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Percolation Testing of Soils for On-site Wastewater Treatment

Authors: Joanne Mac Mahon, Jan Knappe and Laurence Gill

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Rialtas na hÉireann
Government of Ireland

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4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

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Percolation Testing of Soils for On-site Wastewater Treatment

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Identifying pressures

Estimation of soil permeability is a critical aspect of on-site wastewater treatment system design. In Ireland, domestic wastewater of approximately one-third of the population (approximately 500,000 dwellings) is treated by on-site domestic wastewater treatment systems (DWWTSs), of which around 90% are septic tanks. Site assessment (and subsequent DWWTS design) is prescribed in the Irish Code of Practice (CoP) and requires an on-site falling head percolation test, known nationally as the T-test. The test, however, is not practical for very low permeability soils due to the time required to obtain a valid result. It also produces results in units that are not directly comparable with current processes/standards in Ireland or other jurisdictions. This research, therefore, comprised carrying out a comprehensive literature review on soil permeability testing and international design standards as well as soliciting opinions from stakeholders and experts in the field of on-site wastewater treatment. It has also used the results of over 900 falling head percolation tests carried out across Ireland to produce equivalent soil permeability values using a numerical modelling approach with Hydrus 2D software, as well as testing an alternative constant head permeameter test.

Informing policy

The findings of this research identify a need to revise the currently available options in the Irish CoP for estimating soil permeability for on-site wastewater system design. This conclusion is based on the current difficulties of conducting falling head percolation tests in less permeable soils, as well as the need to incorporate progress made in soil science theory and permeability estimation internationally in recent decades. A key conclusion from the research is that the constant head well permeameter test is considered a better alternative for in-situ percolation testing because it produces a more rigorous and transferable measure of soil permeability (saturated hydraulic conductivity), which is independent of the dimensions of the hole used in the test and is also the international standard measurement for water transmission through soil. However, many design standards in other international jurisdictions now indicate that in-situ permeability tests should be used only as a complement to detailed site assessments, particularly soil morphology analysis, in terms of texture, structure and consistency. Hence, we recommend that more emphasis be placed on the importance of the soil texture and structure classification aspect of the current site assessment methodology in the CoP.

Developing solutions

In this research, a correlation was developed between field saturated hydraulic conductivity (Kfs) and percolation time (T-values) across a full range of Irish soil texture data. The model trendline was also found to fit with parallel falling head and constant head permeameter test results to a large degree, showing that the constant head permeameter test could be phased in initially as an additional option to the falling head test for on-site assessment in Ireland, particularly for low permeability soils. The research also emphasises that a critical element of site assessment is soil categorisation, which has become the primary recommended method for determining suitable hydraulic loading rates for soil treatment units in many regions. It is recommended that further research be carried out into this area of site assessment and an assessment made of the possibility of switching to an alternative soil categorisation system that provides a more finely tuned and flexible categorisation of soil permeability. Finally, a database of Kfs ranges for Irish soil types, in conjunction with mapping of this information, would be a useful tool for site assessors and local authority personnel in carrying out the overall assessment of sites.

EPA RESEARCH PROGRAMME 2021–2030

Percolation Testing of Soils for On-site Wastewater Treatment

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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DISCLAIMER

This report is based on research carried out/data from 2016 to May 2021. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Contents

List of Figures

List of Tables

Executive Summary

This report summarises the findings of research conducted on the permeability testing of soils for use in on-site domestic wastewater treatment systems. This is particularly required because of the limitations of the falling head percolation test (currently used in Ireland) for low permeability soils.

The findings of a comprehensive literature review on soil permeability testing and international design standards for on-site wastewater treatment systems are presented. This review covers the basic concepts of water movement through soil with various properties. On-site soil treatment units treat effluent from septic tanks or package treatment systems via unsaturated flow of effluent through the soil. The development over time of a biomat at the interface where the effluent percolates through the soil is related to the level of effluent treatment prior to application and influences the movement and the level of treatment of effluent within the soil treatment unit. Design standards used in different international jurisdictions are then summarised, with various alternative in-situ and laboratory-based approaches to estimating soil permeability reported, most notably the constant head well permeameter method and soil texture analysis. A summary of the theoretical framework of soil permeability estimation methods is then presented. This compares various methods to determine K_{fs} from constant head permeameter measurements and summarises attempts to formulate a relationship between the percolation time (or T-value) obtained from falling head tests and the field saturated hydraulic conductivity value, K_{fs}, obtained from constant head permeameter tests.

Engagement was made with stakeholders and experts in on-site wastewater treatment system design in Ireland and abroad to gain their insights into the application of falling head percolation tests and alternative methods for estimating soil permeability. Over 88% of those contacted agreed that the falling head test, while still allowed in many international standards, is not an ideal method and should be replaced. There was also agreement that the constant head test is more reliable and practicable in situ, providing a more useful K_{fs} value because of the inherently more controlled test conditions required and its independence with regard to hole dimensions. However, it is emphasised that the result of such a permeability test needs to be put into the context of a parallel soil texture and structure assessment.

Research was carried out to compare results of the falling head T-test with those of equivalent constant head permeameter tests. Information from a database of over 900 falling head percolation tests carried out in line with the procedure outlined in the Irish Code of Practice, as well as soil texture categorisation in accordance with BS 5930, was collated. Hydrus 2D modelling of a subset of these falling head tests was carried out to produce a correlation of K_{fs} and T-values across a full range of Irish soil texture data. The model was then tested using parallel in-situ falling head and constant head field tests carried out on 17 different sites. The model provides a realistic estimate of the relationship between T-value and K_{fs}, particularly in the low-permeability range, when K_{fs} was solved using the Reynolds (2008) solution.

A key conclusion from the research is that the constant head well permeameter test is considered a better alternative for in-situ percolation testing because it gives a field saturated hydraulic conductivity value, K_{fs}, which is independent of the dimensions of the hole used in the test, and also because K_{fs} is the international standard measurement for water transmission through soil. In addition, many design standards (Australian/New Zealand Standard, 2012; Canadian Standards, 2012; USEPA, 2002, as well as the Irish Code of Practice) now indicate that in-situ permeability tests should be used only as a complement to detailed site assessments, particularly soil morphology analysis in terms of texture, structure and consistency. Results from in-situ tests should not be the main determining factor of site suitability and must not be used to override conclusions drawn from soil and site assessments. Increased emphasis on the importance of the soil texture and structure classification aspect of the current site assessment methodology in the Code of Practice is recommended alongside further research into this area. A database of K_{fs} ranges for Irish soil types, in conjunction with mapping of this information, would be a useful tool for site assessors and local authority personnel in the overall assessment of sites.

1 Introduction

The estimation of soil permeability is a critical aspect of on-site wastewater treatment system design. In Ireland, the domestic wastewater of approximately one-third of the population (approximately 500,000 dwellings) is treated by on-site domestic wastewater treatment systems (DWWTSs), of which around 90% are septic tanks (CSO, 2017). Site assessment (and subsequent DWWTS design) is prescribed in the Irish Code of Practice (CoP) (EPA, 2021, 2009) and requires an on-site falling head percolation test, known nationally as the T-test, which gives a percolation time (T-value) in minutes per 25 mm (min 25 mm^{-1}). Significant field experience has been accumulated in carrying out these falling head tests over a number of decades, and the tests offer a relatively simple procedure, which is an advantage for soil practitioners (Winneberger, 1974). The results from such tests, however, are tied to the specific hole dimensions defined for the test. The implicit falling head conditions throughout the test also mean that the extent of the saturated plume beneath the hole will vary during the test and also by soil type, leading to inconsistency in quantifying soil permeability. In addition, the test is not practicable for very low permeability soils due to the excessive time required to obtain a valid result.

An alternative method for assessing soil permeability is the determination of the saturated hydraulic conductivity (K_{sat}) of the soil either in the laboratory or in the field, known as field saturated hydraulic conductivity, K_{fs}, using an in-situ test such as the constant head well permeameter test. K_{fs} is a unique soil property independent of the test procedure (Van de Graaff and Alexander, 2008; Mulqueen and Rodgers, 2001; Bouwer and Jackson, 1974), and the constant head well permeameter test (also known as the borehole permeameter method or constant head borehole infiltration test) is a convenient and widely used procedure for measuring the K_{fs} of an unsaturated soil in situ (Amoozegar, 2020; Reynolds, 2016; Reynolds and Elrick, 2002; Elrick and Reynolds, 1986).

The new 2021 CoP incorporates key findings from EPA Research Report No. 161 (Gill *et al.*, 2015) with new treatment options for areas with low permeability soils down to T-values of 120. However, it takes over 25 hours to determine a key threshold value of T = 120 using the modified method outlined in the CoP (following a day of pre-soaking). For these low permeability soils, the constant head well permeameter test is a more viable method, as it is quicker than the falling head test and will give a useable result in situations where the T-test will often struggle to yield a value (120 > T-value > 90). In addition, the field saturated hydraulic conductivity value obtained (mm d^{-1} or cm d^{-1}) is the standard measurement used internationally for water movement through soil and is therefore more relevant and useful with respect to DWWTS design.

While soil permeability estimates based on clean water flowing through untampered soil are a useful tool for DWWTS design, it should be noted that biomat development over time at the interface where the effluent first starts to percolate into the soil and the level of effluent treatment prior to application influence both the movement and the level of treatment of effluent within the soil treatment unit (STU), and so this effect must be embedded into the design consideration in what is usually known as the system's long-term acceptance rate (LTAR), irrespective of the methods used to determine the percolation characteristics.

1.1 Objectives

The objectives of this research into percolation test methods for on-site wastewater treatment system design are as follows:

- Review international methods and standards for the estimation of soil permeability in the context of on-site wastewater treatment system design, with a clear comparison of different methods from a common soil science theory perspective. Assess in particular the constant head well permeameter test, as used to estimate field saturated hydraulic conductivity, K_{fs}; saturated hydraulic conductivity estimates derived from soil texture and structure analysis, K_{sat}; and the comparison of these methods with the existing falling head percolation test.

- Compare international soil permeability thresholds for on-site wastewater system design taking into consideration the different permeability estimation methods and the accuracy of direct comparisons of different methodologies.
- Contact international experts to gain insight into various methodologies for estimating soil permeability and the practical application of estimation methods to DWWTS design. Conduct a survey of stakeholders associated with DWWTSs to develop a broad understanding of falling head percolation tests and their application, as well as the stakeholders' attitudes towards alternative permeability testing methods.
- Provide a clear summary of the theory relating to water percolation through soil and the various factors that affect this. Assess correlations between percolation time (or T-value), as measured using a falling head test, and field saturated hydraulic conductivity, K_{fs}, as determined using a constant head well permeameter test, which attempt to unify percolation test results into a common parameter appropriate for engineering design (i.e. hydraulic conductivity).
- Augment an existing dataset of over 900 T-tests around Ireland with other available tests (particularly for T-values >50) and develop a correlation between falling head and constant head test results through variably saturated zone modelling processes (using Hydrus software). Conduct field tests to compare parallel falling head and constant head permeameter tests. Based on Irish field data, Hydrus modelling results and international methodologies, derive a mathematical relationship between the two field testing methods (falling head and constant head) in terms of units of hydraulic conductivity.
- Evaluate the suitability of alternative practices used internationally to estimate soil permeability as part of the site assessment for DWWTSs. Translate research data and findings into a proposed new approach to site assessment and associated percolation testing and provide recommendations/alternative text for the EPA CoP for a potential new method of determining soil percolation to overcome the issues with the existing falling head test, particularly in relation to low permeability subsoils.

2 Literature Review

2.1 Transmission of Water Through Soil

One of soil's most important properties applicable to on-site wastewater treatment is its ability to transmit water through soil pores and between particles, which is known as its hydraulic conductivity, *K* (Thomas *et al*., 2016). Soil acts as an essential component of traditional DWWTSs used in Ireland, which usually consist of a primary treatment unit (e.g. a septic tank) followed by an STU (i.e. percolation area). Wastewater movement through the soil of the STU and beyond is determined by the soil's physical properties, including moisture content, texture, structure and consistency, as well as its parent material and formation processes, the depth of the STU trenches, and the depth of the unsaturated soil to an impermeable layer or water table underneath the bottom of the trenches (Amoozegar *et al*., 2008). The matric potential of soil describes the capillary and adsorptive forces which hold water in soil pore spaces and regulate water movement in unsaturated soils. Soil water retention curves define the relationship between soil's water content and matric potential, and these can be used to estimate the hydraulic properties of different soil types (see Chapter 3).

2.1.1 Soil texture, structure, consistency and porosity

Soil texture, structure, consistency and porosity have a significant influence on hydraulic conductivity. Soil texture refers to the relative sizes of different soil particles, namely clay, silt, sand and gravel. Different soil textures will have different pore sizes depending on the distributions of the particle sizes present, and this in turn affects the ease with which water can pass through the soil. The presence of fines, for instance, is known to significantly reduce hydraulic conductivity, but fines can often be missed in field-based soil texture classification tests (see BS 5930 soil texture classification in the CoP, 2021 and 2009 (BSI, 2015, 2007)).

Soil structure refers to the *arrangement* of soil particles into aggregates or peds by natural processes. The dominant shape, size and strength of the aggregates determine the soil's structural type. When testing the percolation rate of a given soil, certain soil structures might result in a higher or lower apparent permeability than predicted by the soil texture alone. For example, soils with a platy structure, which are characterised by thin, flat plates, tend to slow the downwards movement of water and significantly reduce hydraulic conductivity (Nova Scotia Environment, 2007; Tyler and Kuns, 2000), while soils with a granular structure tend to allow water to flow through quickly, reducing the contact time between effluent and soil particles (Tyler and Kuns, 2000). Soil structure, therefore, can be an important consideration in STU design, but it is not commonly accounted for.

