtures for 50 Storey
WHB	9	90	270	450
WC	10	100	300	500
Total	*19*	*190*	*570*	*950*

A.1.3 Fixture Discharge Flow Rates

Discharge flow rates provided by 'Innovation Engineering' (see Appendix A.6) have been used to test the Wistort and modified Wistort's method. These values have been summarised below in Table 20.

Table 20: Innovation Engineering discharge flow rates for fixtures used in this analysis

Fixtures	Discharge Flow Rate (L/s)
WHB	0.33
SHR	1.12
WC[1]	2.13
KS[2]	1.05
DW	0.16
LS[3]	0.68

An additional arbitrary set of discharge flow rates were also tested to demonstrate the importance of setting an accurate fixture discharge flow rate. The values are summarised in the table below with differences to Table 20 fixture discharge flow rates in green.

Shower flowrates have been rationalised to match the bath discharge rates provided by Innovation Engineering and both the kitchen sink and laundry sink discharge flowrates were rationalised to match the single sink values.

[1] WC with a 6/3L cistern

[2] Kitchen sink assumed to be equivalent to double sink in regard to discharge flow rates

[3] Laundry sink assumed to be equivalent to utility sink in regard to discharge flow rates

Table 21: Additional fixture discharge flow rates used in this analysis for comparative purposes

Fixtures	Discharge Flow Rate (L/s)
WHB	0.33
SHR	0.63
WC[4]	2.13
KS[5]	0.45
DW	0.16
LS[6]	0.45

A.1.4 Fixture Usage Probabilities

The probabilities of fixture discharge are summarised in the table below:

Table 22: Fixture discharge probabilities for residential use cases

Fixtures	Discharge Probability
WHB	0.0075
SHR	0.0450 and 0.0165
WC	0.0033 in residential apartments
WC	0.0042 and 0.0083 for men and women respectively in office buildings
KS	0.0167
DW	0.0050
LS	0.0167

The fixture discharge probabilities were derived based on the following assumptions:

- The WC probability of discharge has been calculated for a residential building by taking the largest supply probability from Figure 28 (0.05) and multiplying it by the conversion factor (5/75) as shown in Figure 30, to arrive at 0.0033. It should be noted that this assumption will overestimate the probability of discharge, since this probability of supply (0.05) is for an average 3.2 occupancy, which we are applying to the 1-, 2- and 3-bedroom apartments within the building.

- We do not have data to convert a supply probability of a sink into a discharge probability; instead we assume that both the kitchen and laundry sink have the same hourly probability of discharge and that they are both equal to the value determined by Table 1.5 of (Wise & Swaffield, 2002) (see Figure 29).

- The DW probability of discharge is assumed equal to the probability of supply value (0.5%) provided in the *Peak Water Demand Study* (Buchberger, et al., 2017).

- We have used data regarding showers from the *Peak Water Demand Study* (Buchberger, et al., 2017), which suggested a supply probability of (0.045) – see Figure 31 below. We assume that the

[4] WC with a 6/3L cistern

[5] Kitchen sink assumed to be equivalent to double sink in regard to discharge flow rates

[6] Laundry sink assumed to be equivalent to utility sink in regard to discharge flow rates

discharge probability will be the same as supply. We note that this study averages discharge events over 1038 homes with an average of 2.72 residents per home and hence, it may overestimate the probability of discharge by applying it to the 1-, 2- and 3-bedroom apartments within the building. A probability of 0.0165 has been tested for comparative purposes.

- The WHB probability of discharge has been calculated for a residential building by taking the largest supply probability from Figure 28 (0.009) and multiplying it by the conversion factor (10/12) as shown in Figure 30, to arrive at 0.0075. We have assumed that this value of discharge probability can also be applied to an office building for the purpose of this analysis.
- The WC probability of discharge for men and women on a given office floor with 50 men allocated 4 WC's and 50 women allocated 6 WC's, is based on the supply probabilities of 0.0625 and 0.125 respectively from Figure 28. Assuming a 5s duration for discharge and 75s duration for inflow (conversion factor of 5/75) we determine outflow probabilities of 0.0042 and 0.0083 for men and women respectively (Wise & Swaffield, 2002).

Table 1.4 Examples of maximum hourly probabilities for water supply points

		Weekday		Saturday		Sunday	
	Water supply point	Maximum probability	Period (hours)	Maximum probability	Period (hours)	Maximum probability	Period (hours)
Flats							
Small, 1.5 occupants on average	WC	0.0155	7–8	0.0133	7–8	0.0116	10–11
	Washbasin (C)	0.0085	8–9	0.0142	14–15	0.0080	9–10
	Washbasin (H)	0.0038	8–9	0.0039	9–10	0.0037	8–9
	Sink (C)	0.0034	9–10	0.0055	8–9	0.0152	10–11
	Sink (H)	0.0154	17–18	0.0136	8–9	0.0179	10–11
	Bath (C)	0.0017	7–8	0.0041	14–15	0.0020	13–14
	Bath (H)	0.0059	16–17	0.0427	14–15	0.0042	13–14
Large, 3.2 occupants on average	WC	0.0501	7–8	0.0417	8–9	0.0443	10–11
	Washbasin (C)	0.0076	7–8	0.0050	9–10	0.0053	9–10
	Washbasin (H)	0.0108	7–8	0.0080	7–8	0.0085	9–10
	Sink (C)	0.0258	17–18	0.0329	10–11	0.0441	11–12
	Sink (H)	0.0342	18–19	0.0310	9–10	0.0415	10–11
	Bath (C)	0.0030	18–19	0.0038	9–10	0.0035	10–11
	Bath (H)	0.0068	22–23	0.0142	11–12	0.0125	14–15
Hospital ward	Washbasin (C)	0.031					
	Washbasin (H)	0.042					
Office building	WC (Men)	Av. interval between uses: 1200 s. Period: 9–12 h Probability based on 75 s inflow duration: 0.0625					
50 men, four WCs 50 women, six WCs	WC (Women)	Av. interval between uses: 600 s. Period: 11–12 h Probability based on 75 s inflow duration: 0.125					

Figure 28: Maximum hourly probabilities of supply points for fixtures within small and large occupancy flats, hospital wards, and office buildings (Wise & Swaffield, 2002)

	Duration of discharge, t(s)	Interval between discharges, T(s)	$p = t/T$
WC	5	1140	0.0044
Washbasin	10	1500	0.0067
Sink	25	1500	0.0167

Figure 29: Maximum hourly probabilities of discharge in domestic use (Wise & Swaffield, 2002)

	WC	Washbasin
Supply probability	0.05	0.009
Duration of flow at an individual water supply point (s)	75	12
Duration of discharge from an appliance (s)	5	10
Conversion factor	5/75	10/12
Supply probability multiplied by conversion factor	0.0033	0.0075
Discharge probability (table 1.5)	0.0044	0.0067

Figure 30: Conversion of supply probabilities to discharge probabilities (Wise & Swaffield, 2002)

Fixture	Design P value (%)	Maximum Recommended Design Flow Rate (gpm)
Bar Sink	2.0	1.5
Bathtub	1.0	5.5
Bidet	1.0	2.0
Clothes Washer	5.5	3.5
Combination Bath/Shower	5.5	5.5
Dishwasher	0.5	1.3
Kitchen Faucet	2.0	2.2
Laundry Faucet	2.0	2.0
Lavatory Faucet	2.0	1.5
Shower, per head	4.5	2.0
Water Closet, 1.28 GPF Gravity Tank	1.0	3.0

Figure 31: Probability of fixture use (p) and fixture flow rate (q) (Buchberger, et al., 2017)

A.1.5 AS/NZS 3500:2:2021 Fixture Unit Method

A summary of fixture units provided by Table 6.3(a) *AS/NZS 3500.2:2021* (Standards Australia, 2021) for the above fixtures is provided below in .

Table 23 below.

Table 23: Fixture Unit ratings for fixtures tested in this analysis

Fixtures	FU
WHB	1
SHR	2
WC (with cistern)	4
KS (double sink)	3
DW	3
LS (utility sink)	5

The formula for the conversion from fixture units (FU) (specified in AS3500.2 (Standards Australia, 2021)) to flow rate is given by Swaffield (Swaffield & Bridge, 1983):

$$Q_{water} = \sqrt{\frac{\sum FU}{6.75}}$$

Although this conversion from FU to equivalent flow in L/s applies only to a single fixture, we believe it is a fair assumption that the flows at the tail end of the building sanitary drainage system approaches a continuous flow, thus ensuring a reasonable accuracy when proceeding with the calculation. Furthermore, it provides a method to reasonably calculate the L/s equivalent of FU.

A summary of the total discharge flow rates for the 10-, 20- and 30-storey residential tower and office building have been summarised below in Table 26 and Table 27 respectively.

Table 24: Total number of FU per typical bedroom layout used in analysis.

Fixtures	**1 Bedroom Fixture Count**	**1 Bedroom FU Total**	**2 Bedroom Fixture Count**	**2 Bedroom FU Total**	**3 Bedroom Fixture Count**	**2 Bedroom FU Total**
WHB	1	1	2	2	3	3
SHR	1	2	2	4	3	6
WC	1	4	2	8	3	12
KS	1	3	1	3	1	3
DW	1	3	1	3	1	3
LS	1	5	1	5	1	5
Total	*6*	*18*	*9*	*25*	*12*	*31*

Table 25: Total number of fixtures and respective FU for the 10-, 20- and 30-storey residential tower using *AS/NZS 3500.2:2021* (Standards Australia, 2021)

Fixtures	**Total No. of Fixtures per Floor**	**Total Fixtures for 10 Storey**	**Total FU for 10 Storey**	**Total Fixtures for 30 Storey**	**Total FU for 30 Storey**	**Total Fixtures for 50 Storey**	**Total FU for 50 Storey**
WHB	13	130	130	390	390	650	650
SHR	13	130	260	390	780	650	1300
WC	13	130	520	390	1560	650	2600
KS	7	70	210	210	630	350	1050
DW	7	70	210	210	630	350	1050
LS	7	70	350	210	1050	350	1750
Total	*60*	*600*	*1680*	*1800*	*5040*	*3000*	*8400*

Table 26: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using *AS/NZS 3500.2:2021* (Standards Australia, 2021)

	10 Storey Apartment	**30 Storey Apartment**	**50 Storey Apartment**
Total FU	1680	5040	8400
Flow Rate (L/s)	15.8	27.3	35.3

Table 27: Total number of fixtures and respective FU for the 10-, 20- and 30-storey office building using *AS/NZS 3500.2:2021* (Standards Australia, 2021)

Fixtures	**Total No. of Fixtures per Floor**	**Total Fixtures for 10 Storey**	**Total FU for 10 Storey**	**Total Fixtures for 30 Storey**	**Total FU for 30 Storey**	**Total Fixtures for 50 Storey**	**Total FU for 50 Storey**
WHB	9	90	90	270	270	450	450
WC – Men	4	40	160	120	480	200	800
WC - Women	6	60	240	180	720	300	1200
Total	*19*	*190*	*490*	*570*	*1470*	*950*	*2450*

Table 28: Total discharge flow rates for the 10-, 20- and 30-storey office building using *AS/NZS 3500.2:2021* (Standards Australia, 2021)

	10 Storey Office	**30 Storey Office**	**50 Storey Office**
Total FU	490	*1470*	*2450*
Flow Rate (L/s)	*8.5*	*14.8*	*19.1*

A.1.6 BS EN 12056-2:2000 Discharge Unit Method

The formula for the conversion from discharge units (DU) to flow rate is given in BS EN 12056-2:2000 (B.S. Institute, 2000):

$$Q_{water} = K\sqrt{\sum DU}$$

where K is the frequency factor provided in Table 8.3 of *BS EN12056-2:2000* (B.S. Institute, 2000), shown below in Figure 32.

Usage of appliances	***K***
Intermittent use, e.g. in dwelling, guesthouse, office	0,5
Frequent use, e.g. in hospital, school, restaurant, hotel	0,7
Congested use, e.g. in toilets and/or showers open to public	1,0
Special use, e.g. laboratory	1,2

Figure 32: Frequency factors provided by *BS EN 12056-2:2000* (B.S. Institute, 2000)

From Figure 32 above, the K-factor for both a residential tower and office would be $K = 0.5$. Discharge unit values for various fixtures tested in this analysis as per System I values in Table 2 of *BS EN 12056.2:2000* (B.S. Institute, 2000) are summarised below in Table 29.

Table 29: Discharge Unit ratings for fixtures tested in this analysis

Fixtures	DU
WHB	0.5
SHR (without plug)	0.6
WC (6L cistern)	2.0
KS	0.8
DW	0.8
LS[7]	0.8

Table 2 — Discharge units (DU)

Appliance	System I	System II	System III	System IV
	DU l/s	DU l/s	DU l/s	DU l/s
Wash basin, bidet	0,5	0,3	0,3	0,3
Shower without plug	0,6	0,4	0,4	0,4
Shower with plug	0,8	0,5	1,3	0,5
Single urinal with cistern	0,8	0,5	0,4	0,5
Urinal with flushing valve	0,5	0,3	-	0,3
Slab urinal	0,2*	0,2*	0,2*	0,2*
Bath	0,8	0,6	1,3	0,5
Kitchen sink	0,8	0,6	1,3	0,5
Dishwasher (household)	0,8	0,6	0,2	0,5
Washing machine up to 6 kg	0,8	0,6	0,6	0,5
Washing machine up to 12 kg	1,5	1,2	1,2	1,0
WC with 4,0 l cistern	**	1,8	**	**
WC with 6,0 l cistern	2,0	1,8	1,2 to 1,7***	2,0
WC with 7,5 l cistern	2,0	1,8	1,4 to 1,8***	2,0
WC with 9,0 l cistern	2,5	2,0	1,6 to 2,0***	2,5
Floor gully DN 50	0,8	0,9	-	0,6
Floor gully DN 70	1,5	0,9	-	1,0
Floor gully DN 100	2,0	1,2	-	1,3

* Per person.
** Not permitted.
*** Depending upon type (valid for WC's with siphon flush cistern only).
\- Not used or no data.

Figure 33: Discharge units as per *BS EN 12056:2000* categorised by system and fixture type (B.S. Institute, 2000)

A summary of the total discharge flow rates for the 10-, 20- and 30-storey residential tower and office building have been summarised below in Table 32 and Table 34 respectively.

[7] DU of a Laundry sink assumed to be equivalent to that of a kitchen sink

Table 30: Total number of FU per typical bedroom layout used in analysis.

Fixtures	1 Bedroom Fixture Count	1 Bedroom DU Total	2 Bedroom Fixture Count	2 Bedroom DU Total	3 Bedroom Fixture Count	2 Bedroom DU Total
WHB	1	0.5	2	1.0	3	1.5
SHR	1	0.6	2	1.2	3	1.8
WC	1	2.0	2	4.0	3	6.0
KS	1	0.8	1	0.8	1	0.8
DW	1	0.8	1	0.8	1	0.8
LS	1	0.8	1	0.8	1	0.8
Total	*6*	*5.5*	*9*	*8.5*	*12*	*11.7*

Table 31: Total number of fixtures and respective DU for the 10-, 20- and 30-storey residential tower using *BS EN 12056-2:2000* (B.S. Institute, 2000)

Fixtures	Total No. of Fixtures per Floor	Total Fixtures for 10 Storey	Total DU for 10 Storey	Total Fixtures for 30 Storey	Total DU for 30 Storey	Total Fixtures for 50 Storey	Total DU for 50 Storey
WHB	13	130	65	390	195	650	325
SHR	13	130	78	390	234	650	390
WC	13	130	260	390	780	650	1300
KS	7	70	56	210	168	350	280
DW	7	70	56	210	168	350	280
LS	7	70	56	210	168	350	280
Total	*60*	*600*	*571*	*1800*	*1713*	*3000*	*2855*

Table 32: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using *BS EN 12056-2:2000* (B.S. Institute, 2000)

	10 Storey Apartment	30 Storey Apartment	50 Storey Apartment
Total DU	571	1713	2855
Flow Rate (L/s)	12.0	20.7	26.7

Table 33: Total number of fixtures and respective FU for the 10-, 20- and 30-storey office building using *BS EN 12056-2:2000* (B.S. Institute, 2000)

Fixtures	**Total No. of Fixtures per Floor**	**Total Fixtures for 10 Storey**	**Total FU for 10 Storey**	**Total Fixtures for 30 Storey**	**Total FU for 30 Storey**	**Total Fixtures for 50 Storey**	**Total FU for 50 Storey**
WHB	9	90	45	270	135	450	225
WC – Men	4–40	80	120	240	200	400	
WC - Women	6	60	120	180	360	300	600
Total	*19*	*190*	*245*	*570*	*735*	*950*	*1225*

Table 34: Total discharge flow rates for the 10-, 20- and 30-storey office building using *BS EN 12056-2:2000* (B.S. Institute, 2000)

	10 Storey Office	**30 Storey Office**	**50 Storey Office**
Total FU	245	735	1225
Flow Rate (L/s)	7.8	13.6	17.5

A.1.7 Wistort's Method

A summary of the total discharge flow rates for the 10-, 20- and 30-storey residential tower with a 0.045 and 0.0165 shower discharge probability have been summarised below in Table 35 and Table 36 respectively. The total discharge flow rates for the 10-, 20- and 30-storey office building is summarised in Table 37. The Wistort's Method involves the equation below as discussed in Section 4.3:

$$Q_{0.99} = \sum_{k=1}^{K} n_k p_k q_k + (z_{0.99}) \sqrt{\sum_{k=1}^{K} n_k p_k (1 - p_k) q_k^2}$$

The discharge rate (q), fixture discharge probability (p) and number of fixtures are detailed in Appendix Sections A.1.1 to A.1.4.

Table 35: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using Wistort's Method and a 0.045 probability of discharge for showers

	10 Storey Apartment	**30 Storey Apartment**	**50 Storey Apartment**
$\sum_{k=1}^{K} n_k p_k (1 - p_k) q_k^2$	10.86	32.58	54.31
$\sum_{k=1}^{K} n_k p_k q_k$	9.87	29.60	49.33
$\sum_{k=1}^{K} n_k p_k$	9.94	29.83	49.71
Total Flow Rate (L/s)	*17.5*	*42.9*	*66.5*

Table 36: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using Wistort's Method and a 0.0165 probability of discharge for showers

	10 Storey Apartment	30 Storey Apartment	50 Storey Apartment
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	6.50	19.50	32.50
$\sum_{k=1}^{K} n_k p_k q_k$	5.72	17.15	28.58
$\sum_{k=1}^{K} n_k p_k$	6.24	18.71	31.19
Total Flow Rate (L/s)	*11.6*	*27.4*	*41.8*

Table 37: Total discharge flow rates for the 10-, 20- and 30-storey office building using Wistort's Method

	10 Storey Office	30 Storey Office	50 Storey Office
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	3.08	9.22	15.36
$\sum_{k=1}^{K} n_k p_k q_k$	1.64	4.92	8.21
$\sum_{k=1}^{K} n_k p_k$	1.34	4.02	6.71
Total Flow Rate (L/s)	*5.7*	*12.0*	*17.3*

A.1.8 Modified Wistort's Method

A summary of the total discharge flow rates for the 10-, 20- and 30-storey residential tower with a 0.045 and 0.0165 shower discharge probability have been summarised below in Table 38 and Table 39 respectively. The total discharge flow rates for the 10-, 20- and 30-storey office building is summarised in Table 40. The Modified Wistort's Method involves the equation below as discussed in Section 4.3:

$$Q_{0.99} = \frac{1}{1-P_0}\left(\sum_{k=1}^{K} n_k p_k q_k + [(1+P_0) z_{0.99}] \sqrt{\left[(1-P_0)\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2\right] - P_0\left(\sum_{k=1}^{K} n_k p_k q_k\right)^2}\right)$$

Where:

$$P_0 = \prod_{k=1}^{K} (1-p_k)^{n_k}$$

The discharge rate (q), fixture discharge probability (p) and number of fixtures are detailed in Appendix Sections A.1.1 to A.1.4.

Table 38: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using Modified Wistort's Method and a 0.045 probability of discharge for showers

	10 Storey Apartment	30 Storey Apartment	50 Storey Apartment
$\prod_{k=1}^{K}(1-p_k)^{n_k}$	4.09681E-05	6.87603E-14	1.15406E-22
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	10.861040	32.583121	54.305202
$\sum_{k=1}^{K} n_k p_k q_k$	9.865890	29.597670	49.329450
$\sum_{k=1}^{K} n_k p_k$	9.942	29.826	49.71
Total Flow Rate (L/s)	*17.5*	*42.9*	*66.5*

Table 39: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using Modified Wistort's Method and a 0.0165 probability of discharge for showers

	10 Storey Apartment	30 Storey Apartment	50 Storey Apartment
$\prod_{k=1}^{K}(1-p_k)^{n_k}$	0.001873592	6.57696E-09	2.30874E-14
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	6.499313	19.497939	32.496564
$\sum_{k=1}^{K} n_k p_k q_k$	5.716290	17.148870	28.581450
$\sum_{k=1}^{K} n_k p_k$	6.237	18.711	31.185
Total Flow Rate (L/s)	*11.7*	*27.42*	*41.8*

Table 40: Total discharge flow rates for the 10-, 20- and 30-storey residential tower using Modified Wistort's Method, a 0.0165 probability of discharge for showers and alternative fixture discharge flowrates

	10 Storey Apartment	**30 Storey Apartment**	**50 Storey Apartment**
$\prod_{k=1}^{K}(1-p_k)^{n_k}$	0.001873592	6.57696E-09	2.30874E-14
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	3.357045	10.071136	16.785226
$\sum_{k=1}^{K} n_k p_k q_k$	3.694970	11.084910	18.474850
$\sum_{k=1}^{K} n_k p_k$	6.237	18.711	31.185
Total Flow Rate (L/s)	*8.0*	*18.5*	*28.0*

Table 41: Total discharge flow rates for the 10-, 20- and 30-storey office building using Wistort's Method

	10 Storey Office	**30 Storey Office**	**50 Storey Office**
$\prod_{k=1}^{K}(1-p_k)^{n_k}$	0.260285551	0.017633973	0.001194676
$\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2$	3.072578	9.217733	15.362888
$\sum_{k=1}^{K} n_k p_k q_k$	1.641330	4.923990	8.206650
$\sum_{k=1}^{K} n_k p_k$	1.341	4.023	6.705
Total Flow Rate (L/s)	*7.2*	*12.1*	*17.3*

A.1.9 Conclusion

A summary of the above analysis is presented in Table 42 and Table 43 below. This analysis demonstrates that determining accurate discharge flow rates and probability of use (discharge) is crucial for obtaining accurate results with both the Wistort's and Modified Wistort's method. For example, significantly larger total discharge flow rates are obtained by the Wistort's and Modified Wistort's method in comparison to the AS and BS method when a probability of use of 0.045 instead of 0.0165 is used. By implementing a lower probability of use and adjusting discharge flowrates of the shower, kitchen sink, and laundry sink, a significant reduction in the discharge flowrate differences is realised.

For the office building, the Wistort's and Modified Wistort's method generally produced similar or slightly lower flow rates compared to AS and BS, with the Wistort's method slightly underestimating the demand of a 10-storey building. The underestimation however falls in line with our understanding of the Wistort's method and is expected.

Table 42: Total Discharge Flow Rates from 10-, 20- and 30- storey residential towers

Calculation Method	**10 Storey Residential Tower**	**30 Storey Residential Tower**	**50 Storey Residential Tower**
AS3500.2:2021	15.8	27.3	35.3
BS EN 12056:2’00	11.9	20.7	26.7
Wistort's Method (*0.0165 probability* of discharge for a shower)	11.6	7.4	41.8
Modified Wistort's Method (*0.0165 probability* of discharge for a shower)	11.7	27.4	41.8
Wistort's Method (*0.045 probability* of discharge for a shower)	17.5	2.9	66.5
Modified Wistort's Method (*0.045 probability* of discharge for a shower)	17.5	’2.9	66.5
Modified Wistort's Method (*0.0165 probability* of discharge for a shower and adjusted discharge flowrates)	8.0	18.5	28.0

Table 43: Total Discharge Flow Rates from 10-, 20- and 30- storey office buildings

Calculation Method	**10 Storey Office**	**30 Storey Office**	**50 Storey Office**
AS3500.2:2021	8.5	14.8	19.1
BS EN 12056:2000	7.8	13.6	17.5
Wistort's Method	5.7	12.0	17.3
Modified Wistort's Method	7.2	12.1	17.3

A.2 Colebrook-White Equation Assessment

A.2.1 Comparison of Tables from Proposed Verification Methods by Lucid to BS EN 12056-2:2000

Variation between the flow rate and velocity values of drains provided by (Lucid Consulting Australia, 2020) and *BS EN 12056-2:2000* (B.S. Institute, 2000) for varying filling degrees, drain diameters and slopes have been identified. The values compared are shown below in Table 44 to Table 47.

It should be noted that the flow rate value reported by *BS EN 12056-2:2000* (B.S. Institute, 2000) for a DN225 diameter drain with a 3% slope was 389.2L/s; this is an obvious error given the data trend and it is assumed that the correct value is 38.9L/s (this amended value is shown in red in Table 46).

The assumptions and values used by both (Lucid Consulting Australia, 2020) and *BS EN 12056-2:2000* (B.S. Institute, 2000) are outlined below:

- Both (Lucid Consulting Australia, 2020) and *BS EN 12056-2:2000* (B.S. Institute, 2000) calculate flow rate and velocity values for 50 and 70% filling degrees. It should be noted that filling degrees (h/D) refer to the ratio of the depth of water (h) to the diameter of the pipe (D), as opposed to the percentage area of the pipe that is filled. For reference, a pipe with a filling degree of $h/D = 0.7$ corresponds to a 75% full pipe.

- Both (Lucid Consulting Australia, 2020) and *BS EN 12056-2:2000* (B.S. Institute, 2000) state use of $k = 0.001\ m$ for the Colebrook-White roughness coefficient (k).

- *BS EN 12056-2:2000* (B.S. Institute, 2000) states the use of a kinematic viscosity of water of $v = 1.31 \times 10^{-6}\ m^2/s$. (Lucid Consulting Australia, 2020) states the use of a kinematic viscosity of 20ºC clean water ($1.31 \times 10^{-6}\ m^2/s$), however, Table 1 of *AS2200-2006* (Standards Australia, 2006) specifies that 10 ºC water has a kinematic viscosity of $1.31 \times 10^{-6}\ m^2/s$ whilst 20ºC clean water with a kinematic viscosity of $1.01 \times 10^{-6}\ m^2/s$. Calculations to compare both kinematic viscosity values have been conducted to determine the value used by Lucid

- (Lucid Consulting Australia, 2020) uses AS internal diameter values adopted from Table 4.1 of *AS/NZS 1260:2017* (Standards Australia, 2017). Plain wall PVC-U was chosen as it is the most common material used in sanitary drainage systems. *BS EN 12056-2:2000* (B.S. Institute, 2000) specifies in Section 6 that all capacities are calculated using British internal pipe diameters. Whilst the Colebrook tables are provided in Appendix B of the document (not section 6), and no clarification within the Appendix sections are given to confirm that British internal diameters are used, it is fair to assume that this is the case. This has been verified in Section A.2.4. of this appendix.

- Both (Lucid Consulting Australia, 2020) and calculations within *BS EN 12056-2:2000* (B.S. Institute, 2000) use the Colebrook White Equation from *AS2200-2016* (Standards Australia, 2006). There are formulas for using either the diameter of the pipe or the hydraulic radius.
The formula for calculating the velocity within a full pipe is:

$$V = -2(gDS)^{0.5} \log\left(\frac{k}{3.7D} + \frac{2.51v}{D(2gDS)^{0.5}}\right)$$

The formula for calculating the velocity within a partially full pipe was developed by substituting the hydraulic radius in place of the diameter ($D = 4R$):

$$V = -(32gRS)^{0.5} \log\left(\frac{k}{14.8R} + \frac{1.255v}{R(32gRS)^{0.5}}\right)$$

Where:

$n =$ Manning roughness coefficient

$k =$ Colebrook-White roughness coefficient (m)

$V =$ Velocity (m/s)

$R =$ Hydraulic Radius (m) (=$D/4$ for circular pipes)

$D =$ Circular cross-sectional pipe, inside diameter (m)

$S =$ Slope (m/m)

- The methodology within (Lucid Consulting Australia, 2020) for calculating 50% and 70% capacity involves calculating the 100% capacity using the above formula and then derating the filling ratio to 50 and 70% using Chart 13 of *AS2200-2006* (Standards Australia, 2006). From Chart 13, (Lucid Consulting Australia, 2020) derived the following values:
    - 50% Filling Ratio
        - Velocity = 99.7% of full pipe velocity
        - Flow rate = 50% of full pipe velocity
    - 70% Filling Ratio
        - Velocity = 111.9% of full pipe velocity
        - Flow rate = 83.7% of full pipe velocity
- *BS EN 12056-2:2000* (B.S. Institute, 2000) states the use of the Colebrook White Equation to calculate the 50% and 70% filling ratio velocities and flow rates, hence it is assumed they do not use Chart 13 to de-rate and use the formula with hydraulic radius.
- Neither (Lucid Consulting Australia, 2020), *BS EN 12056-2:2000* (B.S. Institute, 2000) or *AS2200-2006* (Standards Australia, 2006) qualify how the flow rate is determined, however it is assumed the following formula has been used:

$$Q = V \times A$$

  Where:

    - V is the velocity calculated by the Colebrook-White equation; and
    - A is the cross sectional area of flow

  This formula for flow rate is consistent with the theory presented in various online sources and the Butler and Pinkerton charts (Butler & Pinkerton, 1987).

Table 44: CV2.9 – Drain capacity with a filling degree of 50% (Lucid Consulting Australia, 2020)

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	-	-	-	-	14.9	0.8	28.8	1.0
1.00	-	-	7.2	0.9	21.2	1.2	40.8	1.4
1.50	3.0	0.8	8.9	1.1	26.0	1.4	50.0	1.7
2.00	3.4	1.0	10.3	1.3	30.0	1.7	57.8	2.0
2.50	3.9	1.1	11.5	1.4	33.6	1.9	64.7	2.2
3.00	4.2	1.2	12.6	1.6	36.8	2.0	70.9	2.4
3.50	4.6	1.3	13.6	1.7	39.8	2.2	76.6	2.6
4.00	4.9	1.4	14.6	1.8	42.5	2.4	81.9	2.8
4.50	5.2	1.5	15.5	1.9	45.1	2.5	86.9	2.9
5.00	5.5	1.5	16.3	2.0	47.6	2.6	91.6	3.1

Table 45: CV2.10 – Drain capacity with a filling degree of 70% (Lucid Consulting Australia, 2020)

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	-	-	-	-	25.0	0.9	48.1	1.1
1.00	4.1	0.8	12.1	1.0	35.5	1.3	68.3	1.5
1.50	5.0	0.9	14.9	1.2	43.5	1.6	83.7	1.9
2.00	5.8	1.1	17.2	1.4	50.3	1.9	96.8	2.2
2.50	6.5	1.2	19.3	1.6	56.2	2.1	108.3	2.5
3.00	7.1	1.3	21.1	1.8	61.6	2.3	118.6	2.7
3.50	7.7	1.4	22.8	1.9	66.6	2.5	128.2	2.9
4.00	8.2	1.5	24.4	2.0	71.2	2.6	137.1	3.1
4.50	8.7	1.6	25.9	2.2	75.5	2.8	145.4	3.3
5.00	9.2	1.7	27.3	2.3	79.7	3.0	153.3	3.5

Table 46: B.1 Capacity of drains, filling degree 50 %, (h/d = 0,5) (B.S. Institute, 2000)

Slope (%)	**DN100**		**DN150**		**DN225**		**DN300**	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	1.8	0.5	5.4	0.6	15.9	0.8	34.1	1.0
1.00	2.5	0.7	7.7	0.9	22.5	1.2	48.3	1.4
1.50	3.1	0.8	9.4	1.1	27.6	1.5	59.2	1.8
2.00	3.5	1.0	10.9	1.3	31.9	1.7	68.4	2.0
2.50	4.0	1.1	12.2	1.5	35.7	1.9	76.6	2.3
3.00	4.4	1.2	13.3	1.6	38.9	2.1	83.9	2.5
3.50	4.7	1.3	14.4	1.7	42.3	2.2	90.7	2.7
4.00	5.0	1.4	15.4	1.8	45.2	2.4	96.9	2.9
4.50	5.3	1.5	16.3	2.0	48.0	2.5	102.8	3.1
5.00	5.6	1.6	17.2	2.1	50.6	2.7	108.4	3.2

*Amended error shown in red.

Table 47: B.2 Capacity of drains, filling degree 70 %, (h/d = 0,7) (B.S. Institute, 2000)

Slope (%)	**DN100**		**DN150**		**DN225**		**DN300**	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	2.9	0.5	9.0	0.7	26.5	0.9	56.8	1.1
1.00	4.2	0.8	12.8	1.0	37.6	1.3	80.6	1.6
1.50	5.1	1.0	15.7	1.3	46.2	1.6	98.8	2.0
2.00	5.9	1.1	18.2	1.5	53.3	1.9	114.2	2.3
2.50	6.7	1.2	20.3	1.6	59.7	2.1	127.7	2.6
3.00	7.3	1.3	22.3	1.8	65.4	2.3	140.0	2.8
3.50	7.9	1.5	24.1	1.9	70.6	2.5	151.2	3.0
4.00	8.4	1.6	25.8	2.1	75.5	2.7	161.7	3.2
4.50	8.9	1.7	27.3	2.2	80.1	2.8	171.5	3.4
5.00	9.4	1.7	28.8	2.3	84.5	3.0	180.8	3.6

The degree of variation between the above flow rate and velocities reported by (Lucid Consulting Australia, 2020) and *BS EN 12056-2:2000* (B.S. Institute, 2000) for filling capacities of 50 and 70% (denoted as #) has been quantified as a percentage error, as shown in the equation below. The values provided by the *BS EN 12056-2:2000* (B.S. Institute, 2000) (Table 46 and Table 47) are taken as the reference value.

$$\%\ error = \left|\frac{\#_{\text{EN 12056−2:2000}} - \#_{Lucid}}{\#_{\text{EN 12056−2:2000}}}\right| \times 100$$

These percentage errors for filling degrees of 50 and 70% have been tabulated below in Table 48 and Table 49 respectively. As shown below, a trend is apparent in the percentage differences between the two sets of data:

- The percentage error is greater for the flow rate than velocity;

- The percentage error increases in magnitude for increasing drain diameters; and
- No trend can be established between the pipe slope and the percentage

It is likely that these variations are the results of different pipe diameter values used. This is investigated in subsequent sections. Errors with rounding may also have impacted the differences identified.

Table 48: Percentage error (%) between Table CV2.9 and Table B.1, filling degree 50 % (h/d = 0.5)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	0.1	0.0	0.2	0.0
1.00	-	-	6.5	0.0	5.8	0.0	15.5	0.0
1.50	3.2	0.0	5.3	0.0	5.8	6.7	15.5	5.6
2.00	2.9	0.0	5.5	0.0	6.0	0.0	15.5	0.0
2.50	2.5	0.0	5.7	6.7	5.9	0.0	15.5	4.3
3.00	4.5	0.0	5.3	0.0	5.4	4.8	15.5	4.0
3.50	2.1	0.0	5.6	0.0	5.9	0.0	15.5	3.7
4.00	2.0	0.0	5.2	0.0	6.0	0.0	15.5	3.4
4.50	1.9	0.0	4.9	5.0	6.0	0.0	15.5	6.5
5.00	1.8	6.3	5.2	4.8	5.9	3.7	15.5	3.1
Avg	*2.6*	*0.8*	*5.5*	*1.8*	*5.3*	*1.5*	*14.0*	*3.1*

Table 49: Percentage error (%) between Table CV2.9 and Table B.1, filling degree 70 % (h/d = 0.7)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	5.7	0.0	15.3	0.0
1.00	-	-	5.5	0.0	5.6	0.0	15.3	6.3
1.50	2.0	10.0	5.1	7.7	5.8	0.0	15.3	5.0
2.00	1.7	0.0	5.5	6.7	5.6	0.0	15.2	4.3
2.50	3.0	0.0	4.9	0.0	5.9	0.0	15.2	3.8
3.00	2.7	0.0	5.4	0.0	5.8	0.0	15.3	3.6
3.50	2.5	6.7	5.4	0.0	5.7	0.0	15.2	3.3
4.00	2.4	6.3	5.4	4.8	5.7	3.7	15.2	3.1
4.50	2.2	5.9	5.1	0.0	5.7	0.0	15.2	2.9
5.00	2.1	0.0	5.2	0.0	5.7	0.0	15.2	2.8
Avg	*2.3*	*3.6*	*5.3*	*2.1*	*5.7*	*0.4*	*15.2*	*3.5*

A.2.2 Comparison of Colebrook-White results using Formula 2.1(b) of AS2200-2016 with calculated hydraulic radius and using Chart 13 of AS2200-2016 to derate full pipe velocities and flow rates

Results obtained from directly calculating the flow rate and velocity of 50 and 70% filling ratios from the Colebrook-White equation using hydraulic radius were compared using Chart 13 to derate the flow rate and velocity values calculated from the formula at a 100% filling capacity. The formulas for hydraulic radius and the cross-sectional area of the flow are summarised below and are consistent with the theory presented in online sources and the Butler and Pinkerton charts (Butler & Pinkerton, 1987).

The radius of the pipe (r) is half of the internal pipe diameter (D):

$$r = \frac{D}{2}$$

The central angle θ is calculated by:

$$\theta = 2\cos^{-1}\left(\frac{r-h}{r}\right)$$

The cross-sectional area of the flow (A) is a function of the pipe radius (r) and the central angle (θ)

$$A = \frac{r^2(\theta - sin\theta)}{2}$$

The wetted perimeter (P) is given by:

$$P = r\theta$$

The hydraulic radius (R_H) is the ratio of the cross-sectional area of the flow to the wetted perimeter:

$$test = \frac{A}{P}$$

The radius (r), central angle (θ) and depth of water (h) of a partly filled pipe is depicted in Figure 1 below.

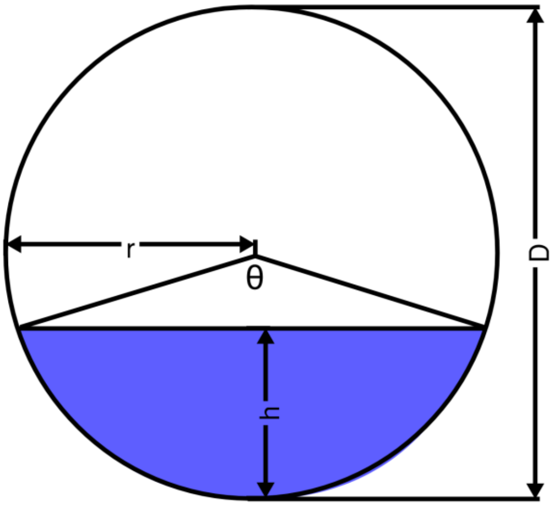

Figure 1: Radius (r), central angle (θ) and depth of water (h) of a partly filled pipe

For a 50% filling degree $(h/D = 0.5)$, the cross-sectional area of the flow is:

$$\theta = \pi$$

$$A = \frac{r^2(\pi - \sin(\pi))}{2}$$

$$= \frac{\pi r^2}{2}$$

The wetted perimeter of a 50% filling degree is:

$$
\begin{aligned}
P &= r\theta \\
&= r\pi
\end{aligned}
$$

The hydraulic radius of a 50% filling degree is:

$$
\begin{aligned}
R_H &= \frac{A}{P} \\
&= \frac{\pi r^2}{2r\pi} \\
&= \frac{r}{2}
\end{aligned}
$$

For a 70% filling degree ($\frac{h}{D} = 0.7$), the cross-sectional area of the flow is:

$$
\begin{aligned}
\theta &= 2\cos^{-1}\left(\frac{r - 0.7(2r)}{r}\right) \\
&= 2\cos^{-1}(-0.4) \\
&\approx 3.96\, rad
\end{aligned}
$$

$$
\begin{aligned}
A &= \frac{r^2(\theta - sin\theta)}{2} \\
&= \frac{r^2(3.96 - \sin(3.96))}{2} \\
&\approx 2.345r^2
\end{aligned}
$$

The wetted perimeter of a 70% filling degree is:

$$
\begin{aligned}
P &= r\theta \\
&= 3.96r
\end{aligned}
$$

Hence, the hydraulic radius of a 70% filling degree is:

$$
\begin{aligned}
R_H &= \frac{A}{P} \\
&= \frac{2.35r^2}{3.96r} \\
&\approx 0.59r
\end{aligned}
$$

It should be noted that approximate values provided above are for demonstration; the exact (non-rounded) values for calculations have been used.

The hydraulic radius and cross-sectional area of the flow of Australian Standard internal diameters for 50, 70 and 100% filling ratios are summarised below in Table 50 to Table 52.

Table 50: Hydraulic radius and cross-sectional area of the flow for 50% filling capacity - h/d = 0.5

Diameter (m)	**AS Internal Diameter (m)**	$r\ (m)$	$R_H\ (m)$	$A\ (m^2)$	D/R_H
0.1	0.098	0.049	0.0245	0.003771	4
0.15	0.143	0.0715	0.03575	0.00803	4
0.225	0.224	0.112	0.056	0.019704	4
0.3	0.274	0.137	0.0685	0.029482	4

Table 51: Hydraulic radius and cross-sectional area of the flow for 70% filling capacity - h/d = 0.7

Diameter (m)	AS Internal Diameter (m)	$r\ (m)$	$h\ (m)$	θ (radians)	$R_H\ (m)$	$A\ (m^2)$	D/R_H
0.100	0.098	0.049	0.0686	3.964626	0.029031	0.00564	3.376
0.150	0.143	0.0715	0.1001	3.964626	0.042362	0.012008	3.376
0.225	0.224	0.112	0.1568	3.964626	0.066357	0.029465	3.376
0.300	0.274	0.137	0.1918	3.964626	0.081168	0.044087	3.376

Table 52: Hydraulic radius and cross-sectional area of the flow for 100% filling capacity - h/d = 1.0

Diameter (m)	AS Internal Diameter (m)	$r\ (m)$	$R_H\ (m)$	$A\ (m^2)$	D/R_H
0.100	0.098	0.049	0.0245	0.007543	4
0.150	0.143	0.0715	0.03575	0.016061	4
0.225	0.224	0.112	0.056	0.039408	4
0.300	0.274	0.137	0.0685	0.058965	4

The derated values deduced from Chart 13 of *AS2200-2016* (Standards Australia, 2006) aligned with those obtained by (Lucid Consulting Australia, 2020) and are summarised below in Table 53.

Table 53: Derated values of Velocity and Flowrate for 50 and 70% filling ratio

Filling Ratio (%)	Derated value of Velocity (%)	Derated value of Flowrate (%)
50	99.7	50
70	111.9	83.7

The following values for the Colebrook-White roughness coefficient (k), gravitational acceleration (g) and kinematic viscosity of water at 20° (v) were used:

$$k = 0.001\ m$$
$$g = 9.8 m/s^2$$
$$v = 1.31 \times 10^{-31}\ m^2/s$$

The results obtained from using (1) the Colebrook-White equation with the values for h/D=0.5 summarised in Table 50, and (2) the Colebrook-White equation with the values for h/D=1 summarised in Table 52 and the derated values for 50% filling ratio summarised in Table 53, are summarised below in Table 54 and Table 55 respectively. Results were presented to 3 decimal places to demonstrate that flow rates obtained via the two methods were identical, however there was a 0.3% discrepancy in the velocity values. This is due to the fact that the derated value of flow rate from Chart 13 is 99.7% of the full flow, whereas the Colebrook White equation with hydraulic radius demonstrates that the velocity for 50% and 100% filling capacity is equal.

Table 54: Arup results for velocity and flow rate using Colebrook-White formula with hydraulic radius equivalent to h/D=0.5 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	1.854	0.492	5.097	0.635	16.840	0.855	28.744	0.975
1.00	2.637	0.699	7.241	0.902	23.896	1.213	40.771	1.383
1.50	3.238	0.859	8.886	1.107	29.311	1.488	50.001	1.696
2.00	3.745	0.993	10.274	1.279	33.876	1.719	57.783	1.960
2.50	4.192	1.111	11.496	1.432	37.899	1.923	64.639	2.192
3.00	4.595	1.218	12.601	1.569	41.535	2.108	70.837	2.403
3.50	4.967	1.317	13.617	1.696	44.879	2.278	76.537	2.596
4.00	5.312	1.409	14.563	1.813	47.992	2.436	81.842	2.776
4.50	5.637	1.495	15.451	1.924	50.915	2.584	86.825	2.945
5.00	5.944	1.576	16.291	2.029	53.680	2.724	91.538	3.105

Table 55: Arup results for velocity and flow rate using Colebrook-White formula with proportional values obtained from Chart 13 of *AS 2200-2006* equivalent to h/D=0.5 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	1.854	0.490	5.097	0.633	16.840	0.852	28.744	0.972
1.00	2.637	0.697	7.241	0.899	23.896	1.209	40.771	1.379
1.50	3.238	0.856	8.886	1.103	29.311	1.483	50.001	1.691
2.00	3.745	0.990	10.274	1.276	33.876	1.714	57.783	1.954
2.50	4.192	1.108	11.496	1.427	37.899	1.918	64.639	2.186
3.00	4.595	1.215	12.601	1.564	41.535	2.102	70.837	2.395
3.50	4.967	1.313	13.617	1.691	44.879	2.271	76.537	2.588
4.00	5.312	1.404	14.563	1.808	47.992	2.428	81.842	2.768
4.50	5.637	1.490	15.451	1.918	50.915	2.576	86.825	2.936
5.00	5.944	1.571	16.291	2.023	53.680	2.716	91.538	3.096

The results obtained from using the Colebrook-White equation with the values for h/D=0.7 summarised in Table 51, is tabulated below in Table 56.

Table 56: Arup results for velocity and flow rate using Colebrook-White formula with hydraulic radius equivalent to h/D=0.7 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	3.11	0.55	8.54	0.71	28.14	0.95	47.99	1.09
1.00	4.42	0.78	12.12	1.01	39.91	1.35	68.05	1.54
1.50	5.43	0.96	14.87	1.24	48.95	1.66	83.44	1.89
2.00	6.28	1.11	17.19	1.43	56.57	1.92	96.42	2.19
2.50	7.03	1.25	19.23	1.60	63.28	2.15	107.85	2.45
3.00	7.70	1.37	21.08	1.76	69.35	2.35	118.19	2.68
3.50	8.32	1.48	22.78	1.90	74.93	2.54	127.69	2.90
4.00	8.90	1.58	24.36	2.03	80.13	2.72	136.54	3.10
4.50	9.45	1.68	25.85	2.15	85.01	2.89	144.85	3.29
5.00	9.96	1.77	27.25	2.27	89.62	3.04	152.71	3.46

The results obtained from using the Colebrook-White equation with the values for $h/D = 1$ summarised in Table 52 and the derated values for 70% filling ratio summarised in Table 53 are summarised below in Table 57.

Table 57: Arup results for velocity and flow rate using Colebrook-White formula with proportional values obtained from Chart 13 of *AS 2200-2006* equivalent to h/D=0.7 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	3.10	0.55	8.53	0.71	28.19	0.96	48.12	1.09
1.00	4.42	0.78	12.12	1.01	40.00	1.36	68.25	1.55
1.50	5.42	0.96	14.88	1.24	49.07	1.66	83.70	1.90
2.00	6.27	1.11	17.20	1.43	56.71	1.92	96.73	2.19
2.50	7.02	1.24	19.24	1.60	63.44	2.15	108.21	2.45
3.00	7.69	1.36	21.09	1.76	69.53	2.36	118.58	2.69
3.50	8.31	1.47	22.79	1.90	75.13	2.55	128.12	2.90
4.00	8.89	1.58	24.38	2.03	80.34	2.73	137.00	3.11
4.50	9.44	1.67	25.87	2.15	85.23	2.89	145.35	3.30
5.00	9.95	1.76	27.27	2.27	89.86	3.05	153.24	3.47

The percentage difference between the values obtained in Table 56 and Table 57 are summarised below in Table 58. As shown below, the percentage differences are negligible and hence, directly using the formula is a valid means of calculating the flow rate and velocity for partially filled pipes.

Table 58: Percentage errors when h/D=0.7, between 'derated' values and values derived from the equivalent hydraulic radius

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error Q	% Error V	% Error Q
0.50	0.25	0.29	0.03	0.07	0.19	0.14	0.27	0.23
1.00	0.19	0.23	0.01	0.03	0.22	0.18	0.30	0.26
1.50	0.16	0.20	0.03	0.01	0.23	0.19	0.32	0.27
2.00	0.15	0.19	0.05	0.01	0.24	0.20	0.32	0.28
2.50	0.14	0.18	0.05	0.01	0.25	0.21	0.33	0.29
3.00	0.13	0.17	0.06	0.02	0.25	0.21	0.33	0.29
3.50	0.12	0.16	0.07	0.03	0.26	0.22	0.34	0.30
4.00	0.12	0.16	0.07	0.03	0.26	0.22	0.34	0.30
4.50	0.11	0.15	0.07	0.03	0.26	0.22	0.34	0.30
5.00	0.11	0.15	0.08	0.04	0.27	0.23	0.34	0.30

Furthermore, it is proposed that using the formula to directly calculate the flow rates and velocities is a more accurate method than using the derated values of Chart 13, since the derating values vary (albeit negligibly) with slope and internal diameter, as demonstrated by the derated values for velocity and flow rate below in Table 59, which were calculated from the results of Table 56. Whilst these results are close to the derated values derived from Chart 13 (Table 53), these variations explain the percentage errors tabulated in Table 58.

Table 59: Calculated 'derated' values for flow rate and velocity with h/D=0.7 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0
0.50	0.839	1.122	0.837	1.120	0.835	1.117	0.835	1.116
1.00	0.839	1.122	0.837	1.119	0.835	1.117	0.834	1.116
1.50	0.838	1.121	0.837	1.119	0.835	1.117	0.834	1.116
2.00	0.838	1.121	0.837	1.119	0.835	1.117	0.834	1.116
2.50	0.838	1.121	0.837	1.119	0.835	1.117	0.834	1.116
3.00	0.838	1.121	0.836	1.119	0.835	1.117	0.834	1.116
3.50	0.838	1.121	0.836	1.119	0.835	1.117	0.834	1.116
4.00	0.838	1.121	0.836	1.119	0.835	1.117	0.834	1.116
4.50	0.838	1.121	0.836	1.119	0.835	1.117	0.834	1.116
5.00	0.838	1.121	0.836	1.119	0.835	1.116	0.834	1.116

A graphical representation of the calculated derating values for flow rate from Table 59 and the constant derating value from Chart 13 (0.837) for a 70% filling ratio is summarised below in Figure 34.