Soil consistency is interrelated with soil texture and structure and refers to the degree and type of cohesion and adhesion that the soil exhibits or the resistance of the soil to deformation and rupture (Gardiner and Radford, 1980). Consistency tests in the field generally describe the ease with which an individual soil ped can be crushed using fingers (USDA, 2021) and is strongly influenced by the moisture content of the soil (USDA, 2021; Gardiner and Radford, 1980).

Soil porosity refers to the space between soil particles, which consists of various amounts of water and air. Soil texture, structure and consistency each contribute information about porosity, with soil structure providing the most (Tyler, 2001). Water can be held tighter in small pores than in large ones by capillary forces, and so, when water moves through pore space, larger pores will transport water quicker than smaller pores. Most soils contain a range of particle sizes, which may lead to interpacking, and in soil mixtures it is the finer particle component that has the greatest influence on porosity and hydraulic conductivity (Tyler, 2001).

2.1.2 Other factors that impact permeability

Distinct colour patterns in soil can indicate the soil's ability to transmit water. Spatial variations in soil colour through the soil profile help to differentiate different soil horizons, giving indications of aeration status (and, thus, of soil drainage) in each horizon (EPA, 2009;

USEPA, 1980). Density refers to how tightly the soil particles and organic content are packed and is related to local formation processes, with soils often classified from uncompact to hard (see BS 5930 descriptions in the CoP, 2009 (BSI, 2007)). A combination of parent material and forming processes (leaching, gleisation/gleying and calcification) defines a soil type (Gardiner and Radford, 1980), and glacial till (or boulder clay) is the most widespread sediment (parent material) on the island of Ireland (McCabe *et al*., 2012). Glacial till is a product of the glacial processes of erosion, transportation and deposition. This is complex soil that is spatially variable in composition, structure, fabric and properties, making it very difficult to sample, test and classify (see Clarke, 2018), which poses particular challenges for estimating permeability. The smallest 10% of particles in the till and the degree of compaction tend to be the dominant features that determine the permeability of glacial deposits (MacDonald *et al*., 2012).

2.2 Soil Treatment Units

STUs use complex physico-chemical and biological soil processes to achieve tertiary treatment of partially treated effluent from septic tanks or package treatment units (Siegrist, 2014). All wastewater applied to the trenches of an STU must infiltrate through the soil without causing ponding at the surface. In addition, the applied wastewater must receive adequate treatment while travelling through the unsaturated soil before it enters groundwater or surface water receptors near the area of treatment. The unsaturated zone is the most important line of defence against faecal pollution of groundwater, since the low velocity of unsaturated flow maximises the time it takes to travel between the source of contamination and the point of water abstraction, thereby allowing natural die-off of such enteric microorganisms (Cave and Kolsky, 1999). STUs depend on the capacity of the soils in the unsaturated zone to both accept (i.e. the wastewater quantity issue) and purify (i.e. the wastewater quality issue) the effluent.

STUs can be considered to comprise three distinct zones in which effluent treatment occurs (BS 6297-2007) (BSI, 2007):

- the infiltrative zone at the interface between the trench base and the top few centimetres of soil, where a biologically active biomat (also called the biozone or biological layer) forms over time and contributes to the further treatment and lateral spread of effluent due to its low permeability;
- the unsaturated zone (or vadose zone) below the infiltrative zone, where additional attenuation is provided depending on its depth and characteristics; oxygen diffusion aids further treatment;
- the saturated zone below the unsaturated zone, where all pore space is filled with water and the percolating effluent mixes with the groundwater and is dispersed and diluted.

The movement of partially treated effluent through these distinct zones involves a complex interplay between hydraulic and treatment processes which often interact dynamically and evolve over the operational life of the STU (Siegrist *et al*., 2012). The ability of an STU to treat and disperse effluent effectively is influenced by both groundwater levels and soil moisture content. As both vary seasonally, it is important that the system is designed to adequately accommodate effluent discharge under the full range of possible soil conditions. A schematic of a typical STU following a septic tank system is shown in Figure 2.1. The performance of an STU in the long term is dependent on a range of soil properties, as well as the correct installation and start-up of the system to avoid compaction and other issues that can reduce hydraulic conductivity (Siegrist *et al*., 2012; USEPA, 1980).

Research indicates that biomat formation, as well as other complex soil processes, significantly impacts soil infiltration rates over time (Knappe *et al*., 2020; Leuther *et al*., 2019; Amoozegar *et al*., 2008; Beal *et al*., 2006, 2004; Siegrist *et al*. 2004; Tyler, 2001; Bouma, 1975; Laak, 1970). However, the relationship between the undisturbed soil percolation rates obtained during pre-installation tests and the infiltration rates of an operational system is not well defined (Siegrist, 2014; Beal *et al*., 2006; Beach and McCray, 2003). In addition, the level of effluent pre-treatment significantly impacts the effluent distribution along the STU trench and should be considered in the design process (Knappe *et al*., 2020; Siegrist, 2014; Gill *et al*., 2009).

2.3 Soil Permeability Tests

To achieve the objective of unsaturated flow through an STU, reliable measurement and estimation of

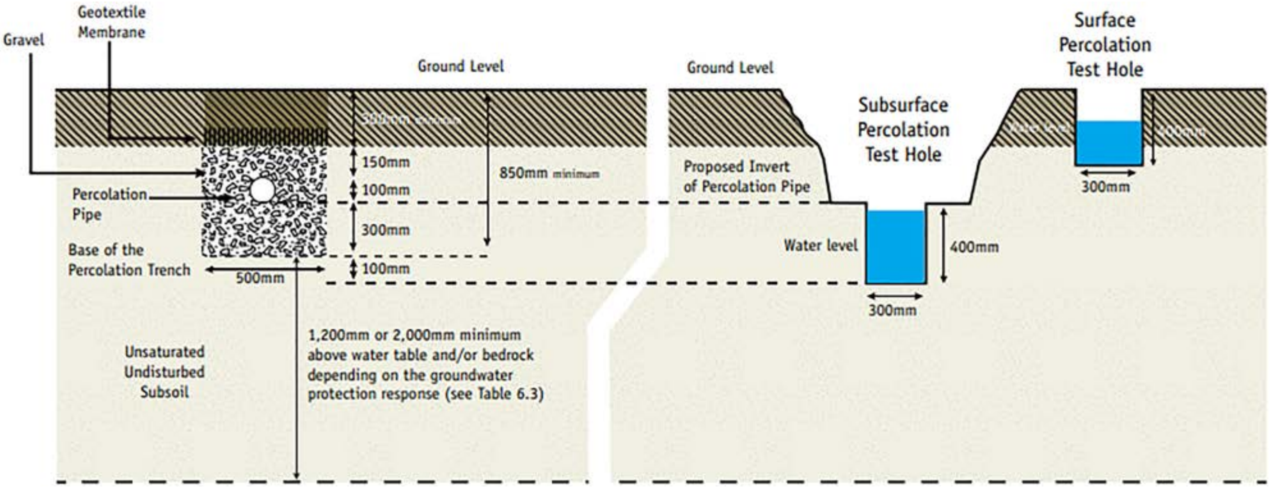


Figure 2.1. Design of conventional subsurface STU (percolation area) following a septic tank system (EPA, 2021).

the soil's capacity to transmit water is required under different levels of saturation for any potential percolation area. One approach is to determine, using either an in-situ field or a laboratory test, the soil's saturated hydraulic conductivity, K_{sat}, which is a fixed value for any soil from which the unsaturated rate of percolation can be inferred. Design standards are then based on loading the soil at a fraction of this value (usually set not to exceed 5–10% of the saturated hydraulic conductivity value (Siegrist, 2014)), so that the soil underneath always remains unsaturated. It is important to note that the hydraulic conductivity of soil varies according to the degree of saturation in a non-linear way, decreasing with soil moisture content.

Falling head percolation tests have traditionally been used to estimate the rate at which water flows through subsoil for the purposes of on-site wastewater treatment design. These tests are based on the original method developed by Henry Ryon in 1926, which involved excavating a 300-mm^2 test hole to the depth of the proposed percolation area, filling it with water and allowing the water to seep away, refilling the hole and then recording the time it took for the water level to drop 2.5 cm (Winneberger, 1974). While a wealth of experience has been gained from carrying out these tests over several decades, the percolation time values (or T-values) obtained cannot be compared easily between jurisdictions due to the different standardised methods used and the dependence of the results on test conditions, such as the dimensions of the test hole, the depth of the test water and the interval allowed for taking readings (e.g. Reynolds, 2016; Van de Graaf and Alexander, 2008; Mulqueen and Rodgers, 2001; Elrick and Reynolds, 1986; USEPA, 1980; Winneberger, 1974). In addition, the T-value does not define soil permeability accurately at high levels of percolation time (i.e. low soil permeability rates) due to the amount of time it takes for the water level to drop a measurable distance and the consequent uncertainty in defining the exact time that it hits the target levels. One of the main advantages of the falling head test is its simplicity, but, while this is an important consideration, it is also necessary for site assessors to understand what is being measured and how the test relates to the soil's hydraulic conductivity (Mulqueen and Rodgers, 2001).

The field saturated hydraulic conductivity of soil, K_{fs}, can be measured using the constant head well permeameter test. The main advantage of this test over the falling head percolation test is that the K_{fs} value obtained is a unique soil hydraulic property. This also enables threshold values to be more easily compared between jurisdictions. The other key advantage, from the perspective of this project, is the test's ability to provide quicker and more accurate results for low permeability soils. Although a difference of approximately 50% has been shown between saturated conductivities measured on soil cores in laboratory tests (K_{sat}) and saturated conductivities measured in the field (K_{fs}), where there is likely to be some entrapped air (Bouwer, 1966), K_{fs} is considered more appropriate than K_{sat} for many unsaturated zone applications because entrapped air is always present here (Elrick and Reynolds, 1986; Bouwer 1978).

To measure K_{fs} using the constant head well permeameter method, a cylindrical hole is bored to the required depth. After establishing and maintaining a constant depth of water in the hole, the rate of water flow from the hole into the soil is measured frequently until steady (Amoozegar, 2020). Steady state conditions can be assumed when the flow rate into the soil is approximately constant over several successive observations (Reynolds, 2008). Once a steady flow rate is attained, the K_{fs} of the soil surrounding the well can be determined from the constant water flow rate, the radius of the well and the head of ponded water in the well using appropriate equations (see Chapter 3).

2.4 Irish and International Standards

The current Irish CoP (EPA, 2009, 2021) uses a standard and modified falling head percolation test based on the original Ryon methodology (Winneberger, 1974) to provide a T-value (min 25 mm^{-1}). The T-value, along with soil texture classification according to BS 5930 and a trial pit assessment, is used to determine the suitability of a site for an on-site wastewater treatment system. To determine the T-value, three percolation test holes must be dug adjacent to the proposed percolation area, each 300 mm × 300 mm × 400 mm deep below the proposed invert level of the percolation pipe. Following the required pre-soaking period, the T-value in minutes per 25 mm for each test hole can be determined using the methodology outlined in the CoP.

While the falling head percolation test is still used in many jurisdictions internationally (for example the UK, South Africa and many US states and Canadian provinces, as detailed in Table 2.1), many have moved away from this test as the determining factor in STU design. Jurisdictions such as Colorado, Georgia and Rhode Island in the USA, the Canadian provinces of British Columbia, Alberta and Nova Scotia, and Australia and New Zealand now place greater emphasis on more rigorous soil analysis, with many also now including the constant head well permeameter test as an alternative to the falling head test. The USEPA Design Manual for On-site Wastewater Systems (2002), the Canadian Standard (2012) and the Australian and New Zealand Standard (2012) do not recommend the use of the falling head permeameter test and, as a result, in many Canadian provinces and Australian territories the falling head test is no longer permitted (for details, see the project literature review). Detailed soil analyses (including soil texture, structure and consistency categorisation) are used instead to estimate the saturated hydraulic conductivity of the soil or to determine the most suitable design hydraulic loading rate for the soil from design tables. In some cases (for example in Nova Scotia and Colorado), where soil analysis is the preferred option, the results of a constant head permeameter test or falling head test can still be included in the overall assessment to supplement the soil analysis results (but the in-situ test result cannot be used to override the soil analysis results). The constant head test is the preferred option in the Canadian and Australia/New Zealand standards for in-situ percolation testing, and supplemental in-situ tests can be particularly useful where there is uncertainty around the soil profile analysis. In the European CEN standards (CEN/TR 12566-2: Small Wastewater Treatment Systems for up to 50 PT- Part 2; CEN, 2005), several different potential approaches to on-site assessment are set out (including both in-situ falling head and constant head percolation tests), but the overall principle is the unification all of the different assessment methods into a single comparative numerical parameter – the LTAR.

Almost all of the 28 standards reviewed across different jurisdictions underline the fact that in-situ tests can only provide indicative values for particular points where tests are carried out, and so it is considered imperative that these values are balanced against hydraulic conductivity estimates obtained from identifying characteristic soil textures and structures. Equally, the drawbacks of relying on soil texture and structure analysis alone are highlighted in many design guidelines. To overcome the limitations of both percolation tests and soil analysis, a two-pronged approach has been adopted in some jurisdictions (e.g. British Columbia and North Carolina) as a way of ensuring that inconsistent results are identified from either percolation tests (e.g. if root holes or soil cracks yield uncharacteristically high hydraulic conductivity rates) or soil analysis (e.g. if the presence of fine sands, which lower soil hydraulic conductivity, is missed). In Ireland, soil texture does need to be categorised according to BS 5930 as part of the site assessment in accordance with the CoP, and theoretically it can be used to override the percolation value (T-value) result or at least necessitate further examination if good correlation is not seen between the soil texture and the expected percolation test results. However, anecdotally this parameter rarely feeds into the subsequent design of the bespoke on-site system for a site, with the system design options and dimensions generally all based on the results of the falling head test (T-value).