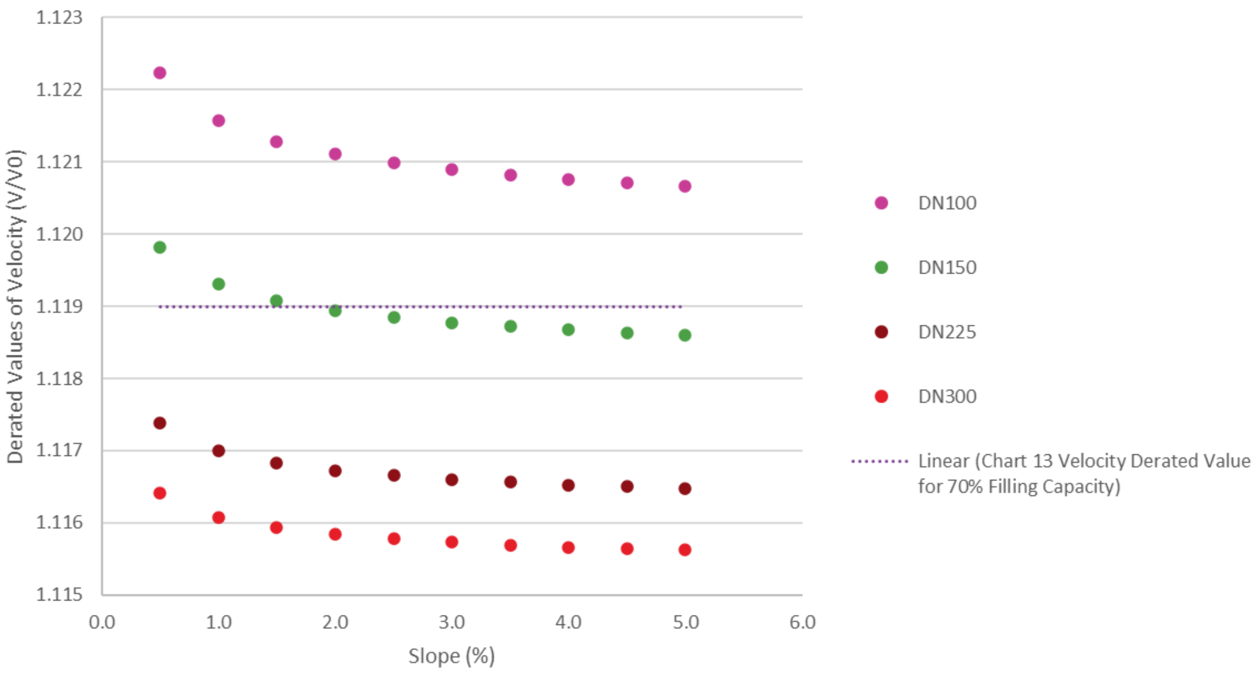

Figure 34: Proportional values of velocity from calculated values

A graphical representation of the calculated derating values for velocity from and the constant derating value from Chart 13 (0.837) for a 70% filling ratio is summarised below in Figure 35.

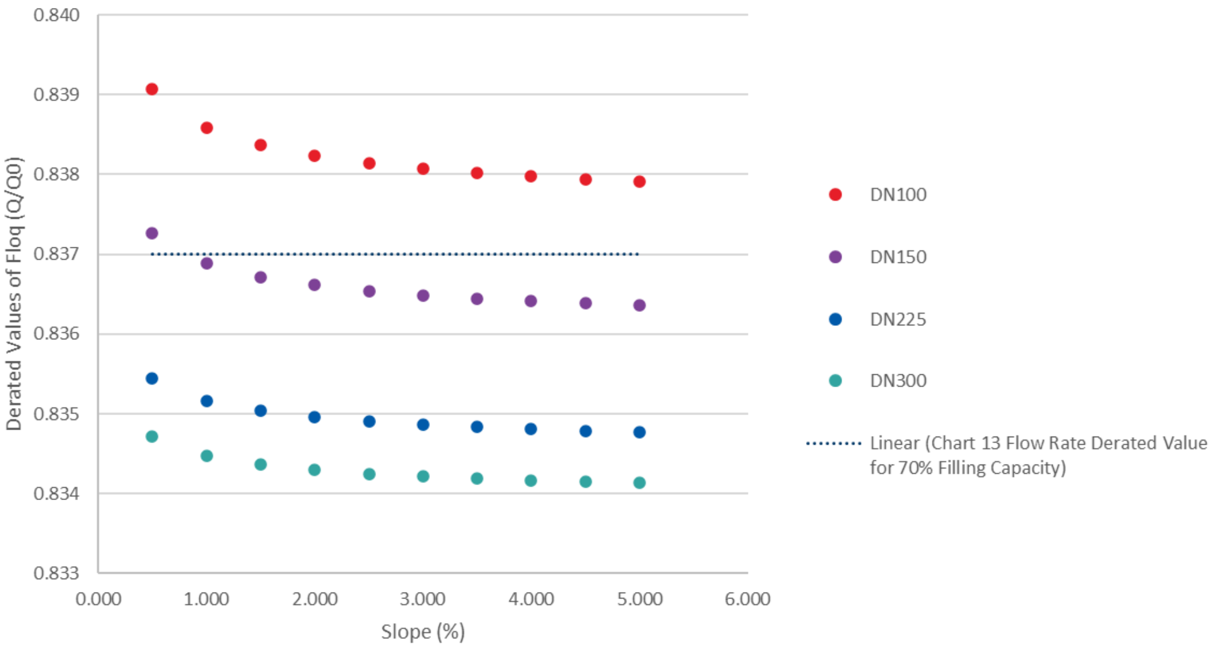

Figure 35: Proportional values of flow rate from calculated values

In addition, Chart 13 of *AS 2200-2006* (Standards Australia, 2006) was validated by the Colebrook-White equation with hydraulic radius by calculating the proportional flow rate and velocities for filling ratios from h/D=0.01 to 1 for a 143 internal diameter pipe at a 5% slope, given $k = 0.001\ m$, $g = 9.8 m/s^2$ and $v = 1.31 \times 10^{-31}\ m^2/s$. The calculated values have been overlayed onto Chart 13 (B.S. Institute, 2000) below in Figure 36, demonstrating similar outcomes.

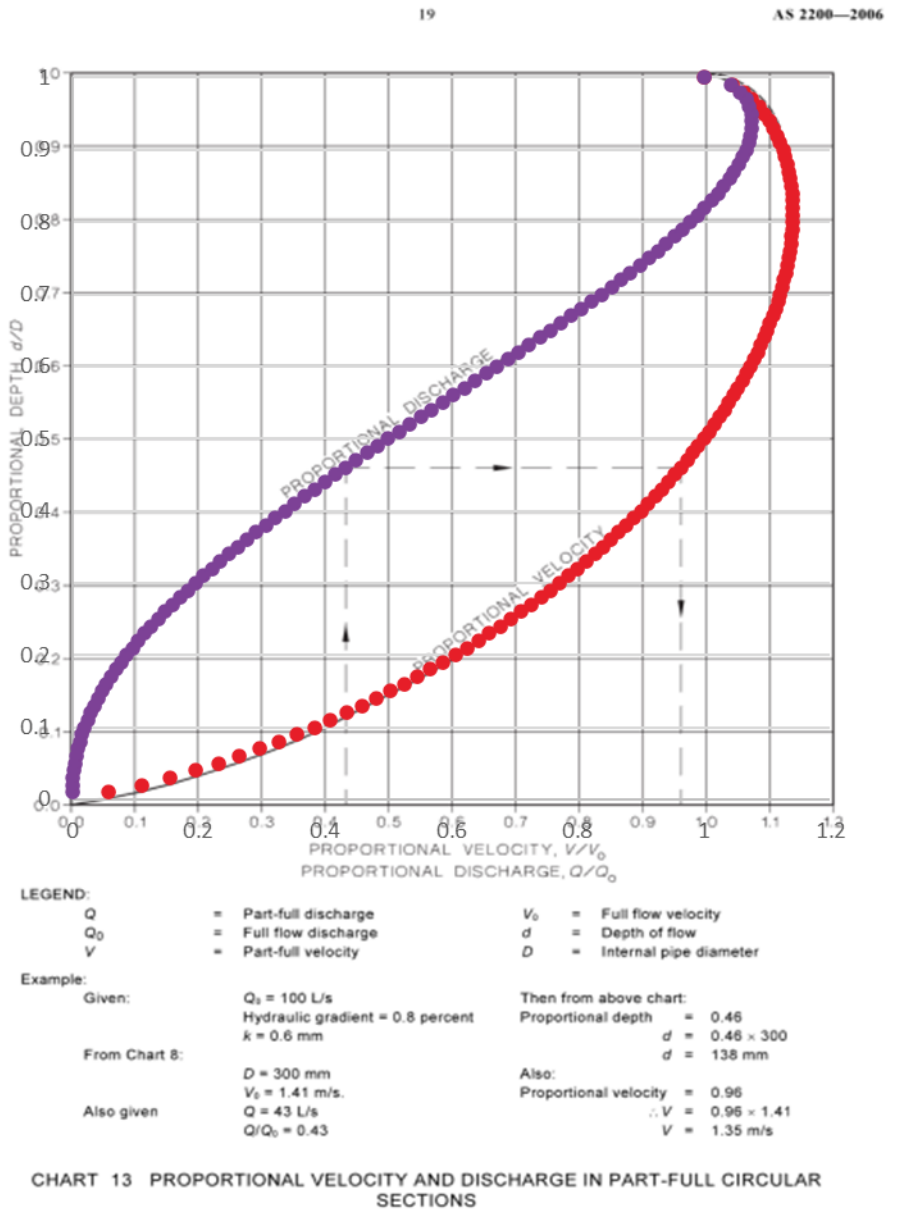

Figure 36: Proportional velocity and flowrate for various filling ratios for 143mm internal diameter pipe at 5% slope (Standards Australia, 2006)

A.2.3 Validating the results achieved by Lucid

The flow rate and velocity results obtained by (Lucid Consulting Australia, 2020) were compared to calculated values using the two calculation methods detailed in Section A.2.2. Calculated values were rounded to 1 decimal place to compare with those presented by (Lucid Consulting Australia, 2020). Given the ambiguity surrounding the viscosity value used (see Section A.2.1), viscosity (ν) values of 1.31×10^{-6} m^2/s (10 ºC) and 1.01×10^{-6} m^2/s (20 ºC) were tested.

Results by (Lucid Consulting Australia, 2020) (Table 44) were compared with the calculated results shown in Table 54 and Table 55, and the percentage errors (taking Lucid's results as the reference value) are summarised below in Table 60. It should be noted that the percentage errors were identical when comparing the Lucid results to the two types of calculation methods (Table 54 using the hydraulic radius for of the Colebrook-White equation and Table 55 using Chart 13 of *AS2200-2006* (Standards Australia, 2006)).

Table 60: Percentage errors (%) between Lucid values and Arup calculated values for filling degree h/D=0.5 and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error Q	% Error V	% Error Q
0.50	-	-	-	-	12.8	12.5	0.3	0.0
1.00	-	-	0	0	12.7	0.0	0.0	0.0
1.50	6.7	12.5	0.0	0.0	12.7	7.1	0.0	0.0
2.00	8.8	0.0	0.0	0.0	13.0	0.0	0.0	0.0
2.50	7.7	0.0	0.0	0.0	12.8	0.0	0.2	0.0
3.00	9.5	0.0	0.0	0.0	12.8	5.0	0.1	0.0
3.50	8.7	0.0	0.0	0.0	12.8	4.5	0.1	0.0
4.00	8.2	0.0	0.0	0.0	12.9	0.0	0.1	0.0
4.50	7.7	0.0	0.0	0.0	12.9	4.0	0.1	0.0
5.00	7.3	6.7	0.0	0.0	12.8	3.8	0.1	0.0

The percentage errors when using $k = 1.01 \times 10^{-6}\ m^2/s$ in calculations is shown below in Table 61. Errors that differ from the values presented in Table 60 have been identified in red italics. The differences identified between Table 60 and Table 61 do not identify a clear trend to determine which viscosity was used by Lucid; one viscosity value does not consistently result in lower percentage errors for all slopes and diameters. In addition, there are relatively large differences identified in red shading, especially for flow rates of 225mm pipe. It is suspected that Lucid may have used a different internal pipe diameter to what was stated.

Table 61: Percentage errors (%) between Lucid values and Arup calculated values for filling degree h/D=0.5 and $\upsilon = 1.01 \times 10^{-6}$ m²/s (20 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error Q	% Error V	% Error Q
0.50	-	-	-	-	*13.4*	12.5	*0.0*	0.0
1.00	-	-	*1.4*	0.0	12.7	0.0	*0.0*	0.0
1.50	6.7	12.5	0.0	0.0	*13.1*	7.1	*0.2*	0.0
2.00	*11.8*	0.0	0.0	0.0	13.0	0.0	*0.2*	0.0
2.50	7.7	0.0	0.0	0.0	12.8	0.0	*0.0*	0.0
3.00	9.5	0.0	0.0	0.0	*13.0*	5.0	*0.0*	0.0
3.50	8.7	0.0	0.0	0.0	12.8	4.5	*0.0*	0.0
4.00	8.2	0.0	0.0	0.0	12.9	0.0	*0.0*	0.0
4.50	7.7	0.0	0.0	0.0	*13.1*	4.0	*0.0*	0.0
5.00	*9.1*	6.7	0.0	0.0	12.8	3.8	*0.0*	0.0

The percentage errors between Lucid values reported for h/D=0.7 (Table 45) and calculated values (Table 56) are summarised below in Table 62. As also found for 50% filling degree, there are relatively large differences identified in red shading, particularly for flow rates of 225mm pipe.

Table 62: Percentage errors (%) between Lucid values and Arup calculated values for filling degree h/D=0.7 and $\upsilon = 1.31 \times 10^{-6}$ m^2/s (10 ºC)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error Q	% Error V	% Error Q
0.50	-	-	-	-	12.8	11.1	0.0	0.0
1.00	-	-	0	0	12.7	7.7	0.0	0.0
1.50	8.0	11.1	0.0	0.0	12.9	6.2	0.0	0.0
2.00	8.6	0.0	0.0	0.0	12.7	0.0	0.1	0.0
2.50	7.7	0.0	0.5	0.0	12.8	4.8	0.1	0.0
3.00	8.5	7.7	0.0	0.0	12.8	4.3	0.0	0.0
3.50	7.8	7.1	0.0	0.0	12.8	0.0	0.1	0.0
4.00	8.5	6.7	0.0	0.0	12.8	3.8	0.1	0.0
4.50	8.0	6.2	0.0	0.0	12.8	3.6	0.1	0.0
5.00	7.6	5.9	0.0	0.0	12.8	0.0	0.1	0.0

A.2.4 Validating the results achieved by BS EN 12056.2:2000

The flow rate and velocity results obtained by *BS EN 12056.2:2000* (B.S. Institute, 2000) were compared to calculated values using the two calculation methods detailed in Section A.2.2. Calculated values were rounded to 1 decimal place to compare with those presented by (Lucid Consulting Australia, 2020).

Results by *BS EN 12056.2:2000* (B.S. Institute, 2000) for 50% filling degree (Table 46) were compared with the calculated results for British internal diameters (Figure 37) below in Table 63 and Table 64, and the percentage errors (taking *BS EN 12056.2:2000* (B.S. Institute, 2000) results as the reference value) are summarised below in Table 65 and Table 66. From a comparison Table 65 and Table 66, it is evident that closer results to those published in *BS EN 12056.2:2000* (B.S. Institute, 2000) for 50% filling capacity are achieved using the modified Colebrook-White equation as opposed to derating using Chart 13.

In addition, there are relatively large differences for flow rates of 225mm pipe (identified in red shading) between our calculations and the values produced by *BS EN 12056.2:2000* (B.S. Institute, 2000) for both 50% and 70% filling degree. We are unable to determine the reason for this discrepancy between our calculations and those by the standard for this pipe size. We also note that this is a similar error trend to that identified between our values and those of (Lucid Consulting Australia, 2020).

Nominal diameter	Minimum internal diameter
DN	$d_{i\ min}$ mm
30	26
40	34
50	44
56	49
60	56
70	68
80	75
90	79
100	96
125	113
150	146
200	184
225	207
250	230
300	290

Figure 37: Nominal diameters (DN) and minimum internal diameters - Table 1 of *BS EN 12056.2:2000* (B.S. Institute, 2000)

Table 63: Arup results for velocity and flow rate directly using Colebrook-White formula for h/D=0.5 and British internal pipe diameters and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 ºC)

Slope (%)	DN100		DN150		DN225		DN300	
	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0
0.50	1.8	0.5	5.4	0.6	13.7	0.8	33.4	1.0
1.00	2.5	0.7	7.7	0.9	19.4	1.2	47.4	1.4
1.50	3.1	0.8	9.4	1.1	23.8	1.4	58.1	1.8
2.00	3.5	1.0	10.9	1.3	27.5	1.6	67.1	2.0
2.50	4.0	1.1	12.1	1.5	30.7	1.8	75.1	2.3
3.00	4.3	1.2	13.3	1.6	33.7	2.0	82.3	2.5
3.50	4.7	1.3	14.4	1.7	36.4	2.2	88.9	2.7
4.00	5.0	1.4	15.4	1.8	38.9	2.3	95.1	2.9
4.50	5.3	1.5	16.3	2.0	41.3	2.5	100.9	3.1
5.00	5.6	1.6	17.2	2.1	43.5	2.6	106.4	3.2

Table 64: Arup results for velocity and flow rate using Colebrook-White formula with proportional values obtained from Chart 13 of *AS 2200-2006* equivalent to h/D=0.5 and British internal pipe diameters and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 ºC)

Slope (%)	DN100		DN150		DN225		DN300	
	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0
0.50	1.8	0.5	5.4	0.6	13.7	0.8	33.4	1.0
1.00	2.5	0.7	7.7	0.9	19.4	1.1	47.4	1.4
1.50	3.1	0.8	9.4	1.1	23.8	1.4	58.1	1.8
2.00	3.5	1.0	10.9	1.3	27.5	1.6	67.1	2.0
2.50	4.0	1.1	12.1	1.4	30.7	1.8	75.1	2.3
3.00	4.3	1.2	13.3	1.6	33.7	2.0	82.3	2.5
3.50	4.7	1.3	14.4	1.7	36.4	2.2	88.9	2.7
4.00	5.0	1.4	15.4	1.8	38.9	2.3	95.1	2.9
4.50	5.3	1.5	16.3	1.9	41.3	2.4	100.9	3.0
5.00	5.6	1.5	17.2	2.1	43.5	2.6	106.4	3.2

Table 65: Percentage errors (%) between Lucid values and Arup calculated values (directly using Colebrook-White formula) for filling degree h/D=0.5 and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 ºC)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	13.8	0.0	2.1	0.0
1.00	-	-	0	0	13.8	0.0	1.9	0.0
1.50	0.0	0.0	0.0	0.0	13.8	6.7	1.9	0.0
2.00	0.0	0.0	0.0	0.0	13.8	5.9	1.9	0.0
2.50	0.0	0.0	0.8	0.0	14.0	5.3	2.0	0.0
3.00	2.3	0.0	0.0	0.0	13.4	4.8	1.9	0.0
3.50	0.0	0.0	0.0	0.0	13.9	0.0	2.0	0.0
4.00	0.0	0.0	0.0	0.0	13.9	4.2	1.9	0.0
4.50	0.0	0.0	0.0	0.0	14.0	0.0	1.8	0.0
5.00	0.0	0.0	0.0	0.0	14.0	3.7	1.8	0.0

Table 66: Percentage errors (%) between Lucid values and Arup calculated values (using Colebrook-White formula and Chart 13) for filling degree h/D=0.5 and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	13.8	0.0	2.1	0.0
1.00	-	-	0	0	13.8	8.3	1.9	0.0
1.50	0.0	0.0	0.0	0.0	13.8	6.7	1.9	0.0
2.00	0.0	0.0	0.0	0.0	13.8	5.9	1.9	0.0
2.50	0.0	0.0	0.8	6.7	14.0	5.3	2.0	0.0
3.00	2.3	0.0	0.0	0.0	13.4	4.8	1.9	0.0
3.50	0.0	0.0	0.0	0.0	13.9	0.0	2.0	0.0
4.00	0.0	0.0	0.0	0.0	13.9	4.2	1.9	0.0
4.50	0.0	0.0	0.0	5.0	14.0	4.0	1.8	3.2
5.00	0.0	6.3	0.0	0.0	14.0	3.7	1.8	0.0

Results by *BS EN 12056.2:2000* (B.S. Institute, 2000) for 70% filling degree (Table 47) were compared with the calculated results for British internal diameters (Figure 37) below in Table 67 and Table 68, and the percentage errors in *BS EN 12056.2:2000* (B.S. Institute, 2000) results are summarised below in

Table 69 and Table 70. When comparing

Table 69 and Table 70, it is evident that in general our calculations using the 100% filling capacity calculated with the Colebrook-White equation and then de-rated using Chart 13 of *AS2200-2006* (Standards Australia, 2006) appear to give closer results to those published in *BS EN 12056.2:2000* (B.S. Institute, 2000), which is in contrast to the finding for 50% filling capacity values.

Hence, the analysis presented in this section demonstrates that for most pipe sizes similar values are produced to those published in *BS EN 12056.2:2000* (B.S. Institute, 2000), however further work is required to determine the discrepancies identified for the 225mm pipe.

Table 67: Arup results for velocity and flow rate directly Colebrook-White formula for h/D=0.7 and British internal pipe diameters and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0
0.50	2.9	0.5	9.0	0.7	22.8	0.9	55.8	1.1
1.00	4.2	0.8	12.8	1.0	32.4	1.3	79.1	1.6
1.50	5.1	0.9	15.7	1.3	39.7	1.6	96.9	2.0
2.00	5.9	1.1	18.2	1.5	45.9	1.8	112.0	2.3
2.50	6.7	1.2	20.3	1.6	51.3	2.0	125.3	2.5
3.00	7.3	1.3	22.3	1.8	56.3	2.2	137.3	2.8
3.50	7.9	1.5	24.1	1.9	60.8	2.4	148.4	3.0
4.00	8.4	1.6	25.7	2.1	65.0	2.6	158.6	3.2
4.50	8.9	1.7	27.3	2.2	69.0	2.7	168.3	3.4

5.00	9.4	1.7	28.8	2.3	72.7	2.9	177.4	3.6

Table 68: Arup results for velocity and flow rate using Colebrook-White formula with proportional values obtained from Chart 13 of *AS 2200-2006* equivalent to h/D=0.7 and British internal pipe diameters and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0	Q/Q_0	V/V_0
0.50	2.9	0.5	9.0	0.7	22.9	0.9	55.9	1.1
1.00	4.2	0.8	12.8	1.0	32.4	1.3	79.3	1.6
1.50	5.1	0.9	15.7	1.3	39.8	1.6	97.3	2.0
2.00	5.9	1.1	18.2	1.5	46.0	1.8	112.4	2.3
2.50	6.6	1.2	20.3	1.6	51.5	2.0	125.7	2.5
3.00	7.3	1.3	22.3	1.8	56.4	2.2	137.8	2.8
3.50	7.9	1.5	24.1	1.9	60.9	2.4	148.9	3.0
4.00	8.4	1.6	25.8	2.1	65.2	2.6	159.2	3.2
4.50	8.9	1.6	27.3	2.2	69.1	2.7	168.9	3.4
5.00	9.4	1.7	28.8	2.3	72.9	2.9	178.1	3.6

Table 69: Percentage errors (%) between Lucid values and Arup calculated values (directly using Colebrook-White formula) for filling degree h/D=0.7 and $\upsilon = 1.31 \times 10^{-6}$ m²/s (10 °C)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	14.0	0.0	1.8	0.0
1.00	-	-	0	0	13.8	0.0	1.9	0.0
1.50	0.0	10.0	0.0	0.0	14.1	0.0	1.9	0.0
2.00	0.0	0.0	0.0	0.0	13.9	5.3	1.9	0.0
2.50	0.0	0.0	0.0	0.0	14.1	4.8	1.9	3.8
3.00	0.0	0.0	0.0	0.0	13.9	4.3	1.9	0.0
3.50	0.0	0.0	0.0	0.0	13.9	4.0	1.9	0.0
4.00	0.0	0.0	0.4	0.0	13.9	3.7	1.9	0.0
4.50	0.0	0.0	0.0	0.0	13.9	3.6	1.9	0.0
5.00	0.0	0.0	0.0	0.0	14.0	3.3	1.9	0.0

Table 70: Percentage errors (%) between Lucid values and Arup calculated values (using Colebrook-White formula and Chart 13) for filling degree h/D=0.7 and $\upsilon = 1.31 \times 10^{-6}$ m^2/s (10 ºC)

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	-	-	-	-	13.6	0.0	1.6	0.0
1.00	-	-	0	0	13.8	0.0	1.6	0.0
1.50	0.0	10.0	0.0	0.0	13.9	0.0	1.5	0.0
2.00	0.0	0.0	0.0	0.0	13.7	5.3	1.6	0.0
2.50	1.5	0.0	0.0	0.0	13.7	4.8	1.6	3.8
3.00	0.0	0.0	0.0	0.0	13.8	4.3	1.6	0.0
3.50	0.0	0.0	0.0	0.0	13.7	4.0	1.5	0.0
4.00	0.0	0.0	0.0	0.0	13.6	3.7	1.5	0.0
4.50	0.0	5.9	0.0	0.0	13.7	3.6	1.5	0.0
5.00	0.0	0.0	0.0	0.0	13.7	3.3	1.5	0.0

A.2.5 Determining an Appropriate Filling Ratio

The safety factor on velocity and flow rate values using the Colebrook-White equation for various filling degrees was investigated to determine an appropriate filling degree to use. Filling degrees of 95% (max flow), 100% (full bore flow), 81% (max velocity), 70% and 50% were compared. The values of hydraulic radius and cross-sectional area of flow for 81% and 95% are summarised below in Table 71 and Table 72 respectively.

Table 71: 81% filling capacity, h/d = 0.81

Diameter (m)	AS Internal Diameter (m)	$r\ (m)$	$h\ (m)$	θ (radians)	$R_H\ (m)$	$A\ (m^2)$
0.080	0.073	0.0365	0.05913	4.479078	0.022214	0.003632
0.100	0.098	0.049	0.07938	4.479078	0.029822	0.006545
0.150	0.143	0.0715	0.11583	4.479078	0.043515	0.013936
0.225	0.224	0.112	0.18144	4.479078	0.068164	0.034195
0.300	0.274	0.137	0.22194	4.479078	0.083379	0.051164

Table 72: 95% filling capacity, h/d = 0.95

Diameter (m)	AS Internal Diameter (m)	$r\ (m)$	$h\ (m)$	θ (radians)	$R_H\ (m)$	$A\ (m^2)$
0.080	0.073	0.0365	0.06935	5.381132	0.020911	0.004107
0.100	0.098	0.049	0.0931	5.381132	0.028072	0.007402
0.150	0.143	0.0715	0.13585	5.381132	0.040963	0.01576
0.225	0.224	0.112	0.2128	5.381132	0.064165	0.038671
0.300	0.274	0.137	0.2603	5.381132	0.078488	0.057862

The results obtained from using the Colebrook-White equation with the values for h/D=0.81 summarised in Table 71, is tabulated below in Table 73.

Table 73: Arup results for velocity and flow rate using Colebrook-White formula with hydraulic radius equivalent to h/D=0.81 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	3.11	0.55	8.54	0.71	28.14	0.95	47.99	1.09
1.00	4.42	0.78	12.12	1.01	39.91	1.35	68.05	1.54
1.50	5.43	0.96	14.87	1.24	48.95	1.66	83.44	1.89
2.00	6.28	1.11	17.19	1.43	56.57	1.92	96.42	2.19
2.50	7.03	1.25	19.23	1.60	63.28	2.15	107.85	2.45
3.00	7.70	1.37	21.08	1.76	69.35	2.35	118.19	2.68
3.50	8.32	1.48	22.78	1.90	74.93	2.54	127.69	2.90
4.00	8.90	1.58	24.36	2.03	80.13	2.72	136.54	3.10
4.50	9.45	1.68	25.85	2.15	85.01	2.89	144.85	3.29
5.00	9.96	1.77	27.25	2.27	89.62	3.04	152.71	3.46

The results obtained from using the Colebrook-White equation with the values for h/D=0.95 summarised in Table 72, is tabulated below in Table 74.

Table 74: Arup results for velocity and flow rate using Colebrook-White formula with hydraulic radius equivalent to h/D=0.95 and Australian PVC-U internal pipe diameters

Slope (%)	DN80		DN100		DN150		DN225		DN300	
	Q (l/s)	V (m/s)	Q (l/s)	V (m/s)	Q (l/s)	V (m/s)	Q (l/s)	V (m/s)	Q (l/s)	V (m/s)
0.50	1.82	0.44	4.01	0.54	10.99	0.70	36.22	0.94	61.76	1.07
1.00	2.59	0.63	5.69	0.77	15.59	0.99	51.34	1.33	87.53	1.51
1.50	3.18	0.77	6.98	0.94	19.13	1.21	62.95	1.63	107.30	1.85
2.00	3.67	0.89	8.07	1.09	22.10	1.40	72.74	1.88	123.97	2.14
2.50	4.11	1.00	9.03	1.22	24.73	1.57	81.36	2.10	138.66	2.40
3.00	4.50	1.10	9.90	1.34	27.10	1.72	89.15	2.31	151.93	2.63
3.50	4.87	1.19	10.70	1.45	29.28	1.86	96.32	2.49	164.14	2.84
4.00	5.21	1.27	11.44	1.55	31.31	1.99	102.99	2.66	175.51	3.03
4.50	5.52	1.34	12.14	1.64	33.22	2.11	109.26	2.83	186.18	3.22
5.00	5.82	1.42	12.80	1.73	35.02	2.22	115.19	2.98	196.28	3.39

A plot of flow rates and velocities for varying filling capacities is shown below in Figure 38 and Figure 39 respectively. Considering a 50 and 70% filling ratio, the factor of safety (FOS) on the flow rate and velocity values can be determined by considering the ratio of the maximum values attained for that pipe to those achieved at the selected filling ratio (X%):

$$FOS_{Q,X\%} = \frac{Q_{Max}}{Q_{X\%}} = \frac{Q_{95\%}}{Q_{X\%}} \approx 1.28$$

$$FOS_{V,X\%} = \frac{V_{Max}}{V_{X\%}} = \frac{V_{81\%}}{V_{X\%}} \approx 1.02$$

The factor of safety for 50 and 70% filling degree are summarised below in Table 75. These calculated factors of safety are consistent for varied slopes and pipe diameters.

Table 75: FOS's on flow rates and velocities using 50% and 70% filling degrees

Filling Degree (%)	Factor of Safety	
	Q (L/s)	V (m/s)
50	2.15	1.14
70	1.28	1.02

The factor of safety for flow rate is particularly important to ensure that at peak design flow the drain can accommodate adequate air ventilation (Butler & Pinkerton, 1987; Water Services Association of Australia, 2002). We deem these factors of safety to be suitable for design implementation and recommend that an upper limit filling degree of 70%-75%. This view is supported by the current industry standard (Water Services Association of Australia, 2002). When applying a filling degree the hydraulic designer should consider the impacts of installation configuration, air flow, velocity and self-cleansing of the system.

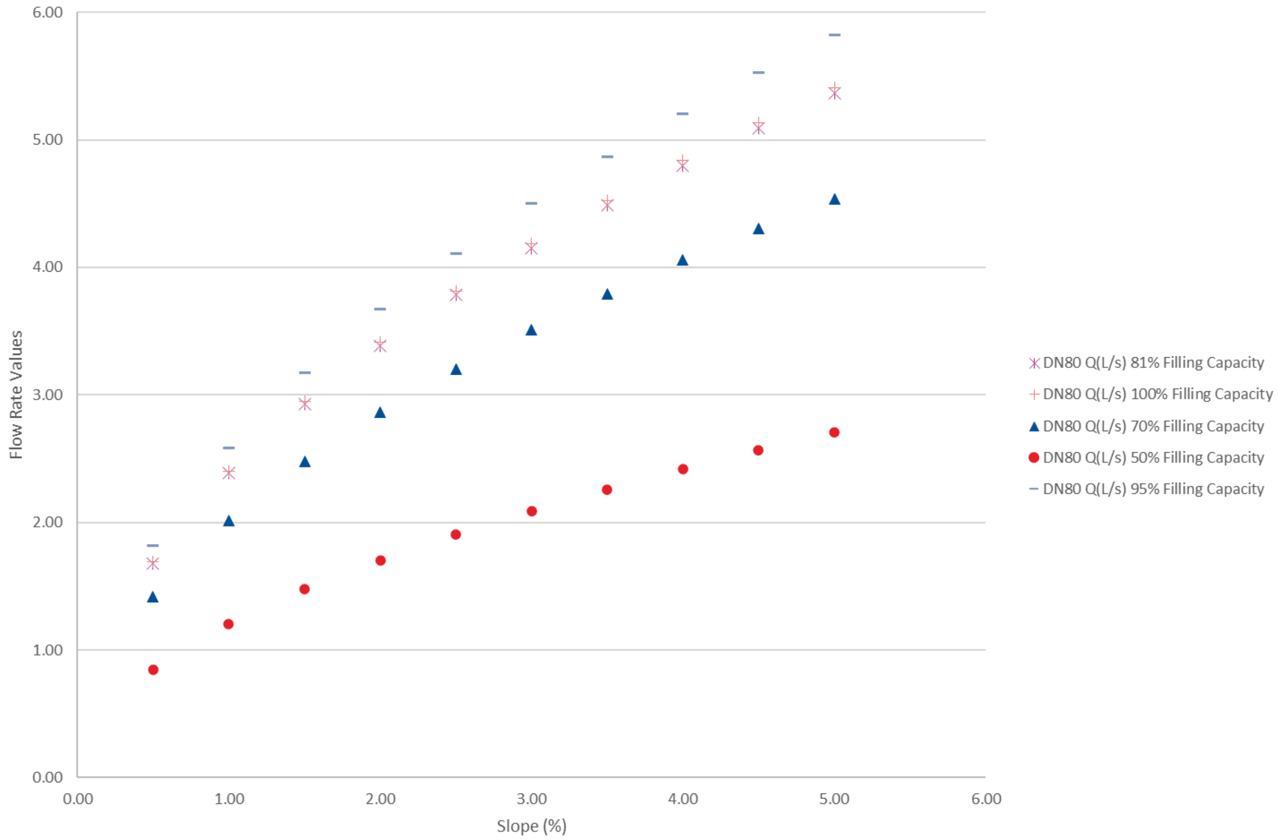

Figure 38: Flow rates for varying filling capacities for DN80 pipe (Australian internal diameter)

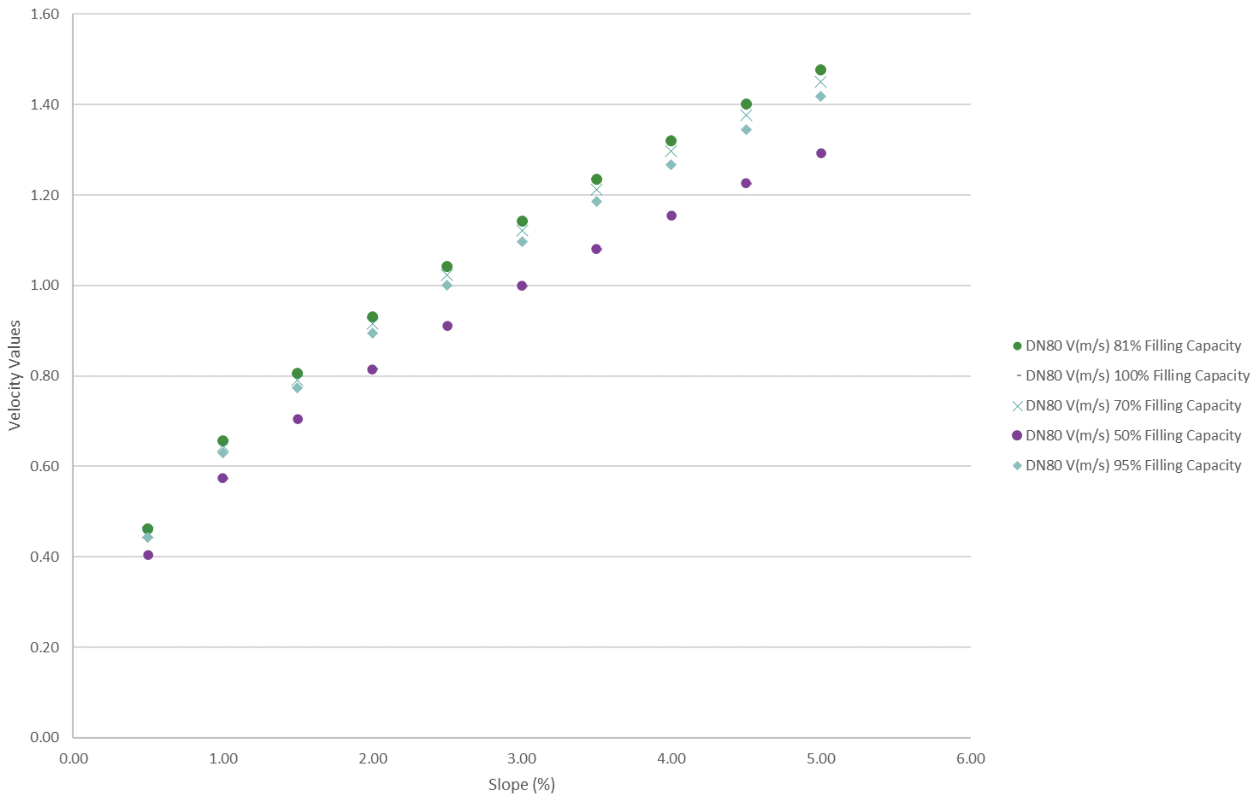

Figure 39: Velocities for varying filling capacities for DN80 pipe (Australian Internal diameter)

A.2.6 Manning's Formula versus Colebrook-White's Equation

Manning's formula was developed originally to describe rough, turbulent flow in large open channels (Swaffield & Bridge, 1983; Butler & Davies, 2000). The Colebrook-White equation is suitable for relatively small pipe diameters, with surfaces that are relatively smooth and turbulent flows. It should be noted that the Colebrook-White equation is not applicable to flows that are laminar or have a Reynolds number less than 2000 (Anon., n.d.).

A study was conducted comparing Manning's and Colebrook-White's equations against observed parameters (Swaffield & Bridge, 1983). It found that the Colebrook-White equation predicts flow characteristics with more accuracy and reliability than Manning's equation with a constant value of n. This finding was also supported by (B.S. Institute, 2000). It should be noted that Manning's coefficient (n) varies with slope, flow depth and flow rate, and this variation is particularly apparent for circular small-bore pipes (less than 1 meter). Conversely, the Colebrook-White roughness coefficient demonstrates stability over a range of flow rates. In addition, the effect of roughness on velocity and flow rate values is relatively small given the logarithmic relationship of roughness to velocity (Swaffield & Bridge, 1983).

Flow rate and velocity values derived from Manning's and Colebrook-White equation were compared. Hydraulic radius and cross-sectional areas of flow tabulated in Table 50 and Table 51 were used. Manning roughness coefficient of $n = 0.009$ was used, which aligns with online sources for PVC (Jenkins, 2017) and Table 2 of AS2200-2016 (Standards Australia, 2006).

The Manning's formula for velocity is given by (Standards Australia, 2006):

$$V = \frac{1}{n} R_H^{\frac{2}{3}} S^{0.5}$$

Flow rate and velocity values for 50% filling capacity using the Manning Equation are summarised below in Table 76.

Table 76: Manning's values of velocity and flow rate for h/D=0.5 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	2.50	0.66	6.85	0.85	22.66	1.15	38.78	1.32
1.00	3.53	0.94	9.68	1.21	32.05	1.63	54.84	1.86
1.50	4.33	1.15	11.86	1.48	39.25	1.99	67.17	2.28
2.00	5.00	1.33	13.69	1.71	45.32	2.30	77.56	2.63
2.50	5.59	1.48	15.31	1.91	50.67	2.57	86.71	2.94
3.00	6.12	1.62	16.77	2.09	55.51	2.82	94.99	3.22
3.50	6.61	1.75	18.12	2.26	59.95	3.04	102.60	3.48
4.00	7.07	1.87	19.37	2.41	64.09	3.25	109.68	3.72
4.50	7.50	1.99	20.54	2.56	67.98	3.45	116.34	3.95
5.00	7.90	2.10	21.65	2.70	71.66	3.64	122.63	4.16

When compared to the results obtained from the Colebrook-White equation for 50% filling capacity in Table 56, Manning's values for flow rate and velocity are found to be larger, on average by ~33.7%, as shown below in Table 77.

Table 77: Percentage errors between values obtained from Colebrook-White and Manning's equation for h/D=0.5

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error V
0.50	34.79	34.79	34.32	34.32	34.56	34.56	34.91	34.91
1.00	34.03	34.03	33.72	33.72	34.10	34.10	34.51	34.51
1.50	33.69	33.69	33.45	33.45	33.90	33.90	34.33	34.33
2.00	33.48	33.48	33.29	33.29	33.78	33.78	34.22	34.22
2.50	33.34	33.34	33.18	33.18	33.70	33.70	34.15	34.15
3.00	33.23	33.23	33.10	33.10	33.63	33.63	34.10	34.10
3.50	33.15	33.15	33.03	33.03	33.59	33.59	34.05	34.05
4.00	33.09	33.09	32.98	32.98	33.55	33.55	34.02	34.02
4.50	33.03	33.03	32.94	32.94	33.52	33.52	33.99	33.99
5.00	32.98	32.98	32.90	32.90	33.49	33.49	33.97	33.97
Avg	33.48	33.48	33.29	33.29	33.78	33.78	34.23	34.23

Flow rate and velocity values for 70% filling capacity using the Manning Equation are summarised below in Table 78.

Table 78: Manning's values of velocity and flow rate for h/D=0.7 and Australian PVC-U internal pipe diameters

Slope (%)	DN100		DN150		DN225		DN300	
	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$	$Q\ (l/s)$	$V\ (m/s)$
0.50	4.19	0.74	11.46	0.95	37.94	1.29	64.93	1.47
1.00	5.92	1.05	16.21	1.35	53.66	1.82	91.83	2.08
1.50	7.25	1.29	19.86	1.65	65.72	2.23	112.47	2.55
2.00	8.37	1.48	22.93	1.91	75.89	2.58	129.87	2.95
2.50	9.36	1.66	25.64	2.13	84.84	2.88	145.20	3.29
3.00	10.25	1.82	28.08	2.34	92.94	3.15	159.06	3.61
3.50	11.07	1.96	30.33	2.53	100.39	3.41	171.80	3.90
4.00	11.84	2.10	32.43	2.70	107.32	3.64	183.66	4.17
4.50	12.56	2.23	34.39	2.86	113.83	3.86	194.80	4.42
5.00	13.24	2.35	36.26	3.02	119.99	4.07	205.34	4.66

When compared to the results obtained from the Colebrook-White equation for 70% filling capacity in Table 54, Manning's values for flow rate and velocity are found to be larger, on average by 33.9% as shown below in Table 79.

Table 79: Percentage errors between values obtained from Colebrook-White and Manning's equation for h/D=0.7

Slope (%)	DN100		DN150		DN225		DN300	
	% Error Q	% Error V	% Error Q	% Error V	% Error Q	% Error Q	% Error V	% Error Q
0.50	34.50	34.50	34.32	34.32	34.85	34.85	35.32	35.32
1.00	33.81	33.81	33.78	33.78	34.44	34.44	34.96	34.96
1.50	33.51	33.51	33.54	33.54	34.25	34.25	34.79	34.79
2.00	33.32	33.32	33.39	33.39	34.14	34.14	34.70	34.70
2.50	33.19	33.19	33.29	33.29	34.07	34.07	34.63	34.63
3.00	33.10	33.10	33.22	33.22	34.01	34.01	34.58	34.58
3.50	33.03	33.03	33.16	33.16	33.97	33.97	34.54	34.54
4.00	32.97	32.97	33.11	33.11	33.94	33.94	34.51	34.51
4.50	32.92	32.92	33.08	33.08	33.91	33.91	34.49	34.49
5.00	32.88	32.88	33.04	33.04	33.88	33.88	34.46	34.46
Avg	33.32	33.32	33.39	33.39	34.15	34.15	34.70	34.70

Hence, the above analysis demonstrates that Manning's formula may overestimate the flow and velocity values. This confirms the basis for using Colebrook over Manning, in addition to the points raised above.

A.2.7 Comparison of Colebrook-White results using Australian and British Internal Pipe Diameters, and Nominal Pipe Diameters

The effect of diameter on flow rate and velocities was investigated. A filling degree of 70% for Australian internal diameters of 98mm, 143mm, 224mm and 274mm were compared and their flow rates and velocities have been plotted below in Figure 40 and Figure 41 below. It is evident that flow rate is more significantly influenced by pipe diameter than velocity, which is explained by the respective relationships (correlation) to pipe diameter.

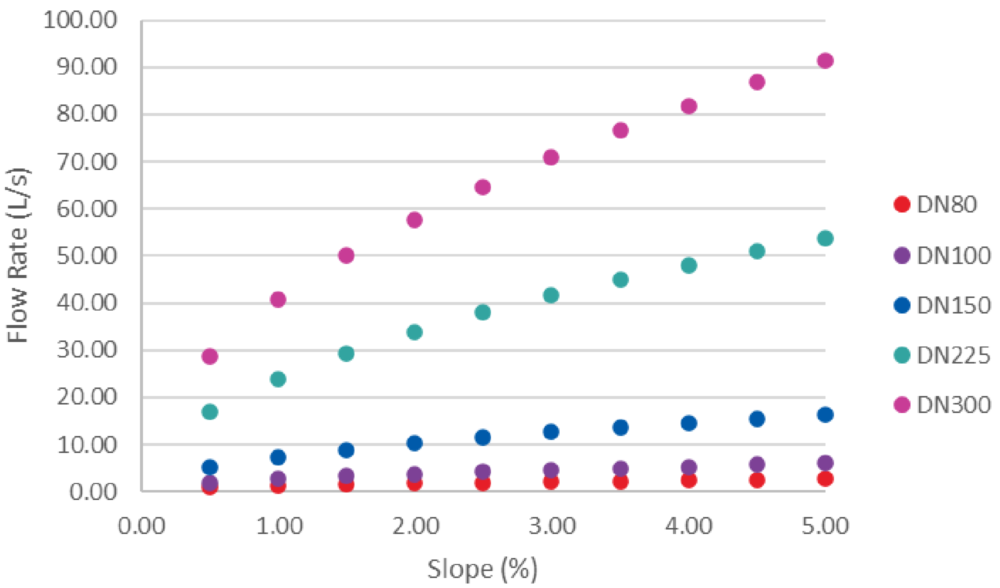

Figure 40: Effect of diameter on flow rate for h/D=0.7 and Australian PVC-U internal pipe diameters

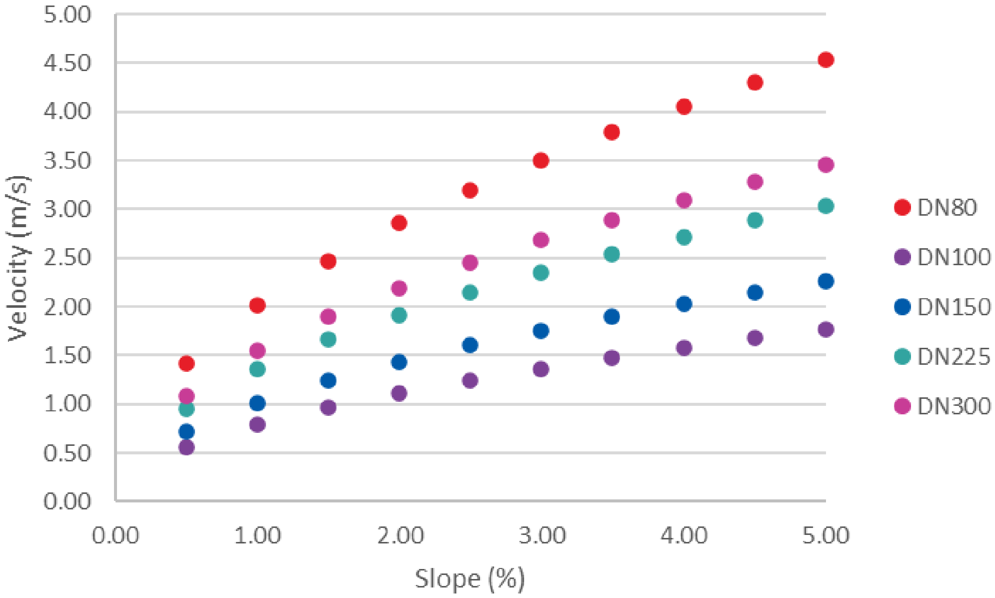

Figure 41: Effect of diameter on velocity for h/D=0.7 and Australian PVC-U internal pipe diameters

A.2.8 Effect of Kinematic Viscosity on Velocity and Flow Rate

The effect of water kinematic viscosity on velocity and flow rate was investigated. Kinematic viscosity values ν of 1.76×10^{-6} and 5.40×10^{-7} which correspond to temperatures of 0 to $50°C$ were compared and the results are shown below in Figure 42 and Figure 43 for flow rate and velocity respectively. As demonstrated by the graphs, the effect of viscosity on velocity and flow rate is negligible, with values varying by a factor of 1.01 (averaged over slopes and pipe sizes).

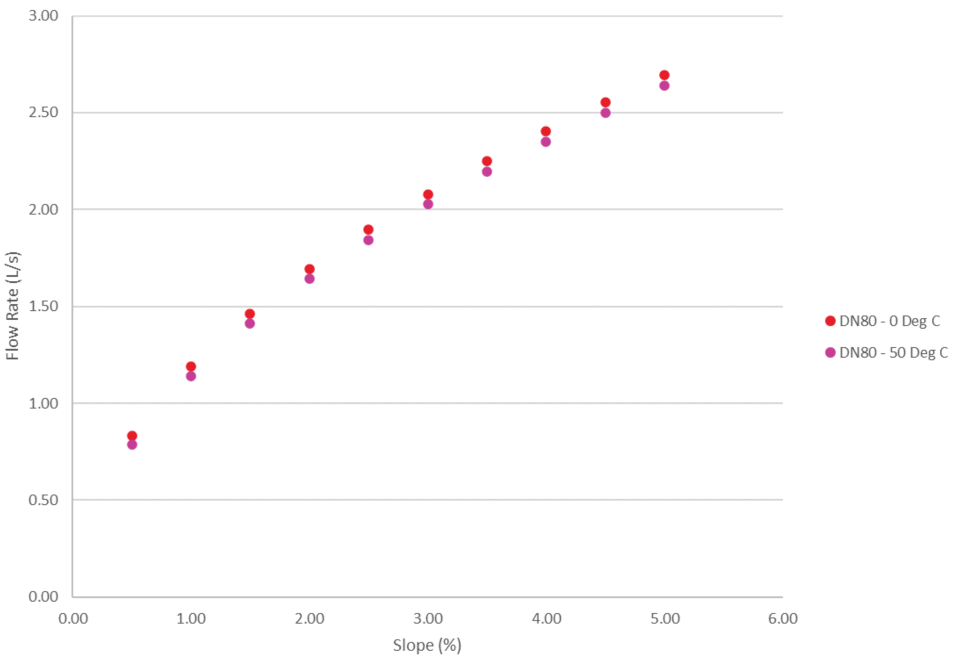

Figure 42: Effect of viscosity on flow rate for h/D=0.5 and Australian PVC-U internal pipe diameters

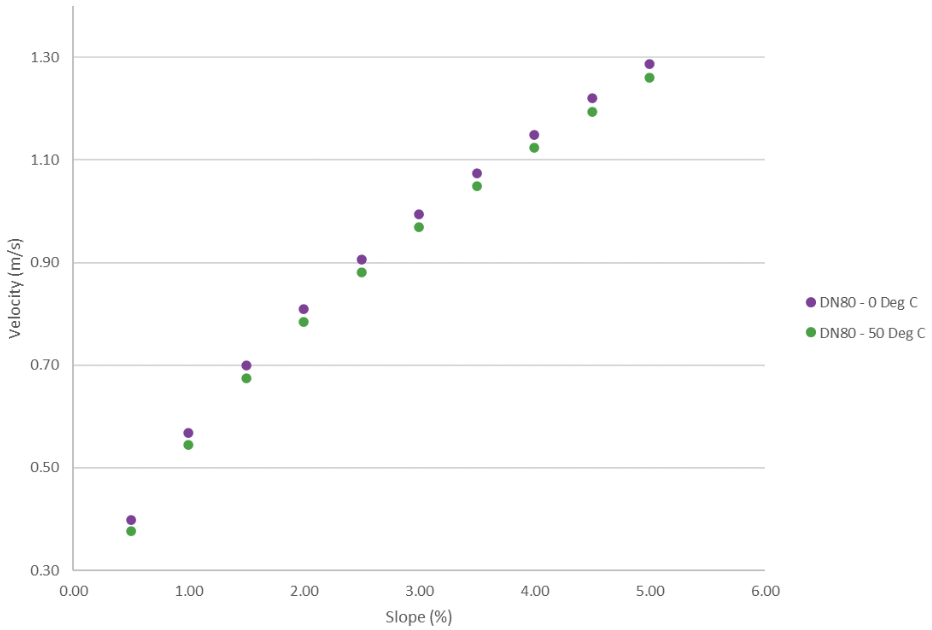

Figure 43: Effect of viscosity on velocity for h/D=0.5 and Australian PVC-U internal pipe diameters

A.3 Proposed Horizontal Drainage Sizing

The Colebrook-White Equation has been used to develop flow and velocity values for various standard drain sizes (AS internal sizes) for 50%, 70% and 81% filling capacity, as summarised below in Table 80, Table 81 and Table 82. Australian PVC-U internal pipe diameters were used for all calculations.