2.5 Other Permeability Estimation Methods

In-situ alternatives to the falling head test and constant head permeameter test, which are used internationally to determine field saturated hydraulic conductivity, include the constant head double-ring infiltrometer method and the constant head pressure (single-ring) infiltrometer method. (See ASTM D5126-90 (2004) and Amoozegar and Warrick (1986) for detailed comparisons and descriptions of in-situ permeability tests.)

Direct and indirect laboratory tests are also used to estimate the infiltration rate of water through saturated subsoil. Direct laboratory methods use soil cores taken from the field. Saturated hydraulic conductivity is then often estimated using a filtration column where measurements are conducted in steady or unsteady conditions (Nieć and Spychała, 2014) with the application of Darcy (1856), Buckingham (1907) or Richards (1931) equations to validate results. Extracted soil samples are very easy to saturate in laboratory tests, but it is difficult to ensure that the samples are representative of the soil in the proposed site (Griggs, 2001). The advantages of soil column infiltration tests over in-situ tests include simplicity and improved control of operation and monitoring, but the construction of soil columns can lead to profile and structural issues such as the presence or absence of macropores, artificial preferential flow paths, non-ideal infiltrate injection and unrealistic moisture regimes (Wefer-Roehl *et al*., 2012). For this reason, it is suggested that saturated hydraulic conductivity be measured directly in the field, where possible, to minimise disturbance of the sampled soil volume and maintain its functional connection with the surrounding soil (Bouma, 1982).

Indirect laboratory methods use empirical soil models to estimate hydraulic conductivity from information about the physical characteristics of investigated soils, such as bulk density, effective porosity and particle size distribution (soil texture). Pedotransfer functions (PTFs) are a class of largely data-driven empirical models aimed at estimating K_{sat} (Zhang and Schaap, 2019), and they rely heavily on the quality and quantity of the data used to create the function (Nieć and Spychała, 2014). The mass fractions of clay, silt and sand determined from particle size distribution analysis are used as input variables in most soil models, but the results are constrained by the limitations of the laboratory setting and the reliability of empirical equations, which depend on the original dataset used to develop them as well as the input data available for the K_{sat} evaluation. PTFs for the estimation of saturated and unsaturated hydraulic conductivity have been evaluated by a number of researchers (Gootman *et al*., 2020; Zhang and Schaap, 2019; Nieć and Spychała, 2014; Hart *et al*., 2008; Wagner *et al*., 2001), and variability is evident between different models. Despite this variability, however, PTFs can be a very useful tool, particularly when used in conjunction with other estimation methods or in situations where data are limited. It is recommended that PTF results be checked against local soil texture data and field permeability test results, where possible.

2.5.1 Field-based soil texture classification hand tests

Field-based soil texture hand tests can be used to classify soil texture and structure, from which an indicative K_{sat} can be estimated. They form an important part of standards in the USA, Canada, Australia and New Zealand for determining K_{sat} without a direct field percolation test measurement. Hand tests generally take a flow diagram format, such as the Thien (1979) “texture-by-feel” flow chart, whereby assessors are taken through a series of tests from which they can eliminate certain soil types based on grittiness, cohesiveness and stickiness. The Thien system identifies 11 (out of 12) US Department of Agriculture (USDA) soil categories and is widely used in the USA and Canada. The method is similar to the texture analysis used in the Australian and New Zealand Standard (2012) and is also comparable to the classification of fine-textured soils according to field-based hand tests outlined in BS 5930 and the simplified subsoil classification flow chart detailed in the Irish CoP (EPA, 2009) design guidelines (although this divides soils into only five categories).

While experienced soil scientists can estimate texture class and the percentage of sand, silt and clay in soil with accuracy using “texture-by-feel” methods (Vos *et al.*, 2016; Post *et al.*, 1986; Foss *et al.* 1975), less experienced soil assessors need training and practice to achieve accurate results (Salley *et al*, 2018; Levine *et al.*, 1989). Adequate training, including access to calibration samples of soils from the local area for comparison, can significantly improve the accuracy of estimates (Salley *et al.*, 2018), and decision support tools and technology (e.g. mobile apps) could also be developed to guide observers through iterative manipulative checks (Salley *et al.*, 2018). The level of accuracy required in soil texture classification depends on objectives; for assigning an indicative K_{sat} for use in STU design, the accuracy obtained from simple soil hand tests could be sufficient, particularly if the result is compared with estimates obtained using constant head well permeameter tests or falling head percolation tests.

2.6 Comparison of Thresholds

Falling head percolation test criteria are not standardised. This includes the dimensions and shape of test holes, the required water depth and duration of the pre-test soaking period, the initial and final water heights for testing, the percolation time calculation method and the range of acceptable T-values, all of which vary widely among jurisdictions (Reynolds, 2016). This lack of standardisation makes comparing the results and threshold values from various countries extremely challenging, as the T-value obtained under one set of test conditions may differ significantly from that obtained under different conditions, even if soil types are similar.

Since field saturated hydraulic conductivity obtained from a constant head well permeameter test is a unique value independent of test conditions, comparisons of K_{fs} or K_{sat} values across jurisdictions are easier and more relevant. Table 2.1 compares threshold T-values and K_{sat} values from various jurisdictions for a conventional on-site septic tank wastewater system, where the T-value is in min 25 mm^{-1} and K_{sat} is in cm d^{-1}. Most jurisdictions allow some form of on-site wastewater treatment system to be considered with special engineering design beyond these threshold limits (apart from areas where thresholds limits are set at 120 min 25 mm^{-1} or slower). It is important to remember, however, that the T-values listed are generally not directly comparable to T-values obtained in Ireland because of the different test methodologies used.

2.7 Literature Review Conclusions

Research shows that all soil permeability estimation methods have some inherent flaws, and no perfect test currently exists to estimate K_{fs}. Therefore, no single estimation method, whether a direct field test or an indirect laboratory method based on soil properties and empirical models, should be the only basis of STU design; a thorough investigation and understanding of the site factors that can influence subsoil hydraulic conductivity is also required to put K_{fs} estimates into context. It must also be recognised that the development of biomat over time greatly modifies the natural infiltration of effluent at its point of entry into the soil, and, therefore, assuming 5–10% of K_{fs} values for LTAR design purposes provides significant safety against the general uncertainty of K_{sat}/K_{fs} estimation methods.

An important point that is evident from a review of the literature and design standards is that in jurisdictions where significant research into on-site wastewater system design and measurement of soil permeability has taken place, particularly from the 1970s onwards (i.e. the USA, Canada, and Australia/New Zealand), changes have been made to national guidance in relation to soil permeability assessment for on-site wastewater treatment design. A large body of the literature in the area of soil permeability as applied to STUs comes from these jurisdictions, and this draws the clear conclusion that reliance on a field-based percolation test alone to assess soil permeability is inadequate. While the Canadian Standards retain reference to T-values as a comparison with K_{fs} values from constant head permeameter tests (to aid transition to K_{fs} for people who are more familiar with percolation time), the falling head test is not recommended. (Note that national standards are not always legally binding, and so most states, provinces, territories, counties, etc., still use the falling head test, despite recommendations to the contrary in national design standards.) It should be noted that the European standard EN 12566 attempts to harmonise all of the various methodologies used in different European countries and so includes field percolation

Table 2.1. Threshold T-value and K_{sat} values from various jurisdictions for a conventional on-site septic tank wastewater system (compiled from Reynolds (2016) and various design standards)

Jurisdiction	Falling head test		Constant head test	
	High permeability threshold, T-value (min 25 mm^{-1})	Low permeability threshold, T-value (min 25 mm^{-1})	High permeability threshold, K_{sat} (cm d^{-1})	Low permeability threshold, K_{sat} (cm d^{-1})
Ireland	3	75	–	–
UK	6.25	41.7	–	–
Europe (EN 12566-2)	–	–	1200	15
Arkansas, USA	10	75	–	–
Alaska, USA	1	60	–	–
Colorado, USA	5	60	–	–
Connecticut, USA	1	60	–	–
Georgia, USA	20	90	–	–
Minnesota, USA	0.1	60	–	–
Nebraska, USA	5	60	–	–
New Hampshire, USA	1	60	–	–
Pennsylvania, USA	6	90	–	–
Rhode Island, USA	1	40*	–	–
West Virginia, USA	5	60	–	–
Wyoming, USA	1	60	–	–
Canadian Standard	1	60	5000	3
Manitoba, Canada	11	80	–	–
Ontario, Canada	2.5	125	–	–
Saskatchewan, Canada	1	120	–	–
Yukon, Canada	5	60	–	–
British Columbia, Canada	1	120	800	7.5
Nova Scotia, Canada	–	–	4320	26
Australia/New Zealand	–	–	300	6

***Soils with a percolation rate of more than 40 min 25 mm^{-1} are unsuitable for the disposal of wastewater by any means of subsurface leaching.**

tests (falling head and constant head), soil texture analysis and laboratory tests, as all are allowable options for estimating soil permeability. Research in the area of soil permeability (see Chapter 3) has led to greater focus on assessing soil in terms of texture, structure and consistency, as well as the inclusion of the constant head permeameter test as an alternative in-situ test, the results of which can be easily compared with the findings of soil assessments (Australian/New Zealand Standard, 2012; Canadian Standards, 2012; USEPA, 2002). A more thorough review of the international standards is provided in the accompanying project literature review (available from the EPA).

3 Theoretical Framework

3.1 Water Movement Through Saturated Soil

Hydraulic conductivity in saturated soil is a quantitative measure of the soil's ability to transmit water when subjected to a hydraulic gradient. The flow of pore water in soils is driven from positions of higher total head towards positions of lower total head, with the hydraulic gradient reflecting the rate of change of head along the direction of water flow. Saturated hydraulic conductivity is affected by both soil and fluid properties; it depends on the soil pore geometry as well as the fluid viscosity and density. When the soil is saturated, all pores are water-filled and the conductivity depends on all of the soil pores. An important consideration is that pore geometry and continuity within a soil vary depending on the direction of measurement, and so the vertical component of K can be different from the horizontal component. Under saturated conditions, the hydraulic conductivity, K_{sat}, can be taken as a constant at any given time, location and direction in the soil (Amoozegar, 2020).

Darcy's law (Equation 3.1) describes the linear (one-dimensional) relationship between the flow of water and the hydraulic gradient in a saturated porous medium (such as a soil). Saturated hydraulic conductivity is the proportionality factor in Darcy's law, also known as the coefficient of permeability. The rate of flow of water, q, through cross-sectional area A is found to be proportional to the hydraulic gradient, i, according to Darcy's law, where the saturated hydraulic conductivity is a constant:

$$q = K_{sat} \frac{dH}{dZ} = K_{sat} \cdot i \tag{3.1}$$

where q = water flux,

K_{sat} = saturated hydraulic conductivity,

dH/dz = gradient of the hydraulic head, which is composed of the pressure potential h due to capillary forces and the gravitational potential z due to gravity (i.e. $H = h + z$).

Darcy's law assumes that the porous medium is uniform and that the fluid is inert and totally saturates the medium. However, in practice, soils are inherently non-uniform.

3.2 Water Movement Through Unsaturated Soil

The unsaturated or vadose zone is generally defined as the geological media between the land surface and the regional water table (Stephens, 2018). A single common feature of the vadose zone is the heterogeneity of the materials in it, which presents significant challenges to the prediction and measurement of water transport processes (Selker *et al*., 1999). When soil is unsaturated, the pathway for water flow is substantially reduced due to increased empty pore space, and the hydraulic conductivity of the material becomes a non-linear function of the soil water content, which can vary in space and time (Ochsner, 2019).

Soil water is subject to a number of forces, including gravity, hydraulic pressure, the attraction of the soil matrix for water, the presence of solutes and the action of external gas pressure, and so it can be evaluated in terms of its net potential energy levels. When differences in soil water potential occur, water flows from regions of higher potential to regions of lower potential, unless those regions are separated by an impermeable layer. As soils dry out, water in the largest pores drains more readily because these pores have the weakest hold on the water. Water must then move through smaller pores and in films near soil particles. The forces of attraction by which water is held to the surfaces of the soil solids with interactive capillary and adsorptive forces between water and the soil matrix are termed the matric potential (Ochsner, 2019). Since the water is held against the force of gravity, the matric potential has a lower pressure than atmospheric pressure. Matric potential is the main driving force of water movement in unsaturated soil in terms of both direction and magnitude of flow (Horrocks and Valentine, 1999).

The relationship between matric potential (ψ_m) and soil moisture (Θ) can be shown by a non-linear soil water retention curve. This curve describes the amount of water retained in a soil (expressed as gravimetric water content, Θ_g, or volumetric water content, Θ_v) under equilibrium at a given matric potential. It is an important hydraulic property related to the size and connectedness of pore spaces, and it is affected by soil texture and structure as well as other components such as organic content. Figure 3.1 shows typical soil water retention curves for sand, silt loam and clay soils.

Coarse materials retain less water than fine-textured soils of the same matric potential; as shown in Figure 3.1, sand drains quickly at relatively low tensions, while clay particles release only a small volume of water over a wide tension range. Silt loam has coarser pores than clay but finer pores than sand and so its curve lies between clay and sand (Tuller and Or, 2004). The soil water retention curve can also be influenced by whether the soil is undergoing wetting (sorption) or drying (desorption). When the soil water retention curve differs between wetting and drying, the phenomenon is called *hysteresis*. For a soil exhibiting hysteresis, the equilibrium water content associated with any particular matric potential will be lower for a wetting curve than for a drying curve.

As soils become unsaturated, the cross-sectional area of water flow decreases because pore water resides in increasingly smaller pores. In addition, tortuosity (the ratio of shortest pathway through the soil to the straight-line length) increases, as soil water pathways become more difficult and drag forces increase. In these situations, where soil moisture and flux density are changing in time, soil water flow can be described using the Richards equation (Equation 3.2), which is a highly non-linear partial differential equation, where both water content and unsaturated hydraulic conductivity are non-linearly dependent on the soil water matric head (Hopmans, 2011). The Richards equation (1931) has been used widely to develop solutions for the measurement of hydraulic conductivity in the vadose zone (Hopmans, 2011):

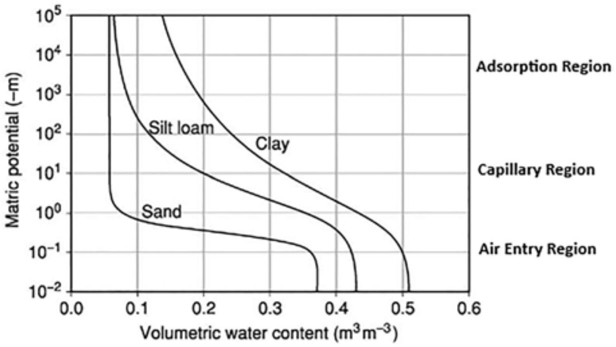


Figure 3.1. Typical soil water characteristic curves for soils of different texture. (Note that the units of the *y*-axis are negative as matric potential is a negative value. Adapted from Tuller and Or (2004) with permission from Elsevier.)

$$\frac{\delta\theta_v}{\delta t} = \frac{\delta}{\delta_z}\left[K\left(\frac{\delta\Psi_m}{\delta_z} + 1\right)\right] \qquad (3.2)$$

where K = unsaturated hydraulic conductivity,

ψ_m = soil water matric head,

z = gravitational potential,

Θ_v = the volumetric water content,

t = time.

Understanding the relationships between the soil's water content, θ_v, its water pressure head, h, and its hydraulic conductivity, K, are essential for predicting water movement in an unsaturated zone, and many models have been developed to describe these relationships, such as that developed by van Genuchten (1980) from a model introduced by Mualem (1976), which is often used in hydrological modelling software such as Hydrus. (See Šimůnek (2007) for Hydrus modelling software details and van Genuchten (1980) for mathematical model details.)

3.3 Constant Head Well Permeameter Test and Solutions

The constant head well permeameter test was first developed by Glover (1953). Using this method, the saturated hydraulic conductivity (K_{fs}) of the vadose zone is determined by the equation

$$K_{fs} = CQ/2\pi H^2 \qquad (3.3)$$

where Q is the steady state rate of water flow into the soil from a cylindrical hole of known diameter under a constant depth of water H, and C is a model parameter which must be determined using the test hole radius and depth (Amoozegar, 2020; Rodgers and Mulqueen, 2006).

A number of permeameters have been developed over the past 40 years (e.g. Talsma and Hallam, Guelph, Aardvark, Pask, Cromer), and the constant head procedure is now widely used for a range of applications internationally (Amoozegar, 2020).

All permeameters operate to similar principles, the aim being to ensure that the depth of water in the borehole does not change during the measurement period. Each permeameter type will indicate the preferable applicable equations to be used at various test hole depths. There is no universal agreement among investigators, however, on the most suitable equation for or approach to calculating K_{fs} using readings and measurements from the constant head well permeameter test. Analyses of permeameter data progressed from those analyses based solely on saturated flow around the auger hole and the hydrostatic pressure contribution (i.e. the original Glover solution) to those using the Richards equation (1931), which include saturated–unsaturated flow and hydrostatic pressure, gravity, and capillary contributions to flow (Elrick *et al.*, 1989; Stephens *et al.*, 1987; Philip, 1985; Reynolds *et al.*, 1985; Stephens and Neuman 1982). The Glover solution (1953) and solutions based on the Richards equation (as presented by Elrick and Reynolds (1986, 1992) and Reynolds (2008)) are the most commonly used internationally and are now described briefly.

3.3.1 Glover solution for K_{fs}

For an impermeable layer located at depth s, where $s > 2H$, the Glover equation for K_{fs} is:

$$K_{fs} = CQ/2\pi H^2 \tag{3.4}$$

where Q is the steady-state flow rate,

H is the depth of water in the auger hole,

r is the radius of the hole, and

C is a shape function given by (Elrick and Reynolds, 1992; Amoozegar and Warrick, 1986)

$$C = \sinh^{-1}\left(\frac{H}{r}\right) - \left(\frac{r^2}{H^2} + 1\right)^{\frac{1}{2}} + \frac{r}{H} \tag{3.5}$$

The Glover solution does not account for the effects of gravity, but it can be adjusted to include a gravitational component, as follows (Reynolds *et al.*, 1983):

$$K_{fs} = \frac{CQ}{2\pi H^2\left[1 + \frac{C}{2}\left(\frac{r}{H}\right)^2\right]}. \tag{3.6}$$

This is of particular importance when the ratio H/r is low, as the effect of gravity on the total flow out of the well hole is $>30\%$ when $H/r = 0.5$ but only 1.5% when $H/r = 10$ (Elrick and Reynolds, 1992). Note that variations of the Glover solution are available for cases in which the depth to the impermeable layer, s, is $< 2H$ (see Amoozegar and Warrick (1986)).

3.3.2 Solution for K_{fs} based on Richards equation

Reynolds (2008) presented the following expression for soil at or below field capacity for determining K_{fs} from the constant head well permeameter test based on this and previous work, including Reynolds *et al.* (1985) and Elrick and Reynolds (1986, 1992):

$$K_{fs} = \frac{CQ}{(2\pi H^2 + C\pi r^2 + 2\pi H\alpha^{*-1})} \tag{3.7}$$

where Q is the steady discharge out of the borehole and into the soil,

α^* is soil sorptive number for ponded infiltration,

H is the steady water head (ponding depth) in the borehole,

r is borehole radius, and

C is a borehole shape function.

C depends primarily on the H/r ratio and is defined as (Reynolds, 2008; Zhang *et al.*, 1998):

$$C = \left[\frac{(H/r)}{Z_1 + Z_2(H/r)}\right]^{Z_3} \tag{3.8}$$

where Z_1, Z_2 and Z_3 are dimensionless empirical constants obtained for specified soil capillarity, as shown in Table 3.1. The value of α^* can be estimated with sufficient accuracy using the texture–structure classifications shown in Table 3.1, provided that the soil is at field capacity or drier. (This is a reasonable assumption even in humid, temperate regions such as Ireland, where rainfall is relatively high, potential evaporation is low and moist antecedent soil conditions close to field capacity often prevail (Archer *et al.*, 2014).)

Note that Reynolds *et al.* (1992) and Reynolds (2008) recommend making H as large as possible to reduce the effect of errors due to the incorrect selection of α^* from the values listed in Table 3.1 (while also bearing in mind H/r requirements (i.e. $H/r \leq 20$)). However, such errors are generally less than a factor of 2 and often

Table 3.1. Texture–structure classifications with corresponding α* and Z-constants

Soil texture/structure classification	α*(m⁻¹)	Z_1	Z_2	Z_3
Compacted, structureless, clayey materials such as landfill caps and liners, lacustrine or marine sediments	1	2.081	0.121	0.672
Soils which are both fine textured (clayey) and unstructured	4	1.992	0.091	0.683
Most structured soils from clays through to loams; also includes unstructured medium and fine sands; the first choice for most soils	12	2.074	0.093	0.754
Coarse and gravelly sands; may also include some highly structured soils with large cracks and/or macropores	36	2.074	0.093	0.754

Sorptive number (α*) and shape function (*C*) parameters (Z_1, Z_2, Z_3) are for a range of normally consolidated soils with a ratio of steady ponding depth (*H*) to borehole radius (*r*) of ≤20 (Reynolds *et al.*, 2015).

less than 25% (Reynolds *et al*. 1992), which provides sufficient accuracy for many practical applications, given the inherent variability of K_{fs} (Reynolds, 2008).

3.3.3 Comparison of K_{fs} solutions

The Glover solution does not account for gravity and capillary effects, but most authors agree that it can provide good estimates of K_{fs} under particular soil conditions when the hydrostatic pressure effect dominates and capillary effects are minimal, such as in very wet or coarse-textured soils (Amoozegar *et al.*, 2020; Archer *et al*., 2014; Theron *et al*., 2010; Jabro and Evans, 2006; Radcliffe and West, 2000; Elrick and Reynolds, 1992). The Glover solution is the simplest option, requiring no estimation of soil parameters, but it may under- or overestimate K_{fs} in some circumstances because of the assumption that there is saturated flow around the test hole (Reynolds, 2013; Reynolds and Elrick, 2002; Reynolds *et al*., 1992; Stephens and Neuman, 1982). This is an important consideration because, despite best efforts, saturated flow conditions during permeability tests are rarely achieved in practice (Griggs, 2001).

The solution presented by Reynolds (2008), based on the Richards equation, accounts for gravity, hydrostatic pressure and capillary effects, but it is more complicated to apply as is requires the estimation of soil parameters such as α*. The Richards solution (as presented by Elrick and Reynolds (1989), and Reynolds (2008)) is used in Canadian standards, as well as in some US states (e.g. Georgia), where the constant head well permeameter test is recommended. It generally provides more conservative estimates of K_{fs} in fine-textured, structureless soils (i.e. soils in which capillarity is most important) than the Glover solution; the Glover solution can give significantly higher estimates of K_{fs} than the Richards solution in these soils (Archer *et al*., 2014; Jabro and Evans, 2006; Reynolds *et al*., 1992).

Despite the discrepancies between the analytical solutions for constant head permeameter measurements, the consensus remains that the potential levels of inaccuracy are considered to be within acceptable limits, particularly for the purposes of STU design for on-site wastewater treatment systems.

3.3.4 Constant head permeameter application for low permeability soils

Constant head permeameters are used internationally for in-situ testing across the full range of soils from clays to sands. The Reynolds (2008) solution provides soil parameters applicable to coarse, highly permeable soils, as well as to low permeability clay soils. In addition, individual permeameter types specifically indicate suitability for both coarse, high permeability soils and fine, low permeability soils, including the Pask (Engineering Technologies Canada Ltd, 2018), Aardvark (Eijkelkamp, 2011) and Guelph permeameters (SoilMoisture Equipment Corp., 2012). Daniel (1989) reviewed nine methods for the in-situ measurement of compacted clay soils and found that the borehole permeameter was practical and economical and compared well with other methods. This research confirmed that the method is suitable for soils with hydraulic conductivities greater than 0.009 cm d⁻¹ (10^{-7} cm s⁻¹), which is much lower than the hydraulic conductivity of soils considered in on-site wastewater treatment design.

Challenges with low permeability soils include smearing effects when auguring the borehole, which tend to reduce K_{fs}, and seasonal changes between measurements due to varying degrees of wet, dry, cold and hot conditions (Campbell and Fritton, 1994). Swelling of clay due to rainfall can close off pores, thereby reducing the pathways for water flow and resulting in lower K_{fs} (Jabro, 1988). Smearing and seasonal effects can be minimised by following specific permeameter operating instructions and by assessing the impacts of the seasonal water content of soil; these issues are also challenges when conducting falling head percolation tests in low permeability soils.

3.4 Correlation between PT and K_{fs}

In view of the fact that the falling head percolation test is used so widely among site assessors and in design standards but the field saturated hydraulic conductivity is the standard international measurement for water transmission through soils, many attempts have been made over the past several decades to formulate a relationship between percolation time, PT, and K_{fs}, including by Winneberger (1974), Fritton *et al*. (1986), Mulqueen (1995), Radcliffe and West (2000), Mulqueen and Rodgers (2001), Jabro (2009), and Reynolds (2016). Winneberger (1974), Fritton *et al*. (1986) and Jabro (2009) used field datasets to establish correlations, but these types of relationships are often useful only for the specific area from which the data have been taken. Mulqueen (1995), Radcliffe and West (2000), Mulqueen and Rodgers (2001), and Reynolds (2016) developed relationships based on the mathematical descriptions of the test holes, and so these are more useful for comparison.

3.4.1 Radcliffe and West (2000)

Radcliffe and West (2000) used an expression by Elrick and Reynolds (1992) which accounts for the effect of gravity, capillarity and hydrostatic pressure in the borehole:

$$q = \frac{Q}{\pi r^2} = K_{fs}\left[1 + \frac{H\lambda_C}{G\pi r^2} + \frac{H^2}{G\pi r^2}\right] \qquad (3.9)$$

where q is the steady water flux or steady percolation rate per unit area,

Q is the steady percolation rate,

H is the height of water ponded in the borehole,

r is the radius of the hole,

λ_c is the macroscopic capillary length, and

G is a geometric factor that depends primarily on the ratio of H/r.

Equation 3.9 is equivalent to Equation 3.6, and PT is the inverse of q. Equation 3.9 describes flow in three dimensions and shows that q will always exceed K_{fs} (since the second and third terms in brackets are positive). Macroscopic capillary length (λ_c) is a measure of the soil's capillarity, or tendency to absorb water when dry, and is equal to 1/α, where α is the ratio of K_{fs} to the matric flux potential (Bosch and West, 1998).

Radcliffe and West (2000) used an equation by Bosch and West (1998) to determine the value of G:

$$G = 1/2\pi\ [A_1 + A_2(H/r) + A_3(H/r)^2 + A_4(H/r)^3] \qquad (3.10)$$

The values of the coefficients A_1, A_2, A_3, A_4 and λ_c depend on texture and structure; these are shown in Table 3.2.

Rearranging Equation 3.9 gives:

$$K_{fs} = \frac{q}{1 + \frac{H\lambda_c}{G\pi r^2} + \frac{H^2}{G\pi r^2}} \qquad (3.11)$$

PT = 1/q, and so

$$K_{fs} = F\left(\frac{1}{\text{PT}}\right) \qquad (3.12)$$

where:

$$F = \frac{1}{1 + \frac{H\lambda_c}{G\pi r^2} + \frac{H^2}{G\pi r^2}} \qquad (3.13)$$

Table 3.2. Coefficients for Equation 3.12 (Bosch and West, 1998) and values of λ_c adapted from Elrick and Reynolds (1992) (adapted from Radcliffe and West, 2000)

Soil texture/structure	A_1	A_2	A_3	A_4	λ_c (m)
Sand	0.079	0.516	–0.048	0.002	0.02794
Structured loams and clays	0.083	0.514	–0.053	0.002	0.08382
Unstructured clays	0.094	0.489	–0.053	0.002	0.24892

F is a dimensionless factor that has different values depending on r and the texture/structure class and is the ratio of K_{fs} to 1/PT, allowing a direct comparison. Note that, when using the above expression to convert PT to K_{fs}, an average ponding depth over the time interval for the falling head test should be used.