Table 80: 50% filling capacity

Slope (%)	DN40		DN50		DN65		DN80		DN100		DN150		DN225		DN300	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.124	0.243	0.270	0.299	0.495	0.350	0.840	0.401	1.854	0.492	5.097	0.635	16.840	0.855	28.744	0.975
1.0	0.177	0.347	0.386	0.426	0.705	0.499	1.196	0.572	2.637	0.699	7.241	0.902	23.896	1.213	40.771	1.383
1.5	0.217	0.427	0.474	0.524	0.867	0.613	1.470	0.702	3.238	0.859	8.886	1.107	29.311	1.488	50.001	1.696
2.0	0.252	0.495	0.549	0.607	1.003	0.710	1.700	0.812	3.745	0.993	10.274	1.279	33.876	1.719	57.783	1.960
2.5	0.282	0.554	0.615	0.680	1.123	0.794	1.903	0.910	4.192	1.111	11.496	1.432	37.899	1.923	64.639	2.192
3.0	0.309	0.608	0.675	0.746	1.232	0.871	2.087	0.997	4.595	1.218	12.601	1.569	41.535	2.108	70.837	2.403
3.5	0.335	0.658	0.729	0.806	1.331	0.942	2.256	1.078	4.967	1.317	13.617	1.696	44.879	2.278	76.537	2.596
4.0	0.358	0.704	0.780	0.862	1.424	1.008	2.413	1.153	5.312	1.409	14.563	1.813	47.992	2.436	81.842	2.776
4.5	0.380	0.747	0.828	0.915	1.512	1.069	2.561	1.224	5.637	1.495	15.451	1.924	50.915	2.584	86.825	2.945
5.0	0.401	0.788	0.874	0.965	1.594	1.128	2.700	1.290	5.944	1.576	16.291	2.029	53.680	2.724	91.538	3.105

Table 81: 70% filling capacity

Slope (%)	DN40		DN50		DN65		DN80		DN100		DN150		DN225		DN300	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.21	0.27	0.46	0.34	0.83	0.39	1.41	0.45	3.11	0.55	8.54	0.71	28.14	0.95	47.99	1.09
1.0	0.30	0.39	0.65	0.48	1.19	0.56	2.01	0.64	4.42	0.78	12.12	1.01	39.91	1.35	68.05	1.54
1.5	0.37	0.48	0.80	0.59	1.46	0.69	2.47	0.79	5.43	0.96	14.87	1.24	48.95	1.66	83.44	1.89
2.0	0.42	0.56	0.92	0.68	1.69	0.80	2.86	0.91	6.28	1.11	17.19	1.43	56.57	1.92	96.42	2.19
2.5	0.48	0.63	1.04	0.77	1.89	0.89	3.20	1.02	7.03	1.25	19.23	1.60	63.28	2.15	107.85	2.45
3.0	0.52	0.69	1.14	0.84	2.07	0.98	3.50	1.12	7.70	1.37	21.08	1.76	69.35	2.35	118.19	2.68
3.5	0.56	0.74	1.23	0.91	2.24	1.06	3.79	1.21	8.32	1.48	22.78	1.90	74.93	2.54	127.69	2.90
4.0	0.60	0.79	1.31	0.97	2.39	1.13	4.05	1.29	8.90	1.58	24.36	2.03	80.13	2.72	136.54	3.10
4.5	0.64	0.84	1.39	1.03	2.54	1.20	4.30	1.37	9.45	1.68	25.85	2.15	85.01	2.89	144.85	3.29
5.0	0.68	0.89	1.47	1.09	2.68	1.27	4.53	1.45	9.96	1.77	27.25	2.27	89.62	3.04	152.71	3.46

Table 82: 81% filling capacity

Slope (%)	DN40		DN50		DN65		DN80		DN100		DN150		DN225		DN300	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.25	0.28	0.54	0.34	0.99	0.40	1.67	0.46	3.68	0.56	10.08	0.72	33.23	0.97	56.67	1.11
1.0	0.35	0.40	0.77	0.49	1.40	0.57	2.38	0.65	5.23	0.80	14.32	1.03	47.14	1.38	80.35	1.57
1.5	0.43	0.49	0.95	0.60	1.72	0.70	2.92	0.80	6.42	0.98	17.57	1.26	57.81	1.69	98.52	1.93
2.0	0.50	0.57	1.09	0.70	1.99	0.81	3.37	0.93	7.42	1.13	20.31	1.46	66.81	1.95	113.85	2.23
2.5	0.56	0.64	1.22	0.78	2.23	0.91	3.78	1.04	8.30	1.27	22.72	1.63	74.73	2.19	127.35	2.49
3.0	0.62	0.70	1.34	0.86	2.45	1.00	4.14	1.14	9.10	1.39	24.90	1.79	81.90	2.40	139.55	2.73
3.5	0.67	0.76	1.45	0.92	2.65	1.08	4.48	1.23	9.84	1.50	26.91	1.93	88.49	2.59	150.77	2.95
4.0	0.71	0.81	1.55	0.99	2.83	1.15	4.79	1.32	10.52	1.61	28.78	2.06	94.62	2.77	161.22	3.15
4.5	0.76	0.86	1.65	1.05	3.00	1.22	5.08	1.40	11.16	1.71	30.53	2.19	100.38	2.94	171.03	3.34
5.0	0.80	0.91	1.74	1.11	3.17	1.29	5.36	1.48	11.77	1.80	32.19	2.31	105.83	3.09	180.31	3.52

A.4 Fixture Unit versus Discharge Unit

The formula for the conversion from discharge units (DU) to flow rate is given by BS EN 12056-2:2000 (B.S. Institute, 2000):

$$Q_{water} = K\sqrt{\sum DU}$$

Where K is the frequency factor provided in Table 8.3 of *BS EN 12056-2:2000* (B.S. Institute, 2000). A plot of discharge units versus flow rate for the four frequency factors is shown below in Figure 44. As demonstrated by the graph, the frequency factor has an increasing influence on flow rate with greater net number of discharge units.

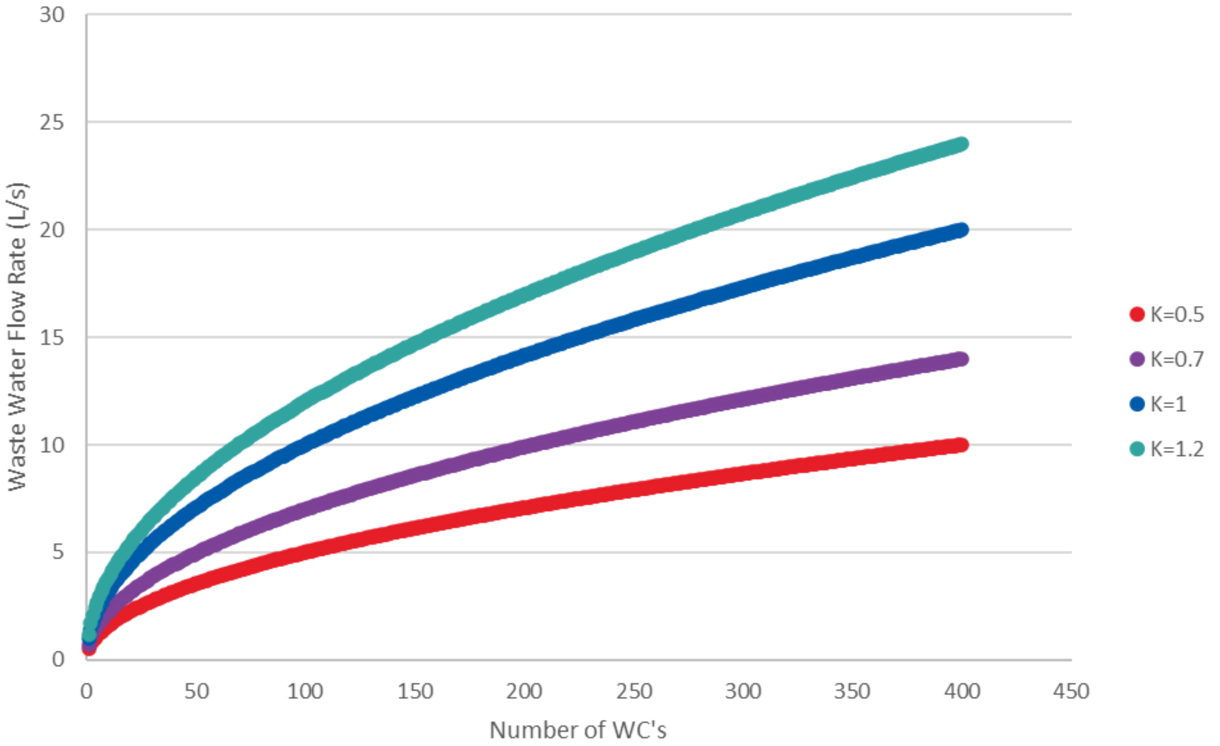

Figure 44: Discharge units versus flow rate for the four frequency factors

The formula for the conversion from fixture units (FU) (specified in AS3500.2 (Standards Australia, 2021)) to flow rate is given by (Swaffield & Bridge, 1983):

$$Q_{water} = \sqrt{\frac{\sum FU}{6.75}}$$

It should be noted that the above formula is not specified in AS3500.2 (Standards Australia, 2021). However, it describes the relationship between fixture units and flow rates, which is documented in Table 6.3(B) of *AS/NZS 3500.2:2021* (Standards Australia, 2021) (shown below in Figure 45) with reasonable accuracy, as demonstrated in the plot below in Figure 46. It should also be noted that the fixture unit to flow rate conversions provided in Section 2.3 of the Lucid standards review report (SPT, 2019), does not align with the results achieved from the above formula. These values have also been plotted below in Figure 46 for comparison.

Table 6.3(B) — Fixture unit ratings for continuous flows

Flow, L/s	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Fixture unit equivalent rating	6	8	15	25	40	60	85	115

Figure 45: Fixture unit ratings for continuous flows (Standards Australia, 2021)

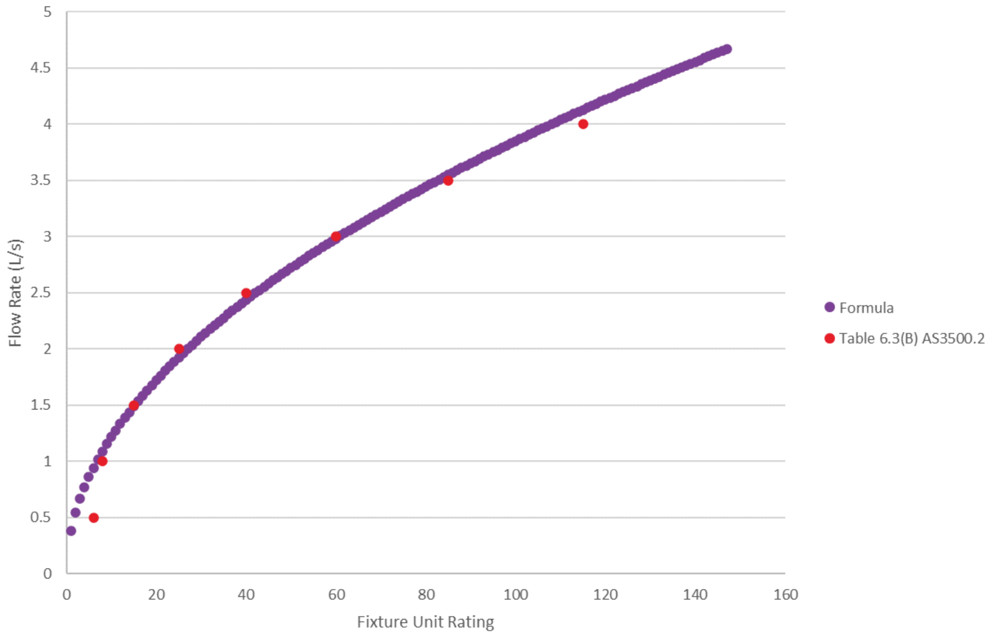

Figure 46: Plot of fixture unit rating versus flow rate

A.5 Simplification Attempts on Wistort's Method

A.5.1 Attempts to exclude the mean

We have attended to manipulate the standard deviation term within Wistort's method to mimic the DU calculation method due to the presence of a square root expression. The resulting expression is as follows:

$$Q_{Total} = F \times \sqrt{\sum_{k=1}^{K} n_k q_k^2 + Q_{Other}}$$

Where:

$$F = 5.16 \times \sqrt{p(1-p)}$$

F = Frequency adjustment factor
p = Universal probability factor based off the average probability of fixture operating depending on building type or classification
n_k = number of fixtures within the fixture type k
p_k = probability of a single fixture operating within fixture type k

This expression was intended to allow designers to use an expression that is familiar and easy to use, whilst still retaining a relatively strong mathematical foundation regarding its derivation. Since the discharge value from fixtures can be measured empirically, and the universal probability factor can be adjusted and refined empirically to better match different building classes, this expression should also allow relatively accurate estimates of peak sanitary discharge to be obtained. As opposed to the more accurate modified Wistort's expression which required specific probability relationships between fixture discharge and building classes, this approach can be used as an alternate method when individual fixture data is not available, or when rapid approximations are required during conceptual design.

The proposed expression above is based on the simplification of Wistort's standard deviation term:

$$(z_{0.99})\sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2}$$

Where the value calculated by this expression represents the difference between the mean flow and the 99th percentile flow. In this expression, each fixture is able to have its own probability of use however, if we allocate a universal probability value that varies based on building type instead of probability, we can further simplify the expression and eliminate the probability values from the summation. I.e.:

$$(z_{0.99})\sqrt{p(1-p)\sum_{k=1}^{K} n_k q_k^2}$$

From here we discovered a discrepancy involving the behaviour of a standard normal distribution with a binomial distribution. The initial understanding was that the z-score provided the measurement for how many standard deviations above the population mean a value resides. The probability of at least that value for that z-score occurring is the area under the standard normal distribution and to the left of that value and would be typically provided by a z-table. In the interest of removing the expression to calculate the mean and retain only a square root function, similar to the *BS EN 12056-2* of calculation, we propose that instead of a 99th percentile score we find the z-scores of the same magnitude that would provide a probability of at least 99%. i.e., the area under the standard normal distribution curve between the two z-scores that would total to at least 0.99.

From z-tables, a z-score of 2.58 has a corresponding area (percentile) of 0.99506 and a z-score of -2.58 has a corresponding area of 0.00494. The difference between the z-score percentiles results in a value of 0.99012. This suggests that 2.58 standard deviations above and below the mean would account for 99% of all occurrences. Since the truncation of the lower tail would in theory exclude occurrences where there are very few fixtures being operated, this simplification may result in a more conservative estimation.

The development of the expression is as follows:

When:

$$z_{0.995} = 2.58$$
$$z_{0.005} = -2.58$$

The probability of an event occurring between 2.58 standard deviations from the mean can then be expressed as:

$$z_{0.995} - z_{0.005} = \frac{x_{0.995} - \mu}{\sigma} - \frac{x_{0.005} - \mu}{\sigma}$$

Since:

$$z_{0.995} - z_{0.005} = 2.58 - (-2.58) = 5.16$$

$$\sigma = \sqrt{Variance(x)}$$

$$Variance(x) = \sqrt{np(1-p)}$$

The equation simplifies to:

$$5.16 = \frac{x_{0.995} - x_{0.005}}{\sqrt{np(1-p)}}$$
$$\therefore 5.16 \times \sqrt{np(1-p)} = x_{0.995} - x_{0.005}$$

Where:
$x_{0.995}$ = Number of busy fixtures that occur 99.5% of the time

$x_{0.005}$ = Number of busy fixtures that occur 0.5% of the time

From above we can determine the approximate flows that will occur 99% of the time for K different number of fixtures by:

$$5.16 \times \sqrt{p(1-p)\sum_{k=1}^{K} n_k q_k^2}$$

If we remove the constants from the expression, we are left with:

$$5.16 \times \sqrt{p(1-p)} \times \sqrt{\sum_{k=1}^{K} n_k q_k^2}$$

If we assign an arbitrary letter, say F, to the constants in front of the square root sign, we will result in an expression that closely resembles the *BS EN 12056-2* sanitary discharge equation:

$$Q = F \times \sqrt{\sum_{k=1}^{K} n_k q_k^2}$$

During testing, we recognised the inaccuracies of this simplification and upon further testing, the error of this derivation and simplification was found.

A.5.2 Approximating mean and variance in low p-value binominal distributions

After unsuccessfully manipulating Wistort's Method through statistical means, we further progressed our analysis on approximating the mean and standard deviation term for a single fixture type. For a single fixture type, i.e., K=1, the summation operators disappear, and we have the expression:

$$Q_{0.99} = npq + (z_{0.99})\sqrt{np(1-p)q^2}$$
$$= npq + 2.323q\sqrt{np(1-p)}$$

Hence, the 99th percentile of busy fixture would equate to:

$$np + 2.323\sqrt{np(1-p)}$$

Where:

n = number of fixtures
p = probability of a single fixture operating

We aimed to further simplify the result by determining if we could approximate $np(1-p)$ with np. We tested values of p ranging from 0.01 to 0.10 as a starting point and assumed that majority of fixtures will have a probability of operating ranging between these probabilities. Since n is a constant, we can rationalise the comparison to between p and $p(1-p)$.

Table 83: Comparison between the standard deviation and square root of the mean

$\boldsymbol{p}$	$\boldsymbol{p(1-p)}$	$\boldsymbol{Error}$	$\boldsymbol{\sqrt{Error}}$
0.01	0.0099	0.01	0.10
0.02	0.0196	0.02	0.14
0.03	0.0291	0.03	0.17
0.04	0.0384	0.04	0.20
0.05	0.0475	0.05	0.22
0.06	0.0564	0.06	0.24
0.07	0.0651	0.07	0.26
0.08	0.0736	0.08	0.28
0.09	0.0819	0.09	0.30
0.1	0.0900	0.10	0.32

From the table above, the error calculated between p and $p(1-p)$ appeared to be equal to p however, since the approximated term, $p(1-p)$, is square-rooted its error would be too. Alternatively, the p term can be approximated through $p(1-p)$ which would result in smaller errors within approximation. Proceeding with the latter, the 99th percentile of busy fixtures can in theory be approximated by the expression below provided p is small:

$$np(1-p) + 2.323\sqrt{np(1-p)}$$

From this expression, we can manipulate it to equal the standard deviation term through a constant x:

$$np(1-p) + 2.323\sqrt{np(1-p)} = x\sqrt{np(1-p)}$$

The reason the standard deviation term was selected to equation this expression was due to the desired square-root term. This allows the equation above to be simplified as follows:

$$np(1-p) = (x - 2.323) \times \sqrt{np(1-p)}$$

$$\sqrt{np(1-p)} = x - 2.323$$

The expression above suggests that for a selected p and n combination, there is an optimal x that would allow for the 99th percentile of busy number of fixtures to be estimated to a reasonable accuracy. However, this will also mean that for larger values of p, the value of x a lot more significantly across various values of n. The table below illustrates this behaviour:

Table 84: Constant required for accurate approximations of 99th percentile busy fixtures

	P=0.01			**P=0.05**			**P=0.10**		
n	*np(1-p)*	*LHS**	*x*	*np(1-p)*	*LHS**	*x*	*np(1-p)*	*LHS**	*x*
0	0.000	0.000	2.323	0.000	0.000	2.323	0.000	0.000	2.323
1	0.010	0.099	2.422	0.048	0.218	2.541	0.090	0.300	2.623
5	0.050	0.222	2.545	0.238	0.487	2.810	0.450	0.671	2.994
10	0.099	0.315	2.638	0.475	0.689	3.012	0.900	0.949	3.272
20	0.198	0.445	2.768	0.950	0.975	3.298	1.800	1.342	3.665
40	0.396	0.629	2.952	1.900	1.378	3.701	3.600	1.897	4.220
80	0.792	0.890	3.213	3.800	1.949	4.272	7.200	2.683	5.006
100	0.990	0.995	3.318	4.750	2.179	4.502	9.000	3.000	5.323
150	1.485	1.219	3.542	7.125	2.669	4.992	13.500	3.674	5.997
200	1.980	1.407	3.730	9.500	3.082	5.405	18.000	4.243	6.566
250	2.475	1.573	3.896	11.875	3.446	5.769	22.500	4.743	7.066

*LHS = Left-hand side, refers to the expression to the left side of the equal sign of the equation: $\sqrt{np(1-p)} = x - 2.323$

We were unable to identify a trend nor establish a general value of x that would minimise errors during approximation. A potential pathway would be to determine the average number of fixtures within buildings of different classes and assigning a universal probability value to each of these different classes thus allowing for a selection to x values to be provided for different building types. Alternatively, a table such as the one presented above may be provided instead, allowing designers to select their own values of x.

Unfortunately, the method above becomes invalid when more than one fixture, specifically one with a different q, is introduced into the calculation. Through our testing and verification process involving our initial simplification step of assigning $K = 1$ for ease of mathematical manipulation, we realised the importance of the summation within the square root term to get an accurate outcome. Since the proposed method is an estimation for the square root term of a particular fixture time, it is no longer possible to sum the values after when more than one fixture type needs to be accounted for. I.e.,

$$\sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2} \neq \sum_{k=1}^{K} \sqrt{n_k p_k (1-p_k) q_k^2}$$

Where our approximation would effectively be what is shown on the right-hand side (RHS) of the equation versus the left-hand side (LHS) which is what it is supposed to resemble.

A.5.3 Equating Wistort's expression to its square root term

Due to the unsuccessful attempts with simplifying Wistort's Method, we tried to repeat the steps in A.5.2 without removing the summation terms. We would equate Wistort's expression with its own square root term as done previously resulting the in the expression below:

$$\sum_{k=1}^{K} n_k p_k q_k + (z_{0.99}) \sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2} = x \sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2}$$

Where:
n_k = number of fixtures within the fixture type k
p_k = probability of a single fixture operating within fixture type k
q_k = rate of busy fixture of type k
$(z_{0.99})$ = 2.326, or the z-score of the 99th percentile in a standard normal distribution
x = constant

If the probability constant is simplified down to a universal probability value, the expression can further simplified:

$$p \sum_{k=1}^{K} n_k q_k + 2.323 \sqrt{p(1-p) \sum_{k=1}^{K} n_k q_k^2} = x \sqrt{p(1-p) \sum_{k=1}^{K} n_k q_k^2}$$

$$p \sum_{k=1}^{K} n_k q_k = (x - 2.323) \sqrt{p(1-p) \sum_{k=1}^{K} n_k q_k^2}$$

From the final expression above, we were unable to perform any further simplifications or mathematical manipulations to solve values of x that would allow for reasonable accurate estimations of the 99th percentile flows proposed by Wistort's method. Thus, our attempts to derive a DU-like calculation formula for peak sewer demands based on Wistort's formula concluded that more academic expertise is required to assist with progressing this methodology should it be deemed appropriate or worthwhile.