3.4.2 Mulqueen and Rodgers (2001)

Mulqueen and Rodgers (2001) used an expression by Elrick and Reynolds (1986) for the rate of fall of a water surface in a cylindrical percolation test hole, which allows for gradients due to pressure head and gravitational and matric potentials:

$$\mathrm{d}t = \frac{r^2 C dH}{[2K_{fs}H^2 + 2H\varphi_m + r^2 K_{fs} C]} \tag{3.14}$$

where dt is the percolation time,

r is the radius of the percolation test well,

C is a parameter depending on H/r and on soil type,

H is the pressure head in the test well,

K_{fs} is the field saturated hydraulic conductivity, and

φ_m is the matric flux potential,

$$\varphi_m = \int_{\varphi i}^{0} K(\varphi) d\varphi \quad \phi \leq 0$$

where $K(\varphi)$ is the matric potential-dependent unsaturated hydraulic conductivity and φ_i is the initial or background matric potential.

Mulqueen and Rodgers applied this relationship to the falling head test outlined in Irish Standards (NSAI (1991) SR 6, which has since been replaced by the EPA CoP (2021, 2009)), by transforming the plan area of the square test hole to an equivalent cylindrical hole area. For the standard falling head percolation test (T-test) as described in the Irish CoP, the relationship derived is as follows:

$$K_{fs} = 4.2/\mathrm{PT} \tag{3.15}$$

where PT is in min 25 mm^{-1} and K_{fs} is in m d^{-1}.

Figure 3.2 shows a comparison of percolation rates for various values of K_{fs} using Irish CoP and British Standards falling head tests (t_m and V_p, respectively) using Equation 3.14 and the polynomial curve C compared with H/r outlined in Elrick and Reynolds (1986). As can be seen in Figure 3.2, at high and low values of K_{fs} the relationship between K_{fs} and the percolation rate becomes asymptotic; at high PVs, K_{fs} changes little, with large increases in PT, while at low values there are large increases in K_{fs} with small reductions in PT. Mulqueen and Rodgers concluded that this makes the PV a non-ideal parameter for setting upper and lower boundaries for the suitability of percolation soils.

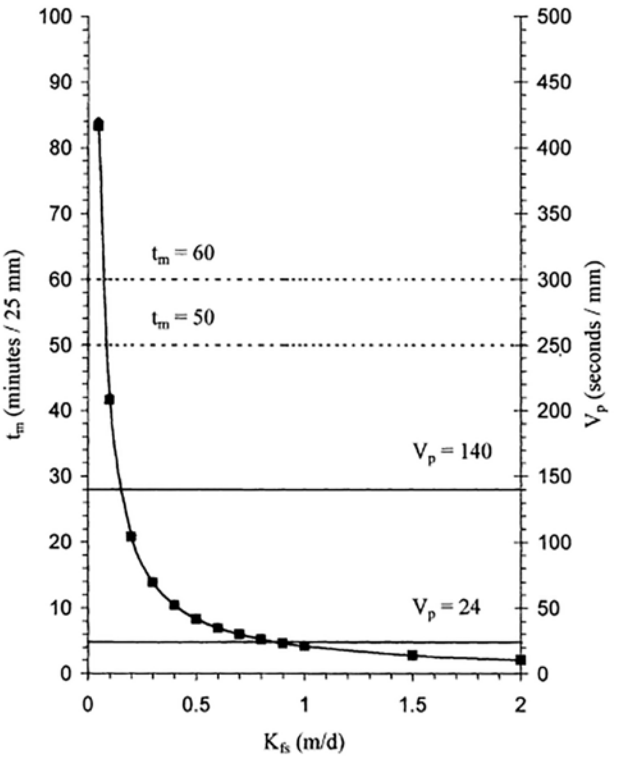


Figure 3.2. Comparison of T-value (t_m), V_p and K_{fs} using Elrick and Reynolds' model (1986), as outlined in Mulqueen and Rodgers (2001). t_m, or T-value, is in min 25 mm^{-1}, V_p is in s mm^{-1} and K_{fs} is in m day^{-1}.

3.4.3 Reynolds (2016)

Reynolds (2016) developed the unified Perc-CHWP analysis for falling head percolation tests and constant head well permeameter tests (see also Reynolds *et al.*, 2015). Field saturated soil hydraulic conductivity, K_{fs}, is determined for the constant head well permeameter test using Equation 3.6. The falling head and constant head well permeameter tests can use a cylindrical borehole, and both tests have a pre-soaking or flow equilibration period before measurements begin, which allows the steady flow–CHWP relationship to be converted to a transient flow–falling head percolation test relationship using (Elrick and Reynolds, 1986):

$$\frac{Q}{\pi r^2} = -\frac{\mathrm{d}H}{\mathrm{d}t} \approx -\frac{\Delta H}{\Delta t} = \frac{1}{\mathrm{PT}} \tag{3.16}$$

where PT is percolation time,

$\mathrm{d}H/\mathrm{d}t$ is the rate of fall of borehole head (ponding depth), and

ΔH is the decline in borehole ponding depth over time period Δt.

By combining Equations 3.7 and 3.16 and then simplifying, the following relationships are derived.

For converting falling head test PT value to K_{fs}:

$$\mathrm{PT} = \frac{\Delta t}{\Delta H} = mK_{fs}^{-1} \tag{3.17}$$

and for converting constant head test K_{fs} to PT:

$$K_{fs} = m\mathrm{PT}^{-1} \tag{3.18}$$

where

$$m = \frac{\bar{C}r^2}{\left[2\bar{H}^2 + \bar{C}r^2 + \dfrac{2\bar{H}[1 - \exp(\alpha\psi_i)]}{\alpha}\right]} = \frac{\bar{C}r^2}{2\bar{H}^2 + \bar{C}r^2 + (2\bar{H}/\alpha^*)}\,;\ 0 < m < 1 \tag{3.19}$$

where PT is percolation time,

ΔH is the decline in borehole ponding depth over time period Δt,

K_{fs} is field saturated hydraulic conductivity,

r is test hole radius,

H is average water level (ponding depth) in the test hole over time interval Δt,

α^* is soil sorptive number for ponded infiltration, and

C is a shape function given by Equation 3.9.

Z-values, α^*, are estimated from Table 3.1 (Elrick and Reynolds, 1992).

The soil sorptive number (α^*) can be expanded to:

$$\alpha^* = \frac{\alpha}{[1 - \exp(\alpha\varphi_i)]} \tag{3.20}$$

where ψ_i is the antecedent pore water pressure head in the soil surrounding the test hole and α is the slope of the soil's unsaturated hydraulic conductivity versus pore water pressure head relationship, $K(\psi)$ (Reynolds and Elrick, 1987). α^* is approximately equal to α in Equation 3.20 when the soil is at field capacity or drier (i.e. $\psi_i \leq -1$ m) (Reynolds *et al.*, 2015).

Equations 3.17–3.19 can be applied from either a CHWP test perspective or a falling head percolation test perspective. The only way to reliably determine PT from K_{fs} or vice versa is to directly apply the equations to each borehole measurement.

4 Stakeholder Engagement

An important aspect of this research was gaining insight into the experiences of stakeholders, both in Ireland and internationally, in the area of permeability estimation for on-site wastewater system design. This included use of the falling head percolation test, alternative permeability testing methods and what is considered best practice by experts across a range of jurisdictions.

4.1 Survey

A questionnaire was developed for four categories of potential stakeholder – site assessors, public service employees, private sector employees and researchers – with slightly different questions for each. In total, 42 respondents completed the survey: 12 site assessors, 13 public service employees, nine private sector employees and eight researchers. A broad range of perspectives on the current methods for determining soil percolation characteristics in Ireland and abroad was observed in the responses. The main finding from the respondents in Ireland was that the current falling head T-test is challenging to perform because of the amount of time, equipment and water needed, as well as the requirement to get the test hole dimensions right. In addition, many respondents indicated that the wide range of results often obtained when carrying out parallel tests on the same site makes reaching conclusions difficult. More research is needed to understand whether this range is due to the inherent variability of soils in the Irish context and/or to the nature of the percolation test. Most respondents in Ireland indicated that they would welcome the exploration of alternative tests for estimating soil percolation, particularly if these were more time efficient. Site assessors in Ireland generally regard the T-test result as a good indicator of a site's ability to receive effluent from on-site systems, but other respondents disagreed, particularly those from other countries. International respondents (from the USA, Australia, New Zealand, Canada and South Africa) tended to favour soil analysis techniques for estimating the field saturated soil hydraulic conductivity, K_{fs}, and, in places where in-situ soil percolation tests are still used, the constant head permeameter test is generally deemed preferable to the falling head test. This confirmed the findings of the literature review that internationally there has been a shift towards the use of soil texture and structure analysis and the constant head permeameter test to estimate the field saturated hydraulic conductivity of soil, K_{fs}.

4.2 Correspondence and Meetings with International Experts

A range of international experts in the field of on-site wastewater system design and soil science were contacted by email and over videoconferencing to provide further insights into the methods used to determine soil permeability and best practice in that area. These experts were in Australia, Canada, the USA and South Africa. Many of those contacted had been involved in the compilation of design standards in their own jurisdictions, as well as in long-term research into on-site wastewater system design and performance. The strong consensus from the correspondence and meetings was that in-situ permeability testing is only one aspect of what needs to be a thorough assessment of the site and the soil in order to estimate the site's ability to receive effluent. All experts agreed that, in their opinion, the falling head test is no longer best practice and the constant head test is a more reliable and practical in-situ test, providing a more useful K_{fs} value. However, they emphasised that the result of the constant head permeability test is useful only when put into the context of a soil texture and structure assessment. Increasing the number of in-situ tests carried out is also recommended.

The correspondence and literature review confirmed that, in areas where significant research in the area of on-site wastewater system design has been carried out (mainly in the USA, Canada and Australia), significant changes to best practice guidance have been implemented, most notably in the emphasis on soil texture, structure and consistency as indicators of permeability (see project literature review for more details) and the introduction of the constant head well permeameter test as an alternative in-situ test. These changes began in the 1980s, and, while some areas have eliminated in-situ tests altogether, others regard them as an important supplemental check. In addition, all experts noted the importance of biomat formation in the STU and the fact that this can often be the key limiting factor for soil permeability once it has been established (which is why design hydraulic loading rates are usually set at 5–10% of the saturated hydraulic conductivity rates measured during a site assessment). Thus, the estimation of the permeability through soil which has not yet received effluent has limitations in terms of predicting STU performance over its long-term operation.

5 Numerical Modelling

5.1 Field Database of T-tests

Over a period of 10 years, the results of 916 percolation T-tests carried out in a range of subsoils across Ireland have been collated into a database. Each site assessment was carried out using the standard and modified T-test procedures outlined in the CoP (EPA, 2009), involving three percolation test holes dug adjacent to the proposed percolation area, each 300 mm × 300 mm × 400 mm deep below the proposed invert level of the percolation pipe. Following the required pre-soaking period, the T-value in min 25 mm^{-1} of each test hole was measured the following day. Subsoil characterisation was determined by means of a trial pit (approximately 2 m deep or to the water table/bedrock), and soils were classified according to BS 5930, which categorises soil into five main constituents: GRAVEL, SAND, SILT, SILT/CLAY and CLAY. When a soil "sticks together when wet and remoulds" it is described as fine, and when it does not stick together and remould it is described as coarse. SAND and GRAVEL are defined as coarse soils, which contain more than 65% sand or gravel (particle size determination). Using the field-based dilatancy, toughness, plasticity and cohesion tests set out in table 24 of BS 5930, fine soils are classified as CLAY, SILT or SILT/CLAY. Secondary descriptors were also added to the soil (gravelly, silty, sandy and clayey) to account for the secondary constituents of the soil sample (e.g. sandy CLAY or silty SAND). The depth to the water table/bedrock was recorded during test pit evaluation, as were the different soil horizon depths.

To increase confidence in the modelling (given that particle size analyses were not carried out at any of these sites), the data for the four main BS 5930 soil types (SAND, SILT, SILT/CLAY, CLAY) were screened for only those values within the 25th to 75th percentile range for each soil type, as shown in Table 5.1. These tests were modelled using the finite element modelling software Hydrus 2D to provide saturated hydraulic conductivity, K_{sat}, values (and soil textures) which are equivalent to field saturated hydraulic conductivity, K_{fs}, values in this case.

Table 5.1. Subsoil classification against percolation 25th to 75th percentile T-values for >900 percolation tests (Gill, 2017)

BS 5950 Soil classification	Percolation T-value (min 25 mm^{-1}); $n = 920$ observations
GRAVEL	2–8 ($n = 81$)
SAND	5–18 ($n = 189$)
SILT	11–31 ($n = 229$)
SILT/CLAY	18–43 ($n = 232$)
CLAY	>41 ($n = 189$)

5.2 Numerical Modelling of Field Saturated Hydraulic Conductivity

Hydrus 2D simulates variably saturated transient water content and volumetric flux using a numerical solution to the Richards equation (Šimůnek *et al*., 2007). To simulate a falling head percolation test, the developer of the programme changed the software code with respect to the well boundary condition, as follows. A seepage face boundary condition is specified at the boundary representing the "well" wall (i.e. the edge of the test hole), the well radius, r_w, and the initial position of the water level in the well, h_w. The Hydrus software then evaluates the following mass balance equation to determine the position of the water level in the well:

$$\pi r_w^2 \frac{dh_w}{dt} = Q_{in}(t) - Q_p(t) \qquad (5.1)$$

where r_w is the well radius, h_w is the water level in the well, Q_{in} is the water flow into the well from the soil profile across the well wall (or its screened part), Q_p is the pumping rate, Δt is the time step, and h_w is the water level in the well. In the case of modelling the T-test, the flow is from the well to the soil and the pumping rate is zero. The "2D axisymmetric" option of Hydrus was used and so only a half-model space is visible in the Hydrus figures to follow. It should be noted that six tests across a representative range of soil types were also modelled using the T-test hole geometry in Hydrus 3D to check that they yielded the same results as the Hydrus 2D simulations, which was indeed the case.