A.6 Innovation Engineering's Discharge Flow Rate Values

INNOVATION ENGINEERING

IT19001_FIXTURE UNIT RATINGS

TEST UPDATE

RESULTS

TEST #	ID #	Category	PART #	Description	Waste Size (mm)	Water Depth* (mm)	Waste Flow Rate (L/s)
1	EUT01	BASIN	865635W	CARBONI II - Grate	40	45	**0.33**
2	EUT02	BASIN	675100W	METRO 35	50	100	**0.68**
3	EUT03	BASIN	674103W	LABORATORY	50	100	**0.65**
4	EUT04	BATH	NU7W	NEWBURY 1675 - Popup	40	100	**0.46**
5	EUT04	BATH	NU7W	NEWBURY 1675 - Grate	40	100	**0.63**
6	EUT05	SHOWER	857570W	DOLPHIN SHOWER BASE	50	50	**1.12**
7	EUT06	TROUGH	8011	EUREKA 45 TUB	50	100	**0.47**
8	EUT07	SINK	1503.1R	ADVANCE SINGLE	50	100	**0.45**
9	EUT08	SINK	2503.1L	ADVANCE 1.75	50	100	**1.05**
10	EUT09	SINK	811592W	CLEANERS SINK	50	100	**0.69**
11	EUT10	PAN	618320W	SLOP HOPPER	85	200	**2.75**
12	EUT11	URINAL	678800W	CUBE 0.8L SERIES II	50	50	**0.29**
13	EUT12	CISTERN	233036W	CAROMA SLIMLINE 6/3L	50	240	**2.13**
14	EUT13	CISTERN	234040W	CAROMA AIRE 4.5/3L	50	240	**2.10**
15	EUT14	BIDETTE	611515W	CAROMA CUBE WF BIDETTE	50	100	**0.43**
16	EUT15	S/HOPPER	618320W	SLOP HOPPER 6/3L	85	240	**1.70**
17	EUT16	TOILET PAN / CISTERN	984330W	UNISET 2 CONCORDE 6/3L	85	240	**2.86**
18	EUT17	TOILET PAN / CISTERN	989200W	CARAVELLE EH 4.5/3L	85	240	**1.13**
19	EUT18	URINAL	JRS001	CAROMA URINAL STALL	100	100	**3.85**
20	EUT19	FLUSH VALVE	KH0017	CAROMA MAINS FLUSH	100	240	**2.1**

*measured above waste

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INNOVATION ENGINEERING

IT19001_FIXTURE UNIT RATINGS

TEST UPDATE

FIXTURE UNIT RATING TABLE									
CURRENT AS/NZS:3500.2:2018					CURRENT BS EN 12056.2:2000		PROPOSED REVISED AS/NZS:3500.2:2018		
Fixture	Fixture abbreviations	Min. size of trap outlet and fixture discharge pipe DN		Current Fixture Units AS/NZS 3500.2:2018 Table 6.3A	Min. size of trap outlet and fixture discharge pipe Inches	Flow rate l/s	Min. size of trap outlet and fixture discharge pipe DN	Flow rate L/s	Proposed new Fixture Unit Rating?
		AU (only)	NZ (only)						
BASINS									
Basin	B	40	32	1	32	0.3	40	0.33	
BATHS									
Bath (with or without overhead shower)	Bath	40		4			40	0.63	
SHOWER									
Single	Shr	40		2	40	0.4	50	1.12	
Multiple		50		2 per head			Not tested - UNSPECIFIED		
BIDET or BIDETTE									
	Bid	40	32	1		0.3	50	0.43	
TROUGH									
Ablution	Tr(A)	40		3	50		Not tested - UNSPECIFIED		
Laundry	Tr.L	40		5	50		50	0.47	
CLOTHES WASHING MACHINE									
Domestic	CWM	40		5		0.5	40	0.33	
Commercial		50		See Table 6.3B		1			
DISHWASHING MACHINE									
Domestic	DWM	40		3		0.5	40	0.16	
Commercial		50		See Table 6.3B					
GLASS-WASHING MACHINE									
	GWM	40		3			Not tested - UNSPECIFIED		
SINKS									
Single (with or without disposal unit)	S	50	40	3		0.5	50	0.45	
Double (with or without disposal unit)	DS	50	40	3			50	1.05	
Pot or Utility	PS	50		5			50	0.68	
Laboratory	LS	50		1			50	0.65	
Tea	TS	50	40	1			Not tested - UNSPECIFIED		
Bar - domestic	BS(D)	40		1			Not tested - UNSPECIFIED		
Sink - cleaner	CS	50		1			50	0.69	
SLOP HOPPER or SLOP SINK									
No Cistern	SH or SS	100	100	6			85	2.75	
6/3 litre cistern							85	1.70	
URINAL									
Wall hung	Ur	40	32	1			50	0.29	
Stall or each 600mm length of slab		50		1		0.2	100	3.85	
WATER CLOSETS									
6/3 litre cistern	WC	100	100	4		2	50	2.13	
4.5/3 litre cistern		100	100	4		1.8	50	2.10	
6/3 litre cistern							85	2.86	
4.5/3 litre cistern							85	1.13	
Flush valve		100	100	6			100	2.1	

A.7 Research Expert RFI

This section outlines a request for information submitted to Heriot-Watt University mid-way through Arup's work on this research project and includes a summary of the key discussion outcomes following a meeting with Lynne Jack of Heriot-Watt Universities School of Energy, Geoscience, Infrastructure and Society Research team.

A.7.1 Discharge Unit and K-factor Origins

- We are aware that the Discharge Unit (DU) within *BS EN 12056-2:2000* (B.S. Institute, 2000) are not specifically discharge flowrates of the sanitary fixtures. However, we have noticed its similarity to the expected discharge flowrate from a sanitary fixture (based on crude measurements from an Australian engineering firm, Innovation Engineering shown below in Table 85).
- Are you able to provide your opinion on this matter, specifically regarding to DU for System I (filling degree of 50%) and II (filling degree of 70%) designs as the DU or waste fixture flow rate varies across the systems?
- In your opinion is the *BS EN 12056-2:2000* DU method is a reasonably accurate, but conservative representation of the expected discharge flowrates from each sanitary fixture?
- Are you aware of the derivation of the DU? We were unable to find this information within our investigation.

Table 85: DU values versus discharge flow rates from fixtures tested by Innovation Engineering

Appliance	**System I**	**System II**	**System III**	**System IV**	**Innovation Engineering**
	DU l/s	**DU** l/s	**DU** l/s	**DU** l/s	**DU** l/s
Wash basin, bidet	0.5	0.3	0.3	0.3	0.33
Shower without plug	0.6	0.4	0.4	0.4	1.12
Shower with plug	0.8	0.5	1.3	0.5	
Single urinal with cistern	0.8	0.5	0.4	0.5	0.29
Urinal with flushing valve	0.5	0.3	-	0.3	
Slab urinal	0,2*	0,2*	0,2*	0,2*	
Bath	0.8	0.6	1.3	0.5	0.63
Kitchen sink	0.8	0.6	1.3	0.5	0.45
Dishwasher (household)	0.8	0.6	0.2	0.5	0.16
Washing machine up to 6 kg	0.8	0.6	0.6	0.5	0.33
Washing machine up to 12 kg	1.5	1.2	1.2	1.0	
WC with 4,0 l cistern	**	1.8	**	**	
WC with 6,0 l cistern	2.0	1.8	1,2 to 1,7***	2.0	2.86
WC with 7,5 l cistern	2.0	1.8	1,4 to 1,8***	2.0	
WC with 9,0 l cistern	2.5	2.0	1,6 to 2,0***	2.5	
Floor gully DN 50	0.8	0.9	-	0.6	
Floor gully DN 70	1.5	0.9	-	1.0	
Floor gully DN 100	2.0	1.2	-	1.3	

* Per person.
** Not permitted.
*** Depending upon type (valid for WC's with siphon flush cistern only).
\- Not used or no data.

- We were also unable to properly source the method for which the K-factors was derived within *BS EN 12056-2:2000 (*shown below in Figure 47).
- We suspect there is a relationship between the K-factor and the fixture usage intervals (T) (1200, 600 or 300 seconds) detailed within the *Plumbing Engineering Services Design Guide* (Whitehead, 2002) and developed the following expression through trend fitting the data summarised below in Table 86:

$$K = \left(\frac{300}{T}\right)^{0.5}$$

Where T is the interval of time between fixture use.

Table 86: Data used to derive a relationship between the *BS EN 12056-2:2000* K-Factors and the IOP fixture usage intervals

Fixture usage intervals – T (s) (Whitehead, 2002)	**K-Factor BS EN 12056-2** (B.S. Institute, 2000)
1200	0.5
600	0.7
300	1

- We are unable to determine the significance of the constant 300, nor are we entirely sure that our assumption is correct. Are you able to provide your opinion on this? Are you aware of how the K-factors were derived?
- We note that despite the fraction form closely resembling a fixture usage probability, in our opinion it does not make sense for a typical fixture to be in operation for 300 seconds.

$$p = \frac{duration\ of\ time\ that\ the\ fixture\ is\ busy}{duration\ of\ time\ that\ the\ fixture\ is\ observed}$$

Table 3 — Typical frequency factors (*K*)

Usage of appliances	***K***
Intermittent use, e.g. in dwelling, guesthouse, office	0,5
Frequent use, e.g. in hospital, school, restaurant, hotel	0,7
Congested use, e.g. in toilets and/or showers open to public	1,0
Special use, e.g. laboratory	1,2

Figure 47: Typical frequency factors (K) from *BS EN 12056-2:2000* (B.S. Institute, 2000)

A.7.2 Modified Wistort's Expression & Simplification Attempt

A.7.2.1 Modified Wistort's Formula

- Within our investigation, we are considering the use of the modified Wistort's formula to estimate peak sewerage discharge flows (Hobbs, et al., 2019).
- We understand that this method was initially used to estimate peak water demand based on fixture flowrates and probability of use.

- Are you aware any research that includes the adaptation of this method for use in sanitary plumbing and drainage applications? We provided the formula below for reference:

$$Q_{0.99} = \frac{1}{1-P_0}\left(\sum_{k=1}^{K} n_k p_k q_k + [(1+P_0)z_{0.99}]\sqrt{\left[(1-P_0)\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2\right] - P_0\left(\sum_{k=1}^{K} n_k p_k q_k\right)^2}\right)$$

Where:

- K is the number of different and independent fixture groups
- $Q_{0.99}$ = 99th percentile demand
- n_k = number of fixtures within the fixture type k
- q_k = rate of busy fixture of type k
- $(z_{0.99})$ = 2.326, or the z-score of the 99th percentile in a standard normal distribution
- p_k = probability of a single fixture operating within fixture type k with formula:

$$p_k = \frac{duration\ of\ time\ that\ the\ fixture\ k\ is\ busy}{duration\ of\ time\ that\ the\ fixture\ k\ is\ observed}$$

- P_0 is the probability of all fixtures having zero demand, calculated as:

$$P_0 = \prod_{k=1}^{K}(1-p_k)^{n_k}$$

We believe that the probability a fixture is used would have an identical, or similar probability to a fixture being discharged on the basis that when a fixture is used, it is unlikely it will be used again without the previous load being discharged, except for a few use cases such as irrigation.

- The flows used in Wistort's formula would need to be adjusted to match potential flow rates from plugged fixtures however, since a fixture discharge time may be quite different from its in-use time, we are concerned about any unforeseen consequences with our assumption above. Are you able to provide your opinion on adopting the Wistort's formula for calculating sanitary drainage flows?

A.7.2.2 Attempt to Simplify Wistort's Formula

- We are looking to propose a simplified Wistort's formula, which was designed to closely resemble the sanitary flow, discharge unit formula within *BS EN 12056-2:2000* (B.S. Institute, 2000).
- The motivation for this modified method was (1) the inability determine how the DU and K-factors from *BS EN 12056-2:2000* were derived, and (2) the desire to provide a method with a strong mathematical foundation as well as a resemblance to the DU method. We have taken the below steps in attempt to accomplish this.
- Are you able to provide some commentary on whether our simplification is mathematically sound, and what type of inaccuracies might occur with this method? We understand that this method would be less accurate than Wistort's formula, and even more so against the modified Wistort's formula for lower fixture counts, however, we are unsure of the expected level of inaccuracy.
- The steps taken to simplify the formula are provided below:
    - Wistort's formula, standard deviation section:

$$(z_{0.99})\sqrt{\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2}$$

- Removing association of fixture use probability and replacing with generic universal probability based on building type or classification:

$$(z_{0.99})\sqrt{p(1-p)\sum_{k=1}^{K} n_k q_k^2}$$

- Probability of an event occurring between 2.58 standard deviations away from the mean equates to approximately 99% of all occurrences (as opposed to 99th percentile):

$$z_{0.995} - z_{0.005} = \frac{x_{0.995} - \mu}{\sigma} --$$

$$z_{0.995} - z_{0.005} = 2.58 - (-2.58) = 5.16$$

$$5.16 = \frac{x_{0.995} - x_{0.005}}{\sqrt{np(1-p)}}$$

$$\therefore 5.16 \times \sqrt{np(1-p)} = x_{0.995} - x_{0.005}$$

- Relating the above expression back to Wistort's standard deviation expression and extracting probability constant out of the square root term:

$$5.16 \times \sqrt{p(1-p)} \times \sqrt{\sum_{k=1}^{K} n_k q_k^2}$$

A.7.3 Data Requirement

We are also seeking the data listed below which we believe will greatly assist with future research and investigations. Can we get your opinion on the data we are requesting? I.e., should we request different types of data sets, more specific data, additional measurements, etc.

Data for various fixture types that we believe would significantly assist with the development of the proposed simplified Wistort's method and, the verification of the modified Wistort's method would be:

- Time the fixture is busy
- Time the fixture was observed
- Discharge rate of the fixture
- Type of building the fixture data was obtained from
- Occupancy at time fixture data was obtained
- Total fixture numbers within the building
- Different fixtures observed or tested are to match the fixtures list in AS3500.2

Additional building data that we believe would also be of value, but does not necessarily need to be related to the previous data set include:

- Sanitary drainage flow rate observed over a period of time for different building types (say a week)
- The approximate number of fixtures within the building
- The number of occupants within the building at time of observation

We are also interested in your opinion on how many data sets for each building type / condition we should aim for to create a robust benchmark of low, high and mean usage conditions.

A.7.4 Horizontal Drainage – Branch Drainage & Main Sewer Drains

A.7.4.1 Recommended Filling Ratio

- We want to recommend that a filling ratio of 70-75% for branch drains and main sewer drains. In your opinion is this filling degree appropriate? We would also like feedback on whether this method of sizing would be appropriate for both branch and main drains, or only main drains.
- We note that the Colebrook-White equation for partially filled pipes demonstrates that peak flow is achieved at 95% filling degree. A 70% filling ratio allows for a factor of safety on the flow rate of ~1.28. We also note that this recommendation is supported by current industry standard (Butler & Pinkerton, 1987), *WSA02-2002* (Water Services Association of Australia, 2002) & *BS EN 16933.2-2017* (B.S. Institute, 2018)). Our intent is that this factor of safety ensures that at peak design flow the drain can accommodate adequate air ventilation, as well as account for factors we have not considered the effect of such as junction entries. Can provide your opinion on this justification.
- We would also like some clarification around the following statement of 'Transient Airflow in Building Drainage System' (Swaffield, 2010): "*However, drainage design codes, linking applied water flowrates to drain diameter and slope, are based on the concept that the free surface flow depths should not exceed 50 per cent of the drain diameter and inherently imply steady flow. This result may be confirmed by application of the Chezy expression for steady free surface flow depth at the maximum allowable flow rate acceptable prior to either an increased diameter or a steepened slope recommendation. This essentially empirical result ensures that the increased flow depths generated at pipe junctions still allow an air path above the water free surface and do not result in local surcharge.*"
    - As addressed above, we think that sizing horizontal drainage at 70% filling capacity for peak flows will allow the system to achieve self-cleansing velocities at more regular intervals. However, we would like to understand any impacts of designing to 70% as opposed to 50% filling capacity. Is the above statement suggesting that flows exceeding 50% of the drain diameter are inherently unsteady? Is the concern that intermittent blockages in airflow may result in trap loss events? We note that 70% filling capacity will only occur for peak design flows, which we expect to occur infrequently.
    - The above statement suggests that flows exceeding 50% of the drain diameter may result in local surcharges at pipe junctions. Has there been research (experimental and/or simulation) conducted into the issue of inflows from pipe junctions entering into drains that are already approaching 70% capacity, to understand the impact on the broader system?

Effect of Solids on Filling Ratio

- A study conducted by (Mahajan, 1981) tested the drain depth of 76mm diameter drain tested for unsteady, nonuniform, partially filled pipe flow for varying water volume discharged from the fixture into the drain; drain slope, and the diameter and length of cylindrical solids. It was found that the presence of a solid increases the filling ratio of a horizontal drainage pipe, and the percentage increase in filling ratio varies with the volume of water discharged and the distance along the pipe from the drain entrance (refer to Figure 48 and Figure 49).

- We understand that the presence of solids will increase the filling ratio of horizontal drainage pipes, and this is a factor we have not accounted for in calculations for filling degree. Meaning at peak flow, the actual filling capacity of the pipe may be higher than 70%. We do not believe this will be an issue since as stated in the previous section, peak flows will occur infrequently, and hence the water flow level within the drainage pipes will not typically be 70% full. Hence, we do not believe we need to account for the effect of solids on the filling ratio we recommend. We do however recognise that we will need to account for the presence of solids with regards to meeting minimum travel distances to ensure that the risk of blockages is mitigated, and we address this in Section A.7.4.3.
- We would appreciate your opinion on our above assumption. We would also like your input on whether there is more recent research to validate the findings of (Mahajan, 1981).

Table 87: Maximum water depth to pipe diameter ratio with and without a solid at Station 1 (–60cm from solid) - Results derived from (Mahajan, 1981)

Water discharged (L) (approx.)	Max Water Depth to Pipe Diameter Ratio (No solid)	Max Water Depth to Pipe Diameter Ratio (3.8x5.1 solid)	% Increase in Max Water Depth to Pipe Diameter Ratio
2	0.22	0.45	104.5
4	0.43	0.49	14.0
8	0.51	0.58	13.7
12	0.57	0.67	17.5

Table 88: Maximum water depth to pipe diameter ratio with and without a solid at Station 3 (–50cm from solid) - Results derived from (Mahajan, 1981)

Water discharged (L) (approx.)	Max Water Depth to Pipe Diameter Ratio (No solid)	Max Water Depth to Pipe Diameter Ratio (3.8x5.1 solid)	% Increase in Max Water Depth to Pipe Diameter Ratio
2	0.04	0.16	300.0
8	0.26	0.39	50.0
12	0.28	0.36	28.6

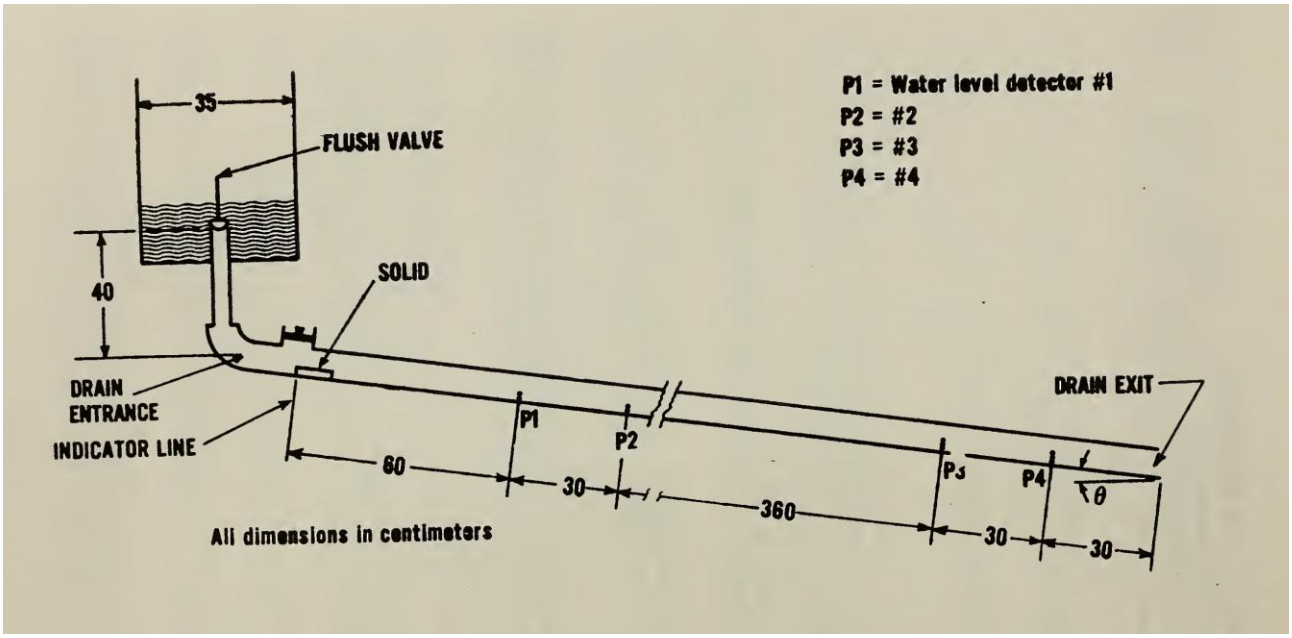


Figure 48: Experimental Setup by (Mahajan, 1981)

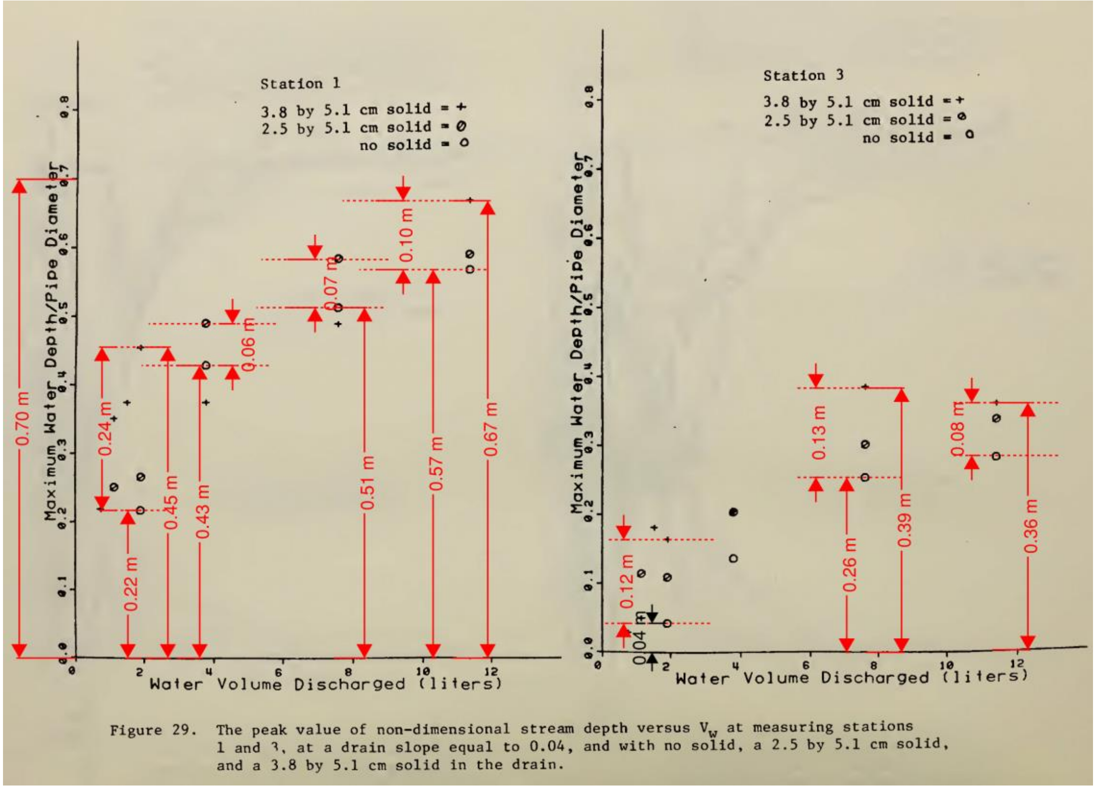


Figure 49: Annotated Results of Flow depth versus water volume discharged at Station 1 and 3 (Mahajan, 1981)

A.7.4.2 Recommendations for Minimum and Maximum Velocities

- Empirical design rules were established to minimise issues with sediment. These design rules were based on a fixed minimum flow velocity or shear which either ensured sediment deposit never occurred or occurred only after a long period of time (Nalluri & Ghani, 1996).
- We understand the need for self-cleaning velocities is specified to facilitate the transport of sediment; either the transport of existing sediment within the sewer bed or based on the criteria for no sediment to be deposited (Vongvisessomjai, et al., 2010).
- Currently, standards recommend a fixed minimum flow velocity or shear stress value to account for self-cleansing, given set pipe flow conditions. We are finding contradictory information around self-cleansing, with codes specifying varying fixed minimum velocities between 0.6 to 0.8m/s to ensure self-cleansing.
- We understand that these fixed values are based off various design criteria based on (1) moving existing sediment on a sewer bed or (2) ensuring no/limited deposition of sediment.
- We would like to understand whether you have any comments on this research and how we can develop suitable velocity recommendations for the code given the variability of velocity required for self-cleansing. It should be noted that we will only be considering sanitary sewers (not storm or combined systems, as some research is based off).
- Some codes state a maximum flow velocity for gravity drainage, however we cannot determine the basis of this. We have seen maximum velocity limits of 3m/s set to prevent turbulence or scouring of pipes. We would like your opinion on this issue to understand whether high velocities imply unsteady flow that would deviate significantly from pipe flow capacity predictions made using the Colebrook-White equation, or whether maximum velocity limits were set purely to precent scouring and damage to pipes.

Table 2. Design Table for Storm Sewers with High Sediment Loading and 2% Allowable Deposition

Sewer diameter D (mm)	Minimum velocity V_m (m/s)	Governing criteria	Deposited bed depth y_s/D (%)	Composite roughness k_c (mm)	Discharge capacity Q (L/s)	Minimum gradient i_m (1/xxx)
150	0.67	3	1	1.8	12	161
225	0.72	3	1	1.9	29	235
300	0.75	3	1	1.9	53	313
450	0.79	2/3	2	3.0	125	423
600	0.90	2	2	3.1	253	467
750	1.06	2	2	3.2	466	445
900	1.22	2	2	3.4	774	421
1,000	1.35	2	2	3.4	1,060	393
1,200	1.59	2	2	3.5	1,790	355
1,500	1.82	2	2	3.7	3,200	356
1,800	2.03	2	2	3.8	5,140	358

Figure 50: Velocity values for storm sewers (Butler, et al., 2003)

A.7.4.3 Recommended Minimum and Maximum Pipe Grades

- We understand that selecting pipe grades involve consideration of the following requirements (1) achieving self-cleaning velocities, (2) meeting minimum travel distances of solids to avoid solid deposition and (3) ensuring that pipe grades of branch discharge pipes that connect into stacks are sufficient to avoid trap seal loss due to siphonage.

- From (Munthali & Huang, 2021) we understand that small slopes for unvented branch discharge pipes have been found to cause local negative pressure near the stack, or hydraulic jump, both of which may result in trap seal loss following the discharge of the appliance (see Figure 51 and Figure 52 below). We are aware that for adequate gradients, the hydraulic jump reaches the stack prior to the end of the appliance drainage, such that it does not provide suction pressure on the trap (see Figure 53). These findings identified by (Munthali & Huang, 2021) draw upon the research conducted by (Qiongxian, 2020). It should be noted that we are unable to access the paper by (Qiongxian, 2020) – and we refer to the commentary provided by (Munthali & Huang, 2021). We note that this commentary does not provide information as to whether this effect is dependent on the filling ratio.

- Are you aware of any research to determine minimum pipe grades for maximum vented and unvented branch pipe lengths to avoid trap seal loss for various pipe sizes? This would be assuming branch pipes are loaded to 70% filling degree (if confirmed this is an appropriate filling degree). If not, can you recommend how this research could be scoped out in future phases of this work?

- We are aware that (Swaffield, 2015) investigated travel distances of solids from a low flush W.C. for 75 and 100mm pipe diameters and grades varying from 1/100 to 1/40. Could testing of travel distances for 125, 150, 225 and 300mm pipes be conducted for various slopes? In your opinion would you agree that main drains also need to accommodate the transport of solids or otherwise that once solids reach main drain they can rely on other adjoining flows to convey solids along?

- We would like to develop a recommendation for minimum pipe grades for each standard pipe size based on requirements (2) for main drains, (2) for branch drains, and (2) & (3) for unvented branch drains, for loading at 70% filling degree (if confirmed this is an appropriate filling degree). Maximum allowable branch lengths would also be specified for each instance. All horizontal drainage would be sized with consideration to achieving minimum self-cleaning velocities. We would like to know your opinion on this approach.

- In addition, we think that it would also be informative to conduct research to determine whether the standard of sizing unvented and vent branch pipes in *BS EN 12056-2:2000* (B.S. Institute, 2000) is over or under sized. We would like to know what your opinion on whether this research would be beneficial, or otherwise already exists, and if not, how this research could be conducted.

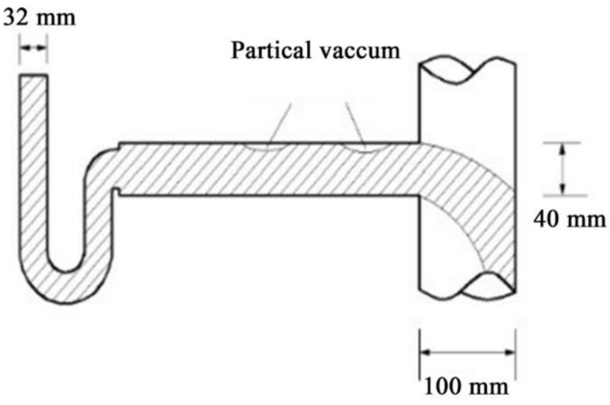


Figure 2. When branch discharge pipe slope is small (adapted from reference [1]).

Figure 51: Local negative pressure near the stack for small slopes (Munthali & Huang, 2021)

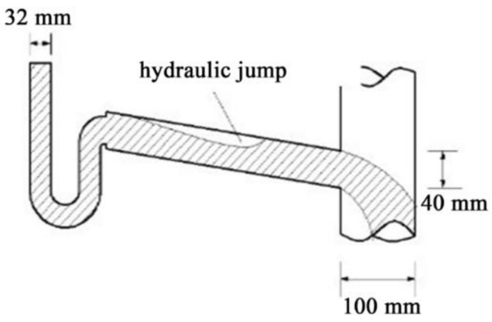


Figure 3. When branch pipe discharge is slightly large (adapted from reference [1]).

Figure 52: Hydraulic jump phenomenon for small slopes (Munthali & Huang, 2021)

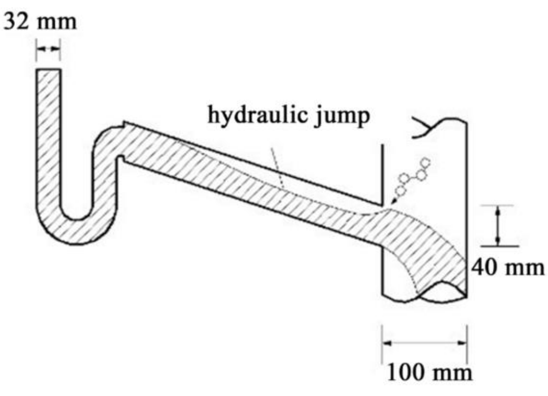


Figure 4. When branch pipe discharge is large (adapted from reference [1]).

Figure 53: Hydraulic jump phenomenon for large slopes (Munthali & Huang, 2021)

A.7.4.4 Steep Gradients

- We are not able to locate any recent research to validate the results of (Ackers, et al., 1996) and (Swaffield & Marriott, 1997), which suggest that the velocities of solids tended to exceed water velocities, and on entry to the pipe, solids "surfed" over the preceding flush water. Note that we are not able to locate either (Ackers, et al., 1996) or (Swaffield & Marriott, 1997), and are relying on commentary from (McDermott, et al., 2019). Could further testing be conducted on other solids to confirm that there is no required maximum grade limit on branch pipes or main drains, or do you have more conclusive research on this?

A.7.4.5 Pipe Junction Effects

- We note the following from (Swaffield, 2015):
  - "*Similarly, junction design becomes a major issue as the hydraulic jumps upstream of a junction of two or more flows present an impediment to solid transport leading to deposition. Swept entry junctions should be used and top entry 90° entries banned.*"
  - "*The flow regime within the horizontal branches and sewer connections in a building drainage system will be predominantly supercritical free surface flow, with transitions, where imposed by local boundary conditions, to zones of subcritical flow.*"
- What do you think about implementing recommendation (1) into code?
- We would like your opinion on whether you are aware of any research into the impact of the above assumption (2) not holding true; i.e. what happens when you have a junction occurring when the flow in the main branch is subcritical?
- Based on any recent research could you recommend implementing minimum separation distance between junction connections into main sewer lines, to ensure that the flow in the main branch/drain has sufficient distance to return to supercritical free surface flow?

A.7.4.6 Recommended Pipe Sizing Methodology

- We suggest that horizontal drainage pipes for both branch and main building drains are sized exclusively using the Colebrook-White equation rather than using Manning equation as an alternative as is currently the case in *AS 2200*:2006 (Standards Australia, 2006) Design charts for water supply and sewerage. We understand that this formula is based on steady flow assumptions, and that drainage is inherently unsteady flow defined by the attenuation of appliance discharges.
- We would like to understand the impact of using a steady flow formula to size branch discharge pipework and main sewer drains; are we oversizing or under sizing by not considering unsteady flow? Could there be experiments to test our recommendations? We hope that our recommendation in specifying a 70% filling degree will serve as a factor of safety to account for unsteady flow effects and the influence of pipe junctions.
- Our suggested method of sizing horizontal pipework consists of the following:
  - Determine the flow rate that will be discharging into the branch to be sized (see section A.7.2).
  - Select a pipe diameter and slope from Table 89 below for 70% filling capacity. Pipe size and slope should be selected with the following in mind:
    - Flow velocity for the selected configuration should be greater than nominated minimum self-cleansing velocity values pending discussion outcomes as per Section A.7.4.2).
    - Pipe gradients should be greater than the minimum specified for each pipe diameter and application (main drain, vented or unvented branch pipe) (see discussion in Section A.7.4.3).

Table 89: Flow rate and velocity values of standard Australian internal diameters using Colebrook-White for 70% filling ratio

Slope (%)	DN40		DN50		DN65		DN80		DN100		DN150		DN225		DN300	
	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)	Q (L/s)	V (m/s)
0.5	0.21	0.27	0.46	0.34	0.83	0.39	1.41	0.45	3.11	0.55	8.54	0.71	28.14	0.95	47.99	1.09
1.0	0.30	0.39	0.65	0.48	1.19	0.56	2.01	0.64	4.42	0.78	12.12	1.01	39.91	1.35	68.05	1.54
1.5	0.37	0.48	0.80	0.59	1.46	0.69	2.47	0.79	5.43	0.96	14.87	1.24	48.95	1.66	83.44	1.89
2.0	0.42	0.56	0.92	0.68	1.69	0.80	2.86	0.91	6.28	1.11	17.19	1.43	56.57	1.92	96.42	2.19
2.5	0.48	0.63	1.04	0.77	1.89	0.89	3.20	1.02	7.03	1.25	19.23	1.60	63.28	2.15	107.85	2.45
3.0	0.52	0.69	1.14	0.84	2.07	0.98	3.50	1.12	7.70	1.37	21.08	1.76	69.35	2.35	118.19	2.68
3.5	0.56	0.74	1.23	0.91	2.24	1.06	3.79	1.21	8.32	1.48	22.78	1.90	74.93	2.54	127.69	2.90
4.0	0.60	0.79	1.31	0.97	2.39	1.13	4.05	1.29	8.90	1.58	24.36	2.03	80.13	2.72	136.54	3.10
4.5	0.64	0.84	1.39	1.03	2.54	1.20	4.30	1.37	9.45	1.68	25.85	2.15	85.01	2.89	144.85	3.29
5.0	0.68	0.89	1.47	1.09	2.68	1.27	4.53	1.45	9.96	1.77	27.25	2.27	89.62	3.04	152.71	3.46

A.7.5 Stack & Vent Sizing

A.7.5.1 Recommended Filling Ratio & Sizing Methodology

- We understand that current codes size stacks assuming steady state annular flows occupying a certain percentage of the cross-sectional area of the stack (Lansing, 2020). In *BS EN 12056-2:2000* (B.S. Institute, 2000), the stack loadings for square e[nt]ries reflect the 1/6th cross-sectional loading whereas the swept connections are arbitrarily higher (Wise & Swaffield, 2002), since swept connections limit disruption of the annular flow in the stack, as reported by (Wyly & Eaton, 1961).
- We understand that current code sizing methods may result in under or oversizing of vertical stacks, depending on the system configuration. For example, the university paper (Gormley, et al., 2021) determined through AIRNET simulations that for 10 storey and taller buildings, the minimum retained trap seal depth of 25 mm required by *BS EN 12056-2:2000* cannot be retained for the bottom trap of the single-stack system.
- We also understand that your research has identified substantial suction pressure differences when varying detergent dosing and discharge temperatures (Campbell, 2007).
- We understand that the assumption of steady state annular flow does not account for various factors that can influence the pressure regime within the drainage system. We understand that the university has been conducting AIRNET simulations, which use fundamental St Venant equations of continuity and momentum to accurately simulate water flow and air pressure transients.
- Whilst best design practice would be to simulate each drainage system, we understand that this cannot be implemented on a large scale for the industry. We would like to incorporate this research into developing more informed maximum flows through vertical stacks for different system configurations, junction types with consideration to the presence of solids, surfactants and varied discharge temperatures. We would appreciate your opinion on how you think this could be achieved in relation to existing research and further research that would need to be conducted.
    - What is your recommendation for filling degree assuming steady state annular flow?
    - Would AIRNET be a suitable method for this testing, or would physical testing also be necessary?
    - How would an AIRNET or physical test be configured to test each stack condition, is a single run of testing sufficient or are multiple runs required to arrive at a conclusive outcome?
    - How complicated is AIRNET to use and can we get a licence for it to do our own testing?

A.7.5.2 Ventilation Conditions/System Configuration

Our understanding of where current research regarding ventilation is to date is listed below:

- We understand that AIRNET and DRAINET simulation studies exist to assess the performance of a building drainage system and understand the impact of varying drainage pipework sizing, vent sizing for given system configurations and discharge loading.
- We understand that the issue of sizing vents is not easily solved. We do not believe there is currently an accurate formula exists for sizing vents (stack, relief, branch, group, header vents, vents with active ventilation). Ventilation in a drainage system is dependent on the size of the stacks and branches and the system configuration, and hence there is no direct method to size vents.
- We understand that some recommendations can be drawn from previous research, particularly (Swaffield, 2010):
    - Comparative assessments of single stack configurations a secondary ventilated stack with unventilated fixture connections and an equal size vent from the stack was capable of reducing the magnitude of stack suction pressures when compared to a stack with individual vents to the fixtures without an auxiliary vent stack.

- Testing conducted suggested that to relieve different pressure fluctuations to maintain trap seals, a vent of equal or greater diameter than the stack is required. This is contradictory to Australian and British standard recommendations which in some cases have smaller secondary stack vents compared to main stack sizes.

We would like your opinion on the following:

- Is our interpretation of the current research on vent sizing correct?
- Has there been any further research that will allow us to further our understanding?
- What is your recommendation for further progressing the research to date and incorporating this into code? Have you any thoughts or comments on the current code regulations to date *BS EN 12056-2:2000* or other?
- Do you think further research to test/validate the sizing standards outlined in the *BS EN 12056-2:2000* (B.S. Institute, 2000) would be productive, to gain a better understanding of the circumstances under which the code recommendations result in over or undersized designs?

A.7.5.3 Key discussion outcomes

The outcomes of the above discussion between Heriot-Watt University and Arup are as follows:

- Many of the points raised above are common queries within the drainage research industry.
- Much of the recent simulation work conducted by HWU using their AIRNET and DRAINET modelling software has been on specific system configurations. HWU generally don't use code guidelines to set boundaries for simulations however they do reference codes as guidance. Simulations are largely determined by physics and dynamic behaviour within the modelled system.
- Dynamic models such as AIRNET and DRAINET are time intensive however allow boundaries to be modified and therefore undertake forensic sizing in building drainage systems to overcome challenges, rather than being deployed for use in the wider industry.
- With regards to defining reliability and setting design thresholds, 99% reliability is what most of the industry works towards however we should consider how many instances of exceeding the design threshold is acceptable I.e., how often can temporary enclosure of air can be accommodated in the system.
- HWU have not explored the application of Wistort's method on drainage design and are unsure how successful this would be but have applied this to water supply demand sizing with sound outcomes. It is worth noting the supply provides the drainage discharge, there is a transition of flows between supply flows and drainage flow, and even with cistern fed fixtures there is a correlation between the supply point and discharge point performance.
- Monte Carlo simulation may have limits in its predictive outcomes however can be used to rapidly verify outcomes of alternative calculation methods such as the Wistort's method for sizing sanitary plumbing and drainage systems which allows the designer to move away from the 99% and test various outcomes rather than be set on a fixed single value.
- It was agreed that although the origins of BS EN 12056 are hard to trace however, the method is tried and tested, and has proved to result in reliable outcomes. It was agreed that even BS EN 12056 or AS/NZS 3500.2 systems have 'failed' in rare cases due to unexplained circumstances, potentially the 1% circumstance.
- The industry generally perceives a difference in occupant and water fixture user behaviours, building design generally and developments in fixture technology. We should consider how significant these changes are collectively on the water supply and the drainage design methods that we use as an industry. It appears that these impacts of such changes are becoming more frequent, but the codes we have which have been tried and tested over many decades, are still likely to be suitable.

A.8 BS EN 12056.2:2000 National Annex and AS/NZS 3500.2:2021 Comparison

The table in this section provides a non-exhaustive comparison between the key design parameters which relate to sanitary plumbing and drainage installations which should be considered by designers when applying the *BS EN 12056.2*:2000 sizing methodology to an otherwise *AS/NZS 3500.2:2021* and *NCC Vol 3 2019* system.

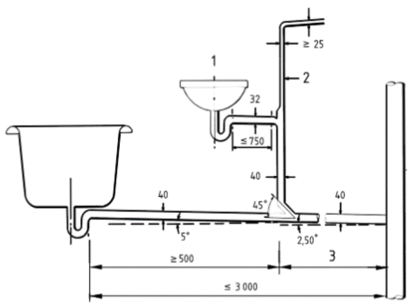
Table 90: *BS EN 12056.2:2000* (B.S. Institute, 2000) National Annex and *AS/NZS 3500.2:2021* (Standards Australia, 2021) comparison table

BS EN 12056.2:2000 National Annex	AS/NZS 3500.2:2021 and NCC Vol 3 2019
NC 2. Advice/information on: • Trap seal loss in branch discharge pipes • Trap seal loss in discharge stacks • Size and shape of ranch inlets to minimise suction • Bends at base of stacks and offsets causing back pressure • Ventilation of surcharging of drains • Interceptor traps • Wind effects on trap terminations	N/A
NC 3. Different discharge system configurations: • Primarily ventilated stack (single stack system) • Secondary ventilated stack (single stack modified) • Ventilated branch system (fully vented + fully vented modified)	Section 8: • Fully vented + fully vented modified system Section 9: • Single stack and single stack modified system
ND System III Design Details	-
ND 2.1 General trap design requirements. • Trap may be positioned a maximum of 750mm from a shower waste outlet	Section 6.5.3: • The maximum distance from the outlet of a fixture to the surface of the water seal of a trap shall be 600mm for fixtures other than floor waste gullies and fixture pairs. Section 6.5.4: • Fixtures of similar spill levels can be connected in pairs to a single fixture trap. Pairs of fixtures shall be connected so that

<table>
<tr><td></td><td>the distance between their outlets does not exceed 1.2m.</td></tr>
<tr><td>ND 2.2 Trap seal
50mm trap seals for up to and including DN 50 pipes for bath and showers. 75mm otherwise.
Traps with outlets for pipes over DN 50 shall have a minimum water seal of 50mm</td><td>NCC Vol 3 2019 C1.2:
Invert level of a trap or gully weir must be a minimum of 10mm higher than the soffit of the pipe to which it connects.
Nothing found regarding trap depths</td></tr>
<tr><td>ND 2.5 Floor drains
No minimum depth. Note on drying of traps</td><td>Section 4.6.7.2:
Maximum distance of fixture to floor waste on Table 4.6.7.2
2.5% grade connection from fixtures to floor waste
Floor wastes must be DN 80 unless the sole function is to dispose of water spillage and wash down which then a DN 50 riser may be used.
Floor waste gully outlet to be sized according to Table 4.6.7.9
Means to charge floor wastes required if it is located in a position that cannot receive a waste discharge.
Section 4.6.7.7:
Floor waste gullies with connections to the gully riser, the minimum height shall conform to Table 4.6.7.7, and the maximum height shall be 600mm. (measured from top of the water seal to the floor surface level)</td></tr>
<tr><td>ND 2.6 Sinks and washing machines
A single trap may receive the discharges from two adjacent sinks, and also from a domestic washing and/or dish washing machine provided the total length of pipework joining the waste outlets of the sinks to the trap does not exceed 750mm.</td><td>Section 13.25:
Pump discharge from domestic clothes washing machine shall be connected to a trapped waste pipe no smaller than DN 40, or into trapped or un-trapped waste pipe not smaller than DN 40 provided it is connected to a floor waste gully.
Pumped discharge from domestic dish washing machines shall be connected to a trapped waste pipe no smaller than DN 40, or above the water seal of a DN 50 trap fitted to the outlet of a kitchen sink.</td></tr>
<tr><td>ND 3.2 Branch discharge pipes
General commentary on recommended minimum gradients (1.8 to 2.2 %) but also</td><td>Section 8.2.2 - Fully vented + fully vented modified discharge pipe:</td></tr>
</table>

flatter gradients down to 0.9% for DN 100 and DN 150 is viable.

- No specific maximum branch pipe lengths
- Junctions between branch discharge pipes should be swept with a 25mm root radius, otherwise 45-degree branches should be used.
- Bath and wash basin connection requirements



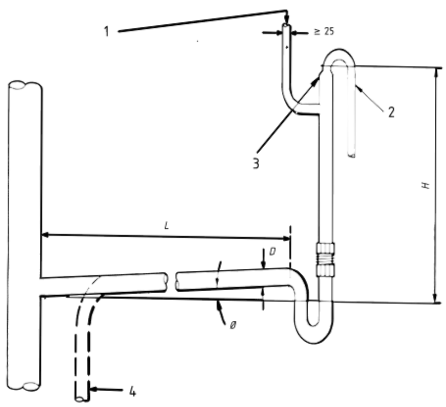
Legend:
1 Wash basin and 32 mm branch pipe (slope 1¼° to 2½°:22 mm/m to 45 mm/m) may be mounted in a plane at 90° to that shown
2 Ventilating pipe
3 Short as practicable but 1,5 m (max.)

NOTE 1 A bend in the horizontal plane can be included in the 40 mm pipe. (Minimum radius 150 mm to centre line.)
NOTE 2 Any deviation from the dimensions (and limits) shown may cause self-siphonage or back flow into the bath.
NOTE 3 Resealing traps can be used instead of venting but noisy bath and wash basin discharge may result.
NOTE 4 See also Figure ND.2 for branch connection to stack.

Figure ND.3 — Combined branch discharge pipe arrangement for a bath and wash basin

- A 40mm discharge pipe is necessary. Dotted line is the alternative connection.

Legend:
1 Machine hose
2 Air gap
H is 600 mm to 900 mm (depends on washing or dish washing machine design)



b) With venting

Legend:
1 Ventilation pipe (to atmosphere) – do not connect to ventilating stack
2 Machine hose
3 Water-tight connection
4 To gully
D is 40 mm
L < 3 m
H is 600 mm to 900 mm (depends on washing or dish washing machine design)
Θ is 1° to 2½° (18 mm/m to 45 mm/m)
Trap of 75 mm seal depth and 40 mm diameter

Figure ND.4 — Branch discharge pipes for washing and dish washing machines

- Table 8.2.2(A) provided the grade required for a specific pipe DN to convey the maximum specified FU. Gradients start at 1% for DN 150 pipes, 1.65% for DN 100 pipes, and 2.5% for DN 65 pipes.
- Minimum size of the discharge pipe is DN 40. No more than two WC pans shall be collected to a DN 80 pipe.

Section 8.5.7.5.4:

- When connected to a group vented branch, each basin and bidet shall have a DN 40 trap and fixture discharge pipe not greater than 2.5m in length with a maximum vertical drop of 1.5m. The maximum number of bends in a fixture discharge pipe shall be in accordance with Clause 9.5.4. Fixtures other than basins and bidets shall be connected separately to the group vented branch except as provided in Clause 8.5.7.2

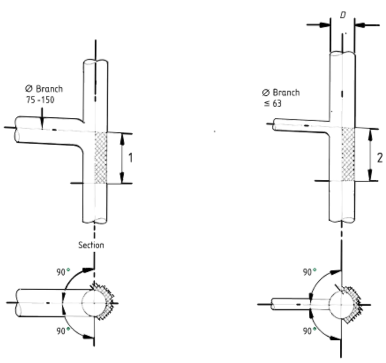
Section 9.5 - Single stack discharge pipes:

- Each fixture shall be connected to the stack by a separate unvented fixture discharge pipe of a prescribed length, size and grade in accordance with Table 9.5.1, except as specified in Clause 9.5.2. Where the length of the discharge pipe exceeds that specified in Table 9.5.1, a trap vent shall be provided in accordance with Clause 8.5.1

ND 3.3 Connections to discharge stacks

- Small diameter branch discharge pipes up to DN 70 may be connected to stacks of DN 90 or larger with straight entry branch connections.
- For DN 30 pipes serving wash basins, the root radius should be greater than 25mm and the change in gradient should be within 250mm from the stack.
- A branch inlet of DN 80 to DN 150 joining a discharge stack of equal diameter should be swept with a radius not less than 50mm for angles 89.5 to 67.5 degrees.
- Branch pipe connections of 45 degrees or less do not need swept inlets.
- Branch inlets of DN 80 joining DN 100 or DN 150 discharge stacks, and branch inlets of DN 100 joining DN 150 stacks may be swept or straight entry.
- Branch discharge pipes should not discharge over a hopper head.
- Prevention of cross flow within discharge pipes due to opposing branch discharge pipe in a stack

Linear dimensions in millimetres



a) No connection zone opposite a large branch

Stack diameter *D*	Height of zone *A*
75	90
100	110
125	210
150	250

b) No connection zone opposite a small branch

Legend:
1 200 independent of stack diameter
2 *A* (see table)

— No connection zones for the prevention of cross-flow

Figure ND.5 — Prevention of cross-flow

Section 6.7.3 - Opposed connections:

- Opposed junctions at ball or aerator junction fittings shall only be used where the opposing pipes are connected to equal number of the same type of fixtures. Other than those junctions, opposed connections shall only be made through double 45 degree or double sweep junctions.
- Restricted connection zones for opposed discharge pipes are specified in Table 6.7.3.2 and illustrated in Figure 6.7.3.2, unless the lower pipe enters the stack at an angle of 45 degrees.

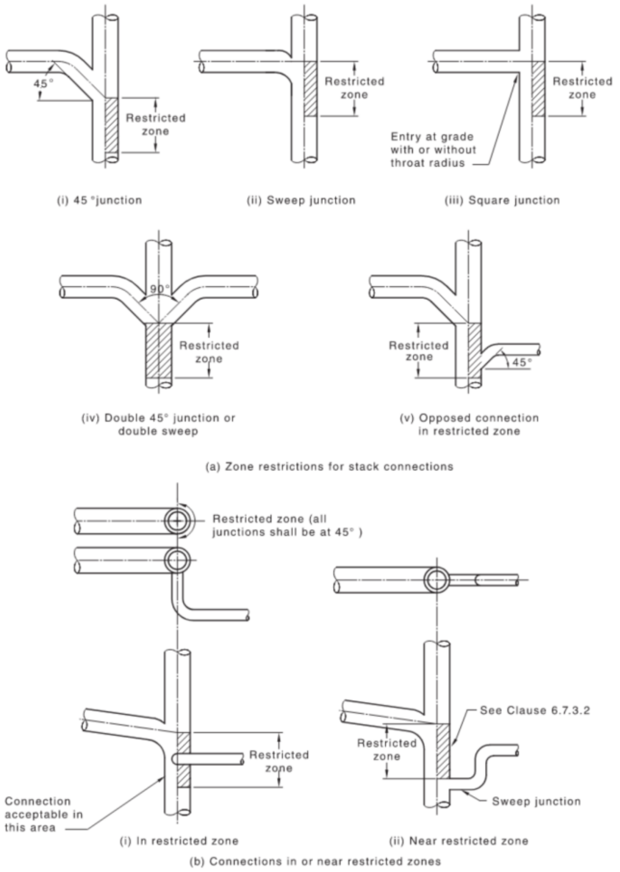


Figure 6.7.3.2 — Connections to stacks

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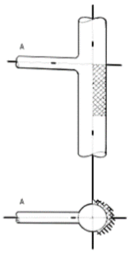
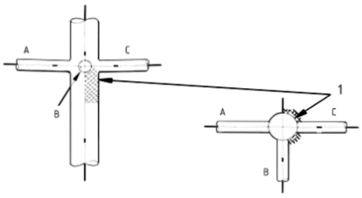
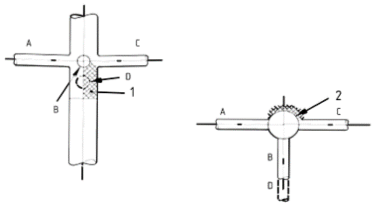


c) Consider a stack with branch A and its no connection zone, shown shaded


d) Other branches may be fitted at the same level as A, as shown at B and C. Each branch creates its own no connection zone. Only that of branch A is shown in this diagram.