Parts of the boundary below and above the water level in the well are then assigned the (time-variable) pressure head (Dirichlet) and the seepage face boundary conditions, respectively. Hydrus then calculates which part of the seepage face boundary is active (with prescribed zero pressure head) and which is inactive (with prescribed zero flux). Hydrus also calculates and reports separately the fluxes across these two parts of the boundary representing a well. To simulate the position of the water level in the well (percolation test hole), h_w, an observation node is specified at the bottom of the well.

For modelling each T-test, each simulation of the actual falling head percolation test was run 24 hours after the first pre-soaking filling of the test hole up to 400 mm deep. This period also acts to initialise the model for the duration of the actual field falling head test. The hydraulic model chosen for simulating was van Genuchten–Mualem with no hysteresis, and the water retention curve parameters were used as default by Hydrus code for each soil type (e.g. θ_r, θ_s, α, n and l), except for K_s, which was calibrated to achieve the best result in agreement with the actual data. A comparison between the BS 5930 and USDA soil classification systems was carried out to choose the most appropriate model parameters (see full project literature review).

For each T-test it was assumed that the soil profile contains only one layer in the percolating zone with no anisotropy. A linear head pressure distribution with depth was applied to the observed profile as the initial condition and for the initial pre-soak filling and refilling of the hole 24 hours later (Figure 5.1).

Figure 5.2a–d shows different head pressure results for various soil textures at the end of the simulation and Figures 5.3 and 5.4 show different head pressure versus time graphs, simulated using Hydrus 2D with the percolation tests across different subsoil textures. As Figures 5.3 and 5.4 show the pressure head in the well, the water level is seen to fall. The red dots in Figure 5.4 indicate the interim readings taken during actual falling head tests in the field, against which the model was calibrated.

These data (388 test measurements) are plotted in Figures 5.5 and 5.6. Figure 5.5 is plotted with a linear *y*-axis to show the distribution of values more clearly across the range of K_{fs} values. As can be seen, the relationship is quite flat for fine-textured soils, with very little change in K_{fs} at larger changes in T-value. Figure 5.6 is plotted with a log-scale *y*-axis to illustrate the trendline more clearly.

From these data a generic relationship between T-value and the more rigorous scientific K_{fs} value (as used in the modelling) was derived. An interesting point revealed in the graph is how few T-tests are completed in low permeability soils for values of T > 90, which is due partly to the length of time that such tests take, but also to the fact that T = 90 has been the threshold for suitability for on-site assessment over the last 10 years, in accordance with the 2009 CoP.

From Figure 5.6, the relationship between field saturated hydraulic conductivity, K_{fs}, and percolation time, T-value, derived from the model is:

$$K_{fs} = 3015\ \text{T-value}^{-0.98} \tag{5.2}$$

where K_{fs} is in mm d^{-1} and T-value is in min 25 mm^{-1}.

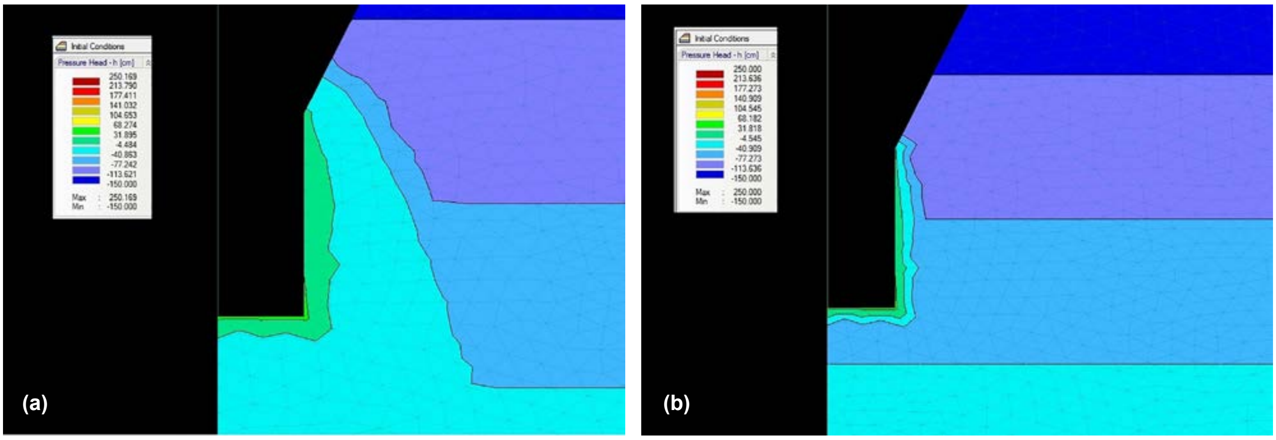
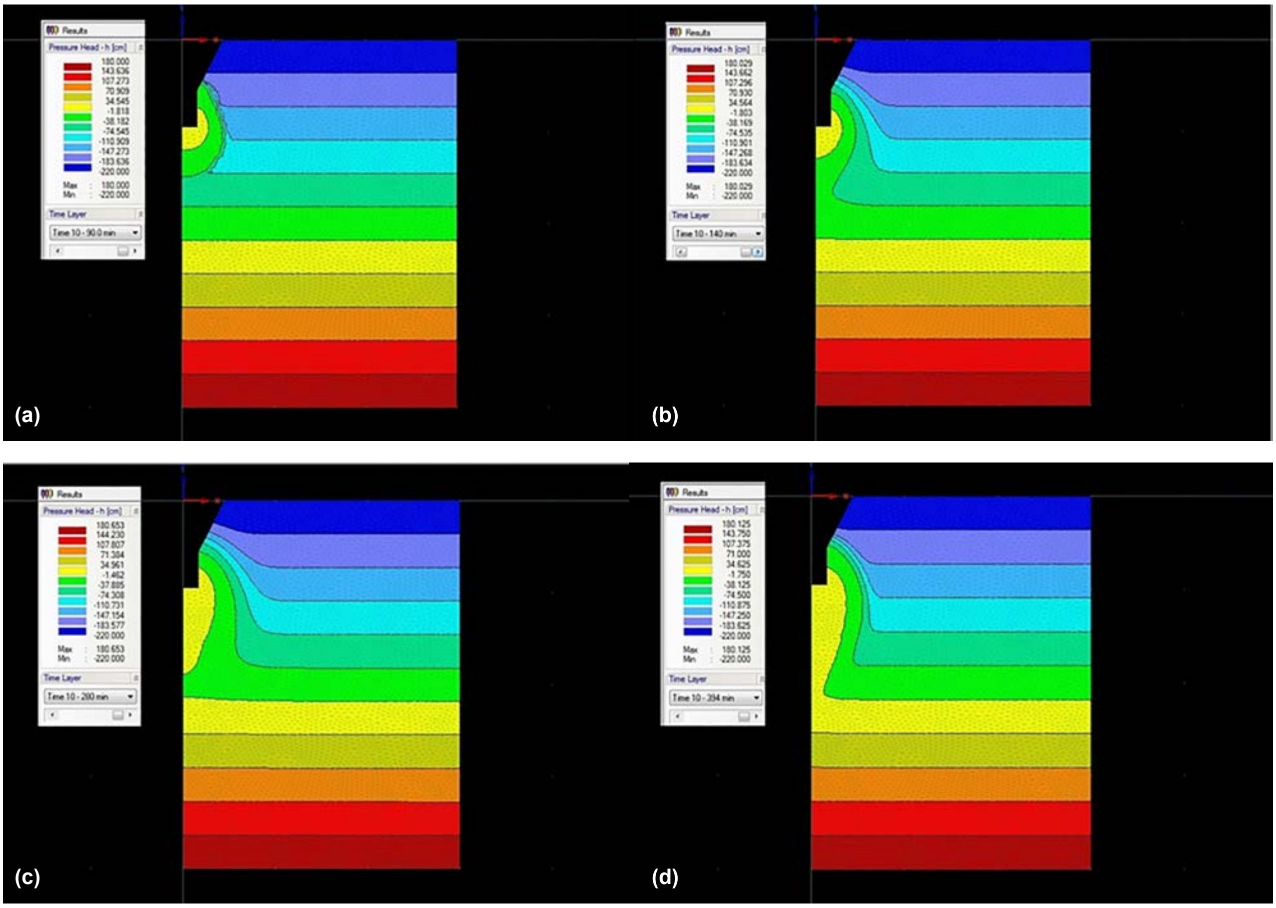


Figure 5.1. Initial conditions with linear head pressure for (a) first filling and (b) refilling.



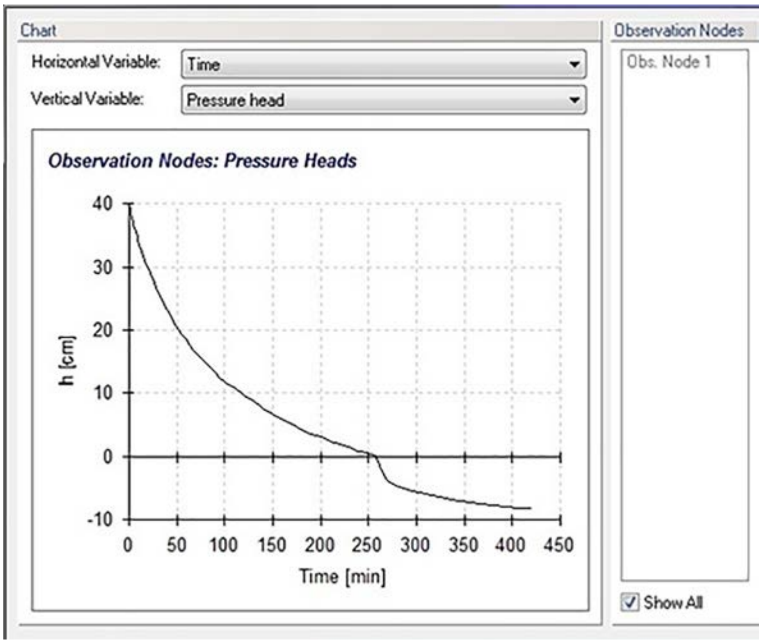
Time Layer: Time 10 - 90.0 min

Time Layer: Time 10 - 140 min

Time Layer: Time 10 - 200 min

Time Layer: Time 10 - 394 min

Figure 5.2. Head pressure results for (a) SAND, (b) SILT, (c) SILT/CLAY and (d) CLAY.



Horizontal Variable: Time

Vertical Variable: Pressure head

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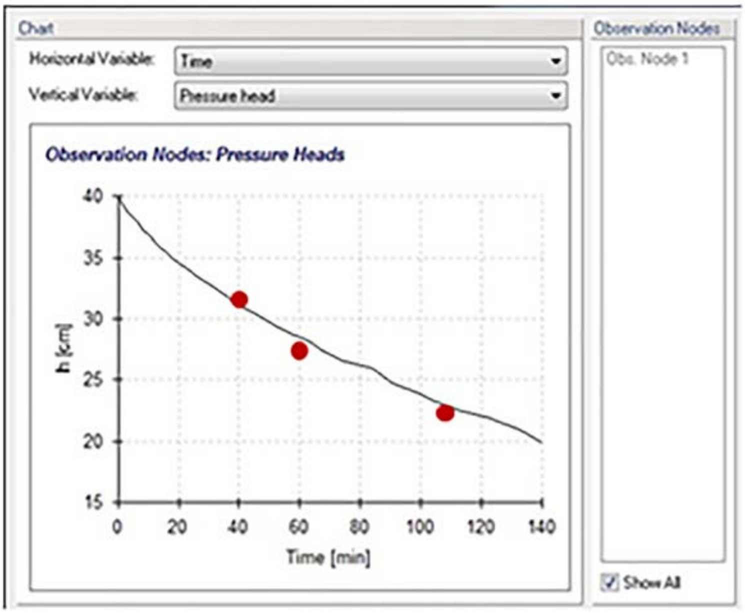
Figure 5.3. Head vs time for SAND for observation node at the base of the hole.



Horizontal Variable: Time

Vertical Variable: Pressure head

Figure 5.4. Head vs time for SILT/CLAY for observation node at the base of the hole (with field values shown as red dots).

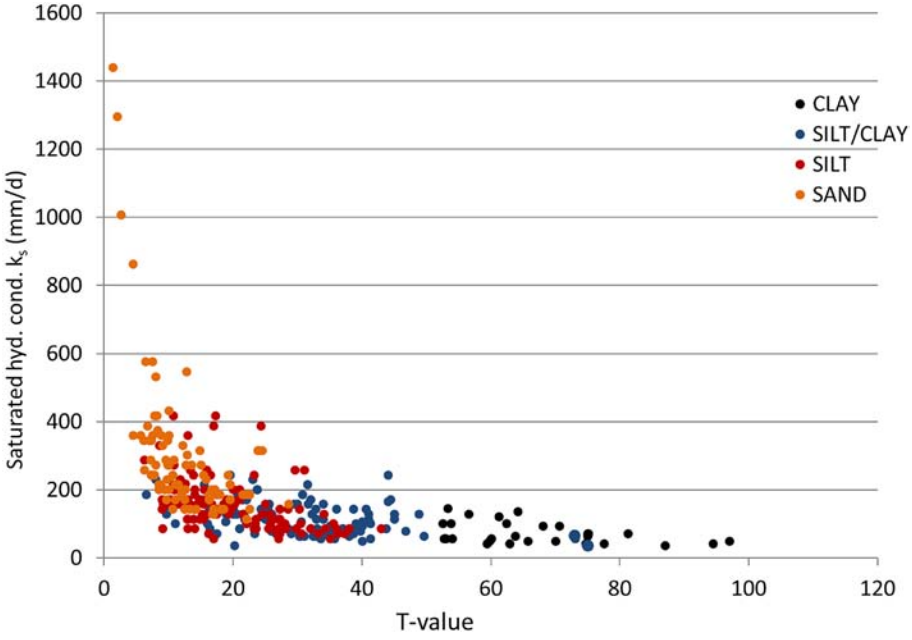


Figure 5.5. T-values (min 25 mm^{-1}) vs field saturated hydraulic conductivity (K_{fs}, mm d^{-1}) as determined by Hydrus 2D.

5.3 In-situ Testing

To assess the findings of the Hydrus 2D modelling, a number of constant head well permeameter tests were carried out in parallel with falling head percolation tests at the same sites, giving a field saturated hydraulic conductivity value K_{fs} and a T-value, respectively. Many constant head permeameter brands are available for determining K_{fs}; the Aardvark permeameter was used for these particular tests and will be described briefly next.

5.3.1 Aardvark constant head permeameter

The Aardvark is a constant head permeameter which ensures that the depth of water in a borehole (H) does

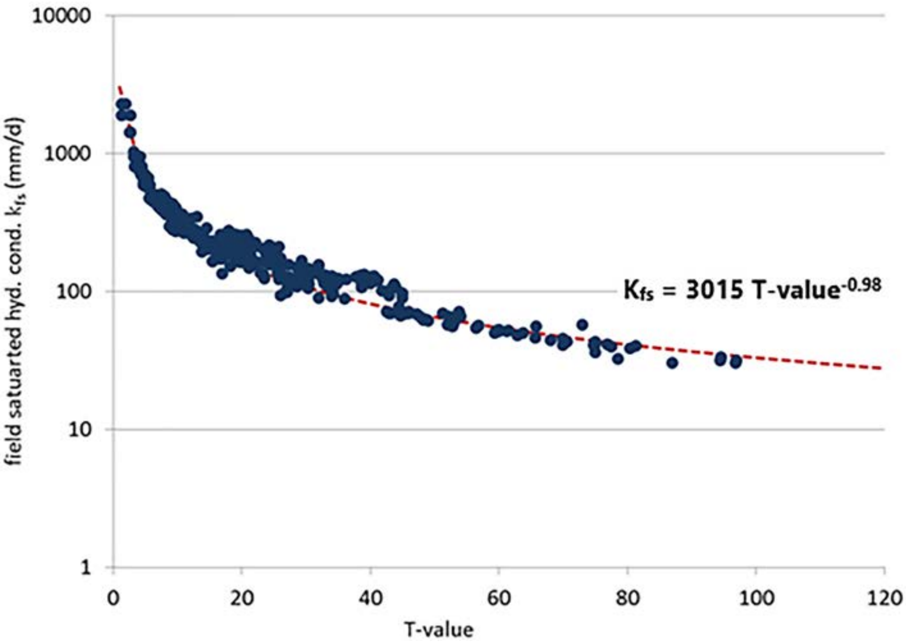


Figure 5.6. T-values (min 25 mm^{-1}) (reduced field dataset for 25th to 75th percentiles) vs saturated hydraulic conductivity (K_{fs}, mm d^{-1}) as determined by Hydrus 2D.

not change during the measurement period. This constant head is achieved via a pressure regulator unit at the bottom of the borehole, as shown in Figure 5.7.

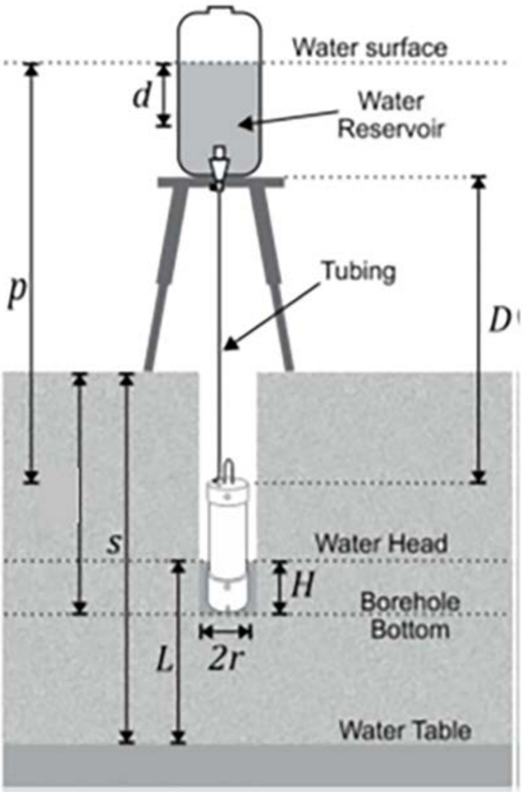


Figure 5.7. Schematic of an Aardvark permeameter (adapted from Eijkelkamp (2011) with permission from Royal Eijkelkamp).

The Aardvark permeameter estimates field saturated hydraulic conductivity (K_{fs}) using the amount of water infiltrated by soil (determined using *d*, the difference between volumetric readings of the reservoir during the specified time period) measured at equal time intervals (Figure 5.7). The measurement ends when the reservoir flow rate (soil–water infiltration rate) does not vary over several consecutive readings (i.e. when the flow rate has reached steady state).

K_{fs} was evaluated from the permeameter data using the Glover and Reynolds solutions outlined in section 3.3 and summarised in Table 5.2.

For the Aardvark permeameter tests carried out in this research, the correct depth for the permeameter with respect to the depth of the proposed percolation trench infiltrative is shown in Figure 5.8. It should be noted that the dimensions of the hole are critical to the determination of K_{fs}, and for all these tests the diameter of the borehole was cored with a 10-cm-diameter augur.

Eleven different parallel tests were carried out on various sites between 2015 and 2017, and a further six were carried out in 2020 and 2021. It should be noted that, although the focus of this project is on lower permeability sites, measuring T-values in such sites proved very difficult as the drops in the water levels were insufficient for actually determining a T-value,

Table 5.2. Solutions for K_{fs} used with constant head well permeameter test data

Solution	Equations
Glover (1953) standard solution	$K_{fs} = CQ/2\pi H^2$ $C = \sinh^{-1}\left(\frac{H}{r}\right) - \left(\frac{r^2}{H^2} + 1\right)^{\frac{1}{2}} + \frac{r}{H}$
Glover solution adjusted for gravity	$K_{fs} = \frac{CQ}{2\pi H^2\left[1 + \frac{C}{2}\left(\frac{r}{H}\right)^2\right]}$ $C = \sinh^{-1}\left(\frac{H}{r}\right) - \left(\frac{r^2}{H^2} + 1\right)^{\frac{1}{2}} + \frac{r}{H}$
Reynolds (2008) solution, using: (a) α^*, Z_1, Z_2, Z_3, recommended for most structured soils (i.e. 12, 2.074, 0.093 and 0.754, respectively) (b) α^*, Z_1, Z_2, Z_3 for fine soils where appropriate (i.e. 4, 1.992, 0.091 and 0.683, respectively) (c) α^*, Z_1, Z_2, Z_3 for coarse sands where appropriate (i.e. 36, 2.074, 0.093 and 0.754, respectively)	$K_{fs} = \frac{CQ}{(2\pi H^2 + C\pi r^2 + 2\pi H\alpha^{*-1})}$ $C = \left[\frac{(H/r)}{Z_1 + Z_2(H/r)}\right]^{Z_3}$

demonstrating the limitations of such a test in low permeability soils. Photographs of the two different test methodologies in the field are shown in Figure 5.9.

The results of the falling head and constant head permeameter tests using these various solutions are summarised in Table 5.3. Unfortunately, the three percolation tests gave inconclusive results from the perspective of gaining T-values, as they had very low percolation rates, and so no T-values could be determined using either the standard or the modified method. The Aardvark permeameter, however, did enable values for these sites to be determined relatively quickly (in approximately 2 hours). Note that alternative soil parameters suitable for use in glacial tills, as presented by Kindred and Reynolds (2020), were applied to the lower permeability field test results but were found to provide very low K_{fs} values, well below the levels suitable for on-site wastewater system design.

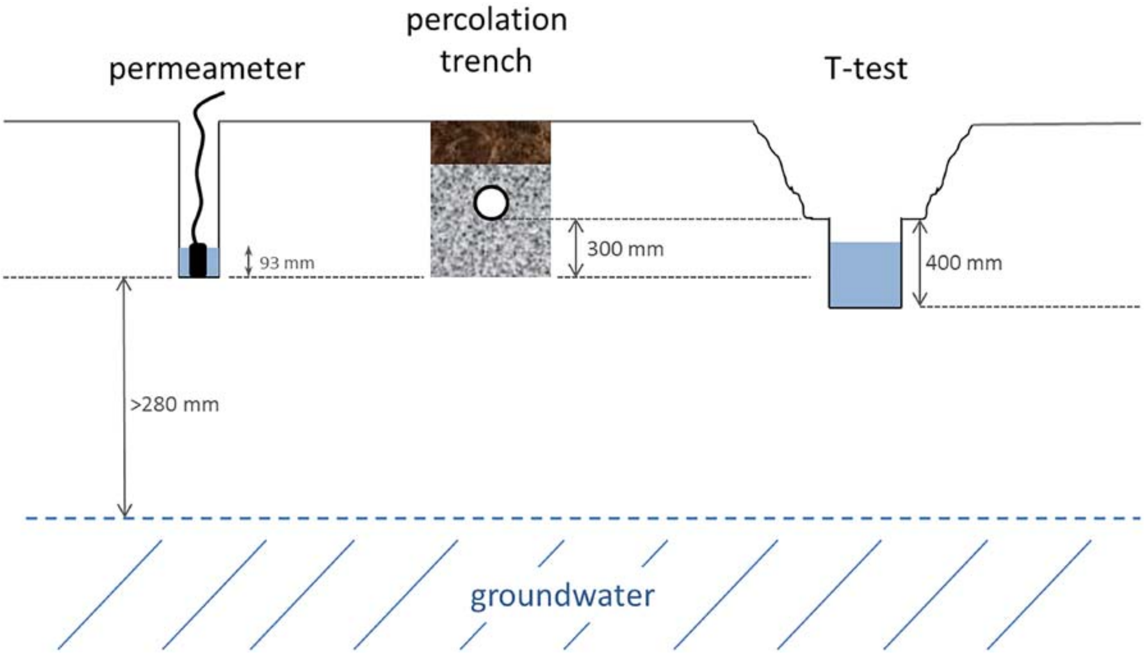


Figure 5.8. Required depth for permeameter.

Figure 5.9. (a) T-test (Limerick). (b) Aardvark permeameter (Limerick).

Table 5.3. Results of parallel falling head T-tests and constant head permeameter tests using different solutions for K_{fs} as outlined in Table 5.2

Site location	Glover K_{fs} (mm d^{-1})	Glover + gravity K_{fs} (mm d^{-1})	Reynolds (2008) a. K_{fs} (mm d^{-1})	Reynolds (2008) b. K_{fs} (mm d^{-1})	Reynolds (2008) c. K_{fs} (mm d^{-1})	Standard T-test, T-value (min 25 mm^{-1})	Modified T-test, T-value (min 25 mm^{-1})
Cork 1 (2015)	399	356	219	–	310	15.0	–
Dublin 1 (2016)	16	14	9	1	–	Fail	Fail
Dublin 2 (2016)	48	43	26	5	–	Fail	Fail
Dublin 3 (2021)	378	337	209	–	295	12.6	–
Dublin 4 (2021)	51	46	28	16	–	–	84.5
Kildare 1 (2017)	92	82	50	28	–	54.0	–
Kildare 2 (2020)	70	62	38	21	–	62.0	–
Limerick 1 (2015)	158	140	87	48	–	35.9	–
Limerick 2 (2015)	239	209	131	–	185	13.3	12.6
Limerick 3 (2016)	385	341	211	–	298	11.8	11.1
Limerick 4 (2016)	249	219	136	–	192	14.7	13.8
Limerick 5 (2021)	85	75	46	26	–	74.9	–
Limerick 6 (2021)	40	35	22	12	–	92.6	–
Louth 1 (2016)	8	7	4	1	–	Fail	Fail
Meath 1 (2017)	137	121	75	42	–	41.0	–
Meath 2 (2017)	225	200	123	69	–	46.0	–
Wicklow 1 (2020)	281	249	154	–	218	6.6	–

Figure 5.10 plots the saturated hydraulic conductivity results from constant head permeameter tests and corresponding T-values from parallel T-tests with the Hydrus 2D best-fit relationship shown in Figure 5.6, i.e. $K_{fs} = 3015 \times \text{T-value}^{-0.98}$. K_{fs} was determined using the options outlined in Table 5.2. The Glover solution (1953) and the Glover solution adjusted for gravity were found to give higher values of K_{fs} than

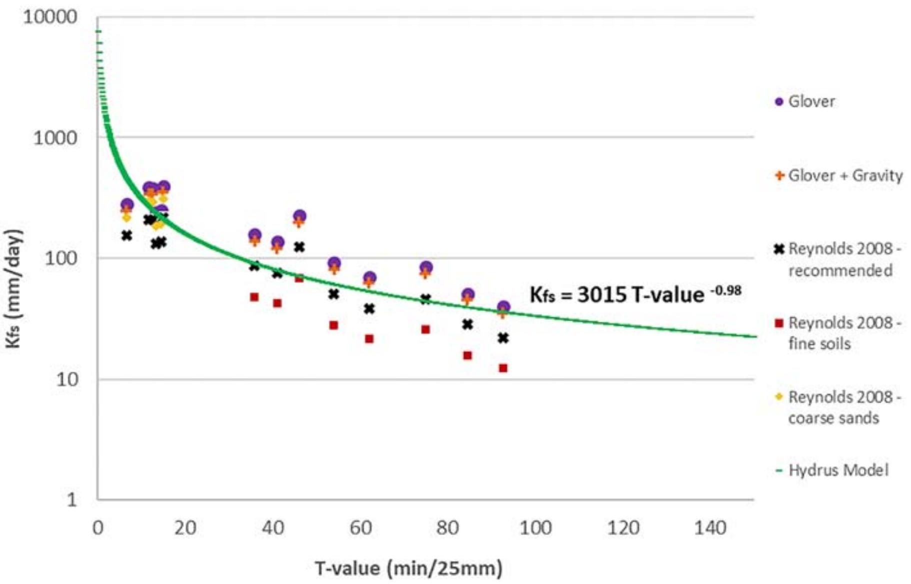


Figure 5.10. T-values (from T-tests) and saturated hydraulic conductivity (K_{fs}) from constant head permeameter tests plotted against Hydrus 2D best-fit trendline from Figure 5.6. K_{fs} solved using Glover solution; Glover solution adjusted for gravity; and Reynolds (2008) solution with (a) parameters recommended for most soils, (b) parameters for fine soils, where appropriate, and (c) parameters for coarse sands where appropriate. Note: *y*-axis is plotted on a log-scale.

the Reynolds (2008) solutions ((a), (b) and (c) in Table 5.2). This is in agreement with the findings of Amoozegar (2020), Archer *et al*. (2014), Reynolds (2008) and Jabro and Evans (2006) for medium- to fine-textured soils.