Legend:
1 Zone of branch A


e) A branch may also be fitted at D, or elsewhere on the same vertical centre line. Although this would be on the boundaries of the no connection zones of branches A and C, its centre line would not be inside either of them. But as branch B has no connection zone on the far side of the stack, it would not be possible to fit a branch opposite branch D.

Legend:
1 Zone of branch A
2 Zone of branch B

— Examples of permitted connections for the prevention of cross-flow

Figure ND.5 — Prevention of cross-flow (concluded)
</td>
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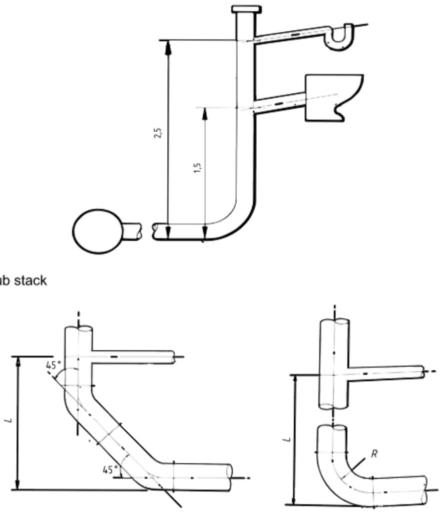
<td>
ND 3.4 Direct connections to an underground drain

- WCs can be connected directly to a drain, without individual venting, provided that the vertical distance from the centreline of the WC branch to the invert of the drain is not more than 1.5m.
- Introduction to the idea of stub stacks: It can be used to connect various appliances to a drain or discharge stack providing the total loading does not exceed 5 l/s, the centre line of the WC branch is not more than 1,5 m and the centre line of the topmost connection is not more than 2,5 m above the invert level of the drain or branch discharge pipe. Where one or more stub stack connections discharge to a drain, the head of that drain should be ventilated by a ventilating stack or discharge stack that terminates externally to the atmosphere.
</td>
<td>N/A</td>
</tr>
</table>

ND 3.5 Discharge stacks

- In certain cases of one and two storey housing economies can be made by using a DN 80 stack vent without detriment to the performance of the system.
- Bends at the base of a discharge stack should be of large radius (minimum centre line radius 200 mm) or two 45º radius bends may be used.



a) Stub stack

b) Preferable arrangement

c) Alternative arrangement

— Bend and branch connections at base of discharge stack

Legend:
$L \geq 450$ mm (for single houses up to three storeys high)
or $L \geq 740$ mm (for multi-storey systems up to five storeys high)
or $L \geq$ one storey height (for multi-storey systems higher than five storeys), i.e. no connections on ground floor level
R is as large as possible [twice internal diameter ($ID \times 2$)]

Figure ND.6 — Discharge from stub stack

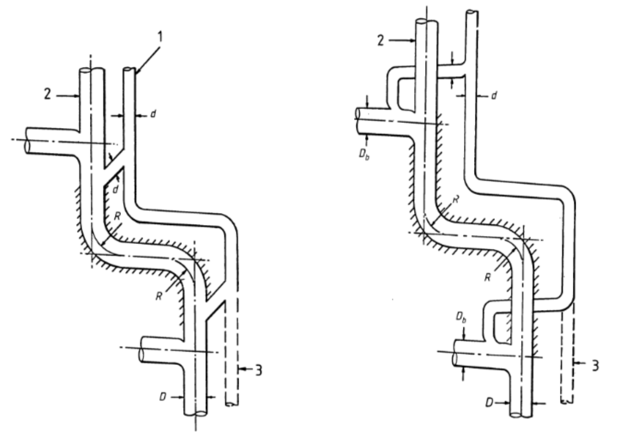
- Connections at base of stacks. Generally, for systems up to five storeys, the distance between the lowest branch connections and the invert of the drain should be at least 750 mm, but 450 mm is adequate for low rise single dwellings. For larger multi-storey systems, it is better to connect the ground floor appliances to their own stack or the horizontal drain and not directly to the main stack. For buildings over 20 storeys high, it may be necessary to connect both the ground and first floor appliances in the same manner.
- Offsets requirements in discharge stacks as per diagram below.

Section 6.8 - Connections near base of stacks:

- Discharge shall connect to a drain of a graded pipe in accordance with Figure 6.8.1
- Branches shall not connect to a stack with the following distances, measured vertically from the base of the stack to the invert of the branch:
- 600mm for stacks that extend not more than five floor levels above the base of the stack
- 1m for stacks that extend more than five floor levels above the base of the stack
- 2.5m for all stacks in areas where foaming is likely to occur
- Connection of stacks to graded pipes or drains above ground shall be made by a 45 degree junction installed on grade in accordance to Clause 6.6.2.4 and a bend at the base of the stack in accordance with Clause 6.8.4, or, a 45 degree junction installed in the vertical plane with an extended branch so that the vertical projection of the stack, on the graded pipe or drain above the ground is wholly outside the junction areas as shown in Figure 6.8.3(b).
- Bends at the base of stacks shall not be smaller in size than the graded pipe or drain to which they connect. The centreline radius shall not be less than that stated in Table 6.8.4. The radius is either 225mm for DN 100 or lower or 300mm for greater than DN 100. Two 45-degree bends with a straight pipe of length no less than twice the bore of the pipe is also acceptable. An 88-degree bend is only acceptable where a stack extends through no more than two floor levels.

Section 8.6 - Offsets in stacks of fully vented + fully vented modified systems

- For steep offsets, see Clause 8.4.g. Where any stack is offset, the offset section shall be sized as a straight stack if the offset is 45 degrees to the horizontal or greater, or as a graded pipe if the offset is less than 45 degrees to the horizontal.
- For graded offsets, the minimum grade shall be in accordance with Table 8.6.2.2. For graded offsets, no connection shall be made within 600mm of the bend when the stack



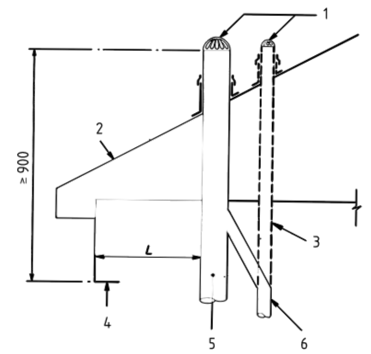
a) Direct connection to ventilation stack b) Indirect connection to ventilation stack

Legend:
1 Ventilating stack to atmosphere (or connected to stack vent)
2 Discharge stack
3 For ventilated systems sized
R is as large as possible ($ID \times 2$ min.)
d $D/2$, or for ventilated systems if larger than $D/2$
$D_b \geq 75$ mm (see note 2)

NOTE 1 No branch connections in shaded area unless vented.
NOTE 2 Arrangement b) is only possible if D_b is 75 mm or larger.
NOTE 3 No offset venting is required for lightly loaded systems of up to three storeys in height.
NOTE 4 Offsets above highest branch connections do not require venting.

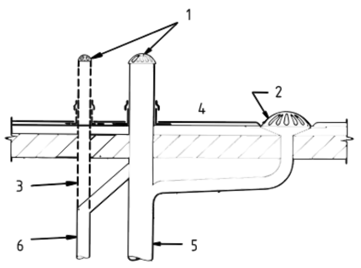
Figure ND.7 — Offsets in discharge stacks

- Stack vent termination requirements as per diagram below



a) Requirement if *L* is less than 3 m

Legend:
1 Domical cage
2 Roof
3 Alternative arrangement
4 Window or other opening
5 Stack vent
6 Ventilating stack to connect to stack vent



b) For stack vents also collecting rainwater from roofs

Legend:
1 Domical cage
2 Rainwater outlet
3 Alternative arrangement
4 Roof
5 Stack vent
6 Ventilating stack

Figure ND.8 — Termination of stack vents and ventilating stacks

extends not more than five floor levels above the offset, 1m of the bend when the stack extends more than five levels above the offset, or 2.5m when foaming is likely to occur. All other restricted zones are shown in Figure 8.6.2.3.

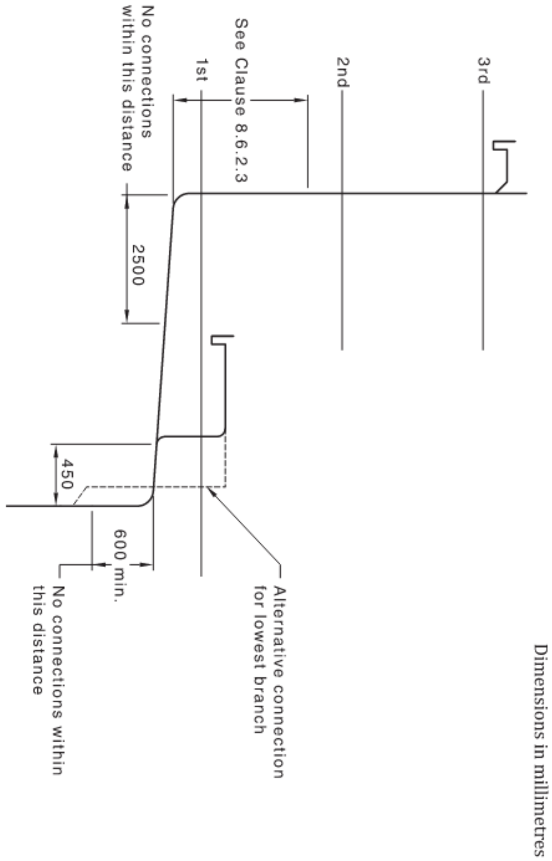


Figure 8.6.2.3 — Connections at graded offset

Section 9.9 - Offsets in stacks of single stack + single stack modified systems

- A steep offset must be 45 degree or steeper whilst a graded offset must be 2.5% for DN 80 or 1.65% for DN 100 stacks.
- DN 100 stacks may have steep offsets provided the height of the stack does not exceed 10 consecutive floors. Laundry troughs have additional requirements as per Clause 6.9.3.
- The minimum distance between the connection of any fixture discharge pipe and the upper offset bend shall be no less than 100mm.
- Connections near the upper and lower offset bends, and the maximum fixture unit loading to the stack is detailed in Table 9.2.2 and illustrated in Figure 9.2.2

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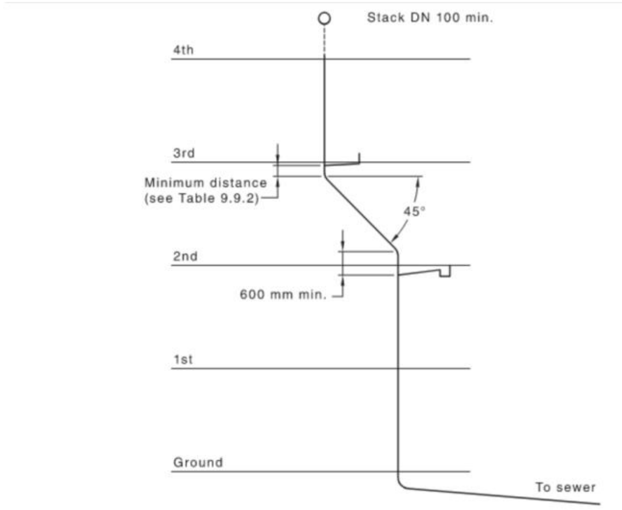

NOTE Measurement increases with height of stack above offset and fixture unit loading.

Figure 9.9.2(A) — Near face measurement

Only one graded offset can be installed in any stack. The height of the stack shall not exceed 10 consecutive floors and the minimum distance between centrelines is 2m.
Connection locations, and minimum and maximum distances from graded offset bend is illustrated in Figure 9.9.5

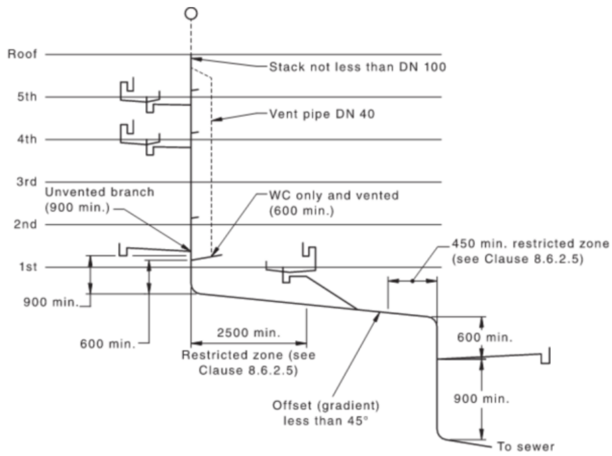

Figure 9.9.5 — Graded offset
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ND 3.6 Ventilating pipes and stacks

The size of ventilating pipes to branches from individual appliances can be DN 25 but, if they are longer than 15 m or contain more than five bends, a DN 30 pipe should be used.
Connections to the appliance discharge pipe should normally be as close to the trap as practicable but within 750 mm.

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Section 6.9 – Vent design in plumbing systems

Vents shall be installed at a minimum grade of 1.25%.
Vents shall only be interconnected above the flood level rim of the highest fixture or floor waste gully served by the vent. Certain vent pipes as documented in Clause 6.9.3 must not be interconnected.
Vents shall terminate as shown in Figure 6.9.4.

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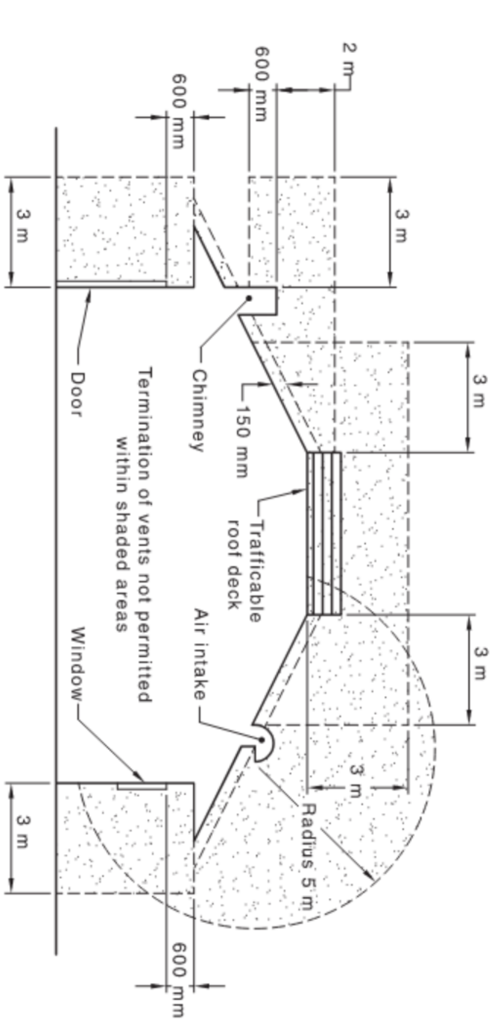
- Branch vents are to be sloped towards the drainage stack at a slope of 1 degree or greater.

- For ventilated branch systems, the ventilating stack is only acting as a common connection for the branch ventilating pipes, and there are no connections to the discharge stack. A ventilating stack of DN 30 is usually sufficient. However, if required, the ventilating stack can be connected to the primary vent stack, otherwise the ventilating stack can pass through the roof to the atmosphere.



NOTE Trafficable decks exclude access workways and work platforms.

Figure 6.9.4 — Termination of vents

Section 8.5 – Venting in fully vented + fully vented modified systems

- This section details how trap, branch, relief, stack, cross-relief, header and group vents are installed.

- Trap vents shall be connected as per Figure 8.5.1.1.

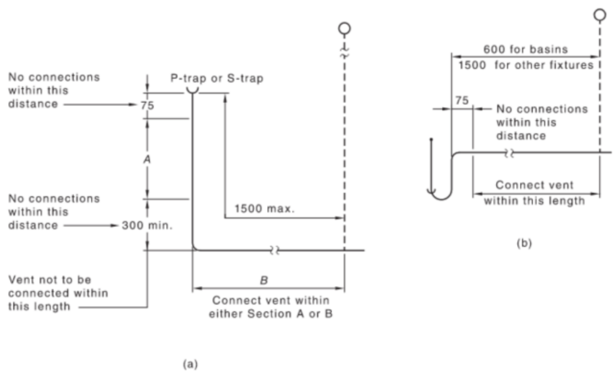


Figure 8.5.1.1 — Trap vents

	• Branch vents are to be no smaller than DN 32 provided the branch discharge pipe is DN 40. Section 9.6 – Venting of stacks in single stack + single stack modified systems • Stacks no more than three floor levels with a maximum loading of 30 fixture units may have the vent reduced to DN 50 • Cross-vents are designed to Table 9.7.2.A and Table 9.7.2.B and will be no smaller than DN 50. • Relief vents are installed in accordance with Clause 8.5.3.
ND 4. Access for testing and maintenance:	Section 4.7 and Section 10.5
ND 5. Special design consideration	N/A

A.9 Stage 2 Plan for Future Work

This section intends to inform the basis of scope for the next stage (Stage 2) of this work. The Stage 2 plan has been developed based on the research, analysis and outcomes identified in this report. We anticipate Stage 2 being delivered by a team consisting of Hydraulic Engineers and expert research group/s with expertise in mathematical and statistical analysis, and complex hydraulic and fluid flow principles, with input from the wider Australian Hydraulic Engineering industry.

This report was constructed through the amalgamation of research literature and technical standards that were accessible to us at the time of writing. As such we do not claim to have reviewed all resources relevant to this subject matter. Furthermore, our testing and analysis methodology centred around Excel based calculations. No complex computer simulations nor any computational or physical modelling was conducted. Thus, we recommend that Stage 2 of this work considers additional components of research and analysis not considered in this report.

The party responsible for the next stage of work is expected to meet the requirements mentioned above and undertake research not conducted in the Stage 1 works whilst considering the suggestions provided in this Appendix. The party assigned to complete the Stage 2 works is encouraged to seek further review and acceptance from the hydraulic industry on their work.

A.9.1 Discharge Unit and K-Factor

To facilitate the short-term adoption of the *BS EN 12056-2:2000* (B.S. Institute, 2000) DU and K-Factor approach as a Verification Method of the NCC Plumbing Code of Australia 2025 revision, future work should include:

- Investigating discharge events within existing buildings to determine probability of fixture use within different types of buildings and occupancy levels as per the NCC.
- Comprehensive review of data provided by the Australian Building Code Board Working Group throughout this report with aim to integrate this data into proposed performance-based methodologies
- Conducting experimental testing to validate typical fixture discharge rates.

Further testing can then be conducted on the Wistort's and Modified Wistort's Method and re-evaluated against *AS3500.2:2021* (Standards Australia, 2021) and *BS EN 12056-2:2000* (B.S. Institute, 2000) recommendations for a range of building classes.

A.9.2 Sanitary Drainage Design

It should be noted however, that whilst the *BS EN 12056.2:2000* (B.S Institute, 2000) method for sizing sanitary drains can be largely adopted as detailed in Section 5.7, we recommend an in-depth review be conducted on the following items to minimise any unforeseen consequences with adopting this method for the Australian Plumbing Industry:

- A further, exhaustive comparison between the sanitary plumbing and drainage configurations as detailed in the National Annex of *BS EN 12056.2:2000* (B.S Institute, 2000), and *AS3500.2:2021* (Standards Australia, 2021). A high-level comparison has been conducted and is presented in Appendix A.8 however the list is not exhaustive.
- Since the System III design, used primarily in the UK, were recommended to be omitted from the *NCC 2025 Volume 3* revision, the National Annex of *BS EN 12056.2:2000* (B.S Institute, 2000) cannot be solely relied upon to determine any design discrepancies with *AS3500.2:2021* (Standards Australia, 2021). Furthermore, the National Annex from countries using predominantly System I and II designs would contain vital information, detailing how these systems are specifically designed within their respective counties. Thus, an exhaustive comparison of the National Annex, or

equivalent, from a country that predominantly uses System I design, and another from a country that predominantly uses System II design is required in future work.

- Guidance into acceptable points of failure, and a range of thresholds should be provided for all EN 12056.2 designs that are to be incorporated into the verification method of the NCC 2025 Volume 3. As identified in our discussion with research representatives from Heriot-Watt University, even with a compliant system designed to *BS EN 12056.2*, trap losses may still occur within the system. Identification of such instances as well as the leading causes should be identified where possible in future work.

- Further research should be conducted to determine the effects of hydraulic jumps near base of stacks with drainage systems designed to a high filling degree. We are uncertain whether there will be a significant difference in pressure transients experienced within a system that is designed to a 50% filling degree and 70% filling degree, assuming all ventilation requirements are met. Additional consideration should be made to drains with changes in grade, particularly from a steeper gradient to a more gradual slope. Insight into the severity of grade changes and means to mitigate the consequences would be beneficial.

In addition to the items above, Stage 2 of this research task should also consider the data from site investigations provided courtesy of the Australian Building Code Board steering committee. One of the datasets provided demonstrates very close similarities between the calculated wastewater peak flowrate (15.53 l/s) using the *DIN 1998-300* method and the recorded peak flow rate (14.52 l/s) tank over a period of 4 weeks at an existing hospital. A relatively exhaustive list was provided containing information on the nominated hospital including, number and type of fixtures, fixture flow rates, fixture units, loading units and discharge units. Using the data provided, we suggest the continued testing of the Modified Wistort's Method as follows:

- Replace the current fixture discharge flowrates for all fixtures without cisterns, presented in Appendix A.1.3, with the flowrates provided here compare the results with the simulated residential and office buildings detailed in Appendix A.1.1 and A.1.2.

- Conduct an in-depth comparison between the *DIN 1998-300* method and the *BS EN 12056.2:2000* DU method to determine the differences between calculation methods. It is assumed that the method used in *BS EN 12056.2:2000* closely resembles the *DIN 1998-300* method.

- From the assumption above, utilise the expanded list of fixture supply flow rates, adjust the cistern-based fixtures flows with those provided in Appendix A.1.3, and attempt to expand the fixture usage probabilities. This could be done through a combination of literature research, monitoring, interpolation, and best engineering judgement. The new expanded list of fixture discharge and usage probability values should then be validated against the recorded drainage flows from another site.

- Where possible, fixture usage probabilities should be obtained through data collection and analysis of existing buildings however, this can be quite a difficult and resource intensive task.

Additional data that we believe would significantly assist with the development of the Modified Wistort's Method for widespread use includes:

- Time the fixture is busy
- Time the fixture was observed
- Discharge rate of the fixture
- Type of building the fixture data was obtained from
- Occupancy at time fixture data was obtained
- Total fixture numbers of each type
- Total sanitary discharge flowrate

A.9.3 Sanitary Plumbing Design

Prior to the adoption of the *BS EN 12056.2:2000* (B.S Institute, 2000) method for the sizing of branches, stacks and vents, we recommend an in-depth comparative assessment between *BS EN 12056.2:2000* (B.S Institute, 2000) and *AS3500.2:2021* (Standards Australia, 2021) is conducted to understand the (1) implications of adopting this method for the Australian Plumbing Industry and (2) to determine whether there are design guidance items provided in *AS3500.2:2021* (Standards Australia, 2021) that could be adopted by the *BS EN 12056.2:2000* (B.S Institute, 2000).We have not conducted this assessment, but in our research, we have identified the following points for consideration:

- Determine the steady state annular flow formula and filling capacity used to determine the stack capacities listed in *BS EN 12056*:2000 (B.S Institute, 2000) for square and swept entries of primary and secondary ventilated discharge stacks.
- Quantify the basis to the varied filling degrees for different entry and venting configurations presented in *BS EN 12056*:2000 (B.S Institute, 2000).
- Investigate the theoretical basis of vent sizing recommendations within *BS EN 12056.2:2000* (B.S Institute, 2000).
- Investigate the theoretical basis of branch sizing provided by *BS EN 12056-2:2000* (B.S. Institute, 2000) and *AS/NZS 3500.2:2021* (Standards Australia, 2021).
- Review recommended minimum grades and maximum length of branch drainage provided by *BS EN 12056-2:2000* (B.S. Institute, 2000) in light of recent literature regarding maximum travel distances of solids subjected to low flow WC flushes; e.g. (Swaffield, 2015). We suspect that higher pipe grades or shorter branch lengths may result in improved performance to account for lower flush volumes transporting solids.
- Impacts of adopting minimum grades specified by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000), which are lower than those specified by Table 6.6.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021).
- Review differences between maximum branch lengths recommended by Table 5 and 8 of *BS EN 12056-2:2000* (B.S. Institute, 2000) and Appendix B.1 of *AS/NZS 3500.2:2021* (Standards Australia, 2021).
- Impacts of adopting *AS3500.2:2021* (Standards Australia, 2021) relief vent sizing based on developed lengths and stack loading in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system.
- Impacts of adopting *AS3500.2:2021* (Standards Australia, 2021) clearance zones at base of stacks and stack entry points in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impacts of using *AS3500.2:2021* (Standards Australia, 2021) stack, main drain and branch vent configurations with an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impact of adopting *AS3500.2:2021* (Standards Australia, 2021) drainage principles for either below ground drainage or elevated above ground drainage in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system
- Impact of adopting *AS3500.2:2021* (Standards Australia, 2021) header vent sizing methodology in an otherwise *BS EN 12056.2:2000* (B.S. Institute, 2000) sized system.

A.9.4 Alternative statistical methods

Alternative statistical and analytical methods via computational means should be considered in future stages. This may include, but is not limited to:

- Consultation with Heriot-Watt university on the use of their own DRAINET and AIRNET complex computer simulation models for drainage and transient air systems.

- Implementation of Fuzzy Logic into computer models for fixture usage profiles.
- Utilisation of Monte Carlo simulations for testing and verifying computer models.

A.9.5 Review of the proposed changes to NCC 2025 Volume 3 Plumbing Code of Australia

The proposed modifications to the *NCC 2025 Volume 3 Plumbing Code of Australia* in Section 5.7 and Section 6.7 should be reviewed, tested and accepted by the Hydraulic Engineering Industry in Australia prior to their adoption.