The K_{fs} results determined using the Reynolds (2008) solution with the parameters in Table 3.1 recommended for most structured soils from clays to loams, as well as for unstructured medium and fine sands, are seen to fit the Hydrus trendline better than those obtained using the Glover solution. In cases where the T-test and K_{fs} results indicated low permeability, fine-textured soils, the parameters outlined in Table 3.1 for fine soils were used (shown as red squares in Figure 5.10), and in cases where sands were indicated, the parameters in Table 3.1 for coarse sands were applied (shown as yellow diamonds on the graph). Fine soil parameters were found to reduce the resultant K_{fs} value when they were applied, and coarse sand parameters slightly increased the K_{fs} values, giving better results than the Hydrus curve in some cases. While the numbers of data points are limited, the field data solved using the Reynolds (2008) equation using recommended parameters for most soils agree well with the Hydrus 2D trendline, as shown in Figure 5.11.

Measured T-values from falling head tests in the field were converted to equivalent K_{fs} values using the Radcliffe and West (2000), Mulqueen and Rodgers (2001) and Reynolds (2016) relationships outlined in section 3.4. The T-value–K_{fs} data points obtained using the models were then plotted against the Hydrus 2D model trendline (Figure 5.12) to verify that they provided a similar correlation between T-value and K_{fs} for the field test measurements. In addition, measured K_{fs} values from field constant head permeameter tests (determined using the Reynolds (2008) equations) were converted to equivalent T-values, and these K_{fs}–T-value data points were then plotted against the Hydrus 2D model trendline (Figures 5.13 and 5.14). Figure 5.13 shows the values within the design range in the Irish CoP, while Figure 5.14 shows the T-values obtained from all K_{fs} field measurements, with some above 120 min 25 mm^{-1}. Note that fewer measured T-values were available than K_{fs} values because, as mentioned, it was not possible to determine a T-value in some of the lower permeability soils tested.

When converting field test T-values to K_{fs}, the Reynolds (2016) correlation was found to fit the model trendline particularly well, while the Mulqueen and Rodgers and Radcliffe and West equations gave slightly higher estimates for K_{fs} than the field test

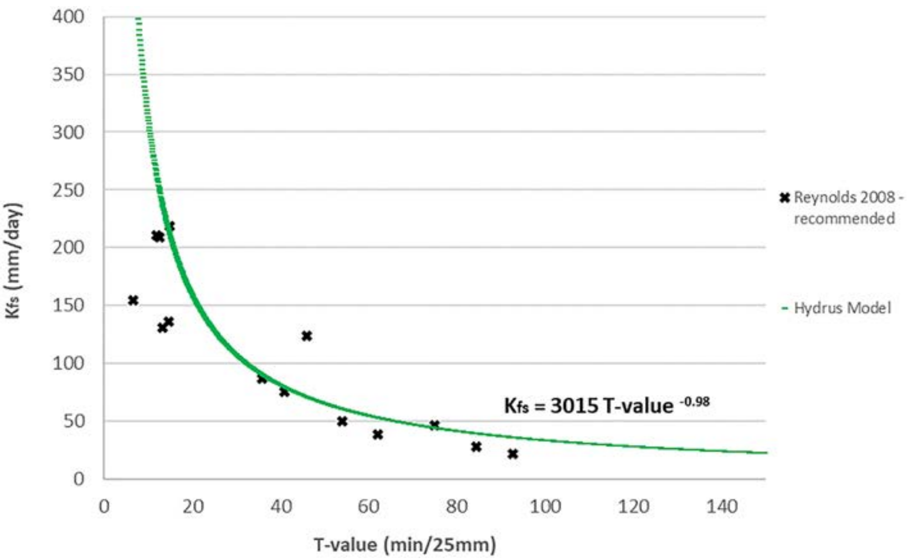


Figure 5.11. T-values (from T-tests) and saturated hydraulic conductivity (K_{fs}) from constant head permeameter tests plotted against Hydrus 2D best-fit trendline from Figure 5.6. K_{fs} solved using Reynolds (2008) solution with recommended parameters for most soils from Table 3.1.

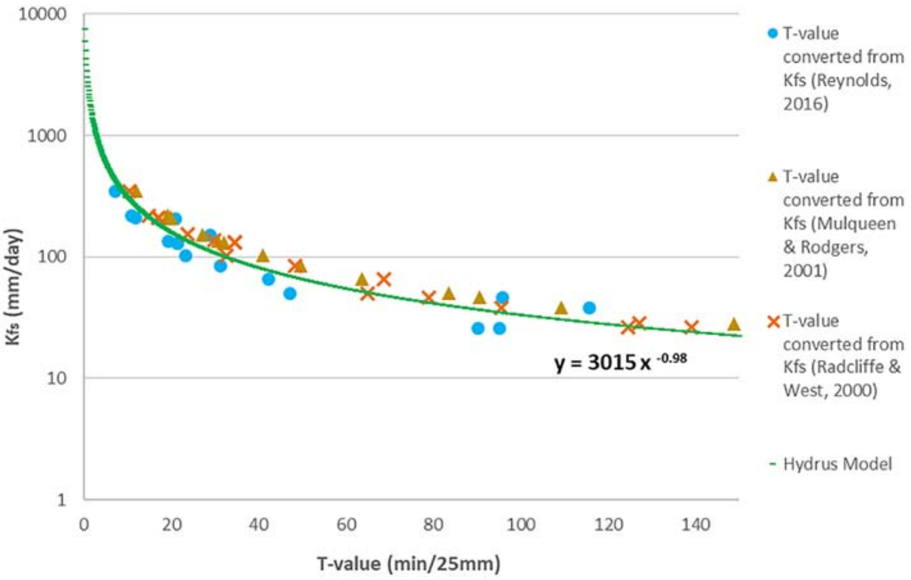


Figure 5.12. Equivalent K_{fs} calculated from measured T-values using Radcliffe and West (2000), Mulqueen and Rodgers (2001) and Reynolds (2016) relationships compared with the Hydrus 2D model trendline. Measured T-values from parallel field tests were converted to K_{fs} values using each PT–K_{fs} correlation. The K_{fs} obtained using each correlation was then plotted with the measured T-value and compared against the Hydrus 2D trendline of $K_{fs} = 3015 \times \text{T-value}^{-0.98}$.

results. When converting field test measurements of K_{fs} to T-values, the Hydrus 2D trendline was found to lie between the three models. A comparison of the Hydrus trendline developed from the Irish dataset and the data points obtained using the three mathematically based models shows strong similarities in the results obtained. This gives further confidence that the modelled trendline is a reasonable reflection of the relationship between the falling head test and K_{fs}.

Note that comparisons were made between the falling head test hole dimensions and the constant head test hole dimensions in terms of their potential impact on permeability rates at various ponding heights when using conversion models. The difference in dimensions

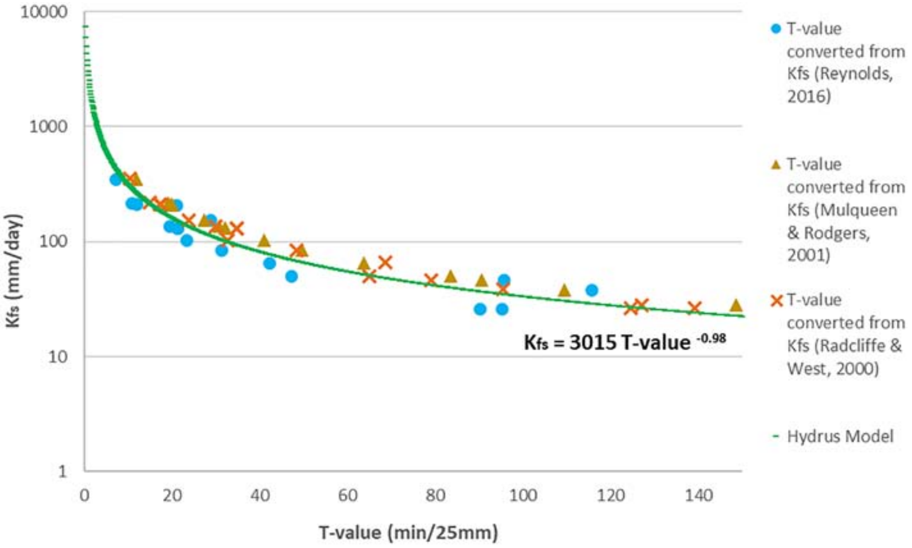


Figure 5.13. Equivalent T-values calculated from measured K_{fs} using Radcliffe and West (2000), Mulqueen and Rodgers (2001) and Reynolds (2016) relationships compared with the Hydrus 2D model trendline within the CoP T-value design range. Measured K_{fs} values (solved using the Reynolds (2008) solution) were converted to T-values using each PT–K_{fs} correlation. The T-value obtained using each correlation was plotted with the measured K_{fs} and compared against the Hydrus 2D trendline of $K_{fs} = 3015 \times \text{T-value}^{-0.98}$.

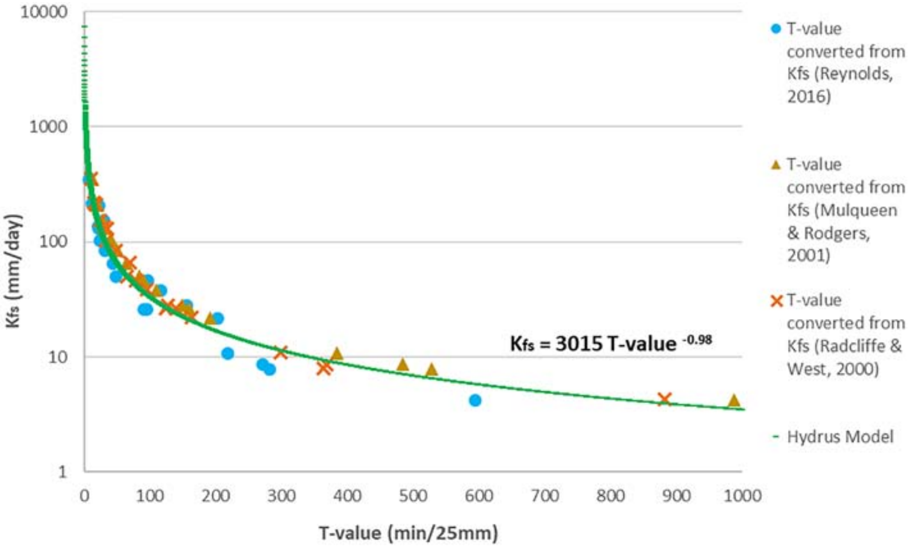


Figure 5.14. Equivalent T-values calculated from measured K_{fs} using Radcliffe and West (2000), Mulqueen and Rodgers (2001) and Reynolds (2016) relationships compared with the Hydrus 2D model trendline; axis includes T-value range obtained from converting all field-measured K_{fs} values. Measured K_{fs} values (solved using the Reynolds (2008) solution) were converted to T-values using each PT–K_{fs} correlation. The T-value obtained using each correlation was plotted with the measured K_{fs} and compared against the Hydrus 2D trendline of $K_{fs} = 3015 \times \text{T-value}^{-0.98}$.

for the specific cases of these falling head and constant head test holes was seen to have little impact on the conversion results, as the ratios of infiltration area to infiltration volume were similar.

5.4 Comparison of Model with International K_{fs} Ranges

Comparisons of T-values across jurisdictions can be problematic due to the wide-ranging methodologies used for the falling head percolation test (such as different test hole dimensions and different initial ponding heights), which directly impact T-value results. To make international comparisons, the indicative T-values provided by Gill (2017), based on Irish T-test methodology for each BS 5930 subsoil texture class, were converted to K_{fs} values using the Hydrus 2D model trendline, $K_{fs} = 3015 \times \text{T-value}^{-0.98}$. These K_{fs} ranges were then compared with those provided in some international design standards, as shown in Table 5.6. This comparison necessitated the conversion of soil texture categories from different soil classification systems to BS 5930 classifications, which was complicated by differences in particle size limits for soil constituents and the fact that some international soil texture groupings include more than one BS 5930 category. In addition, many standards (e.g. those in Australia/New Zealand and British Columbia) classify soils according to structure and consistency. Therefore, the K_{fs} ranges for BS 5930 soils as adapted from the international standards can act only as rough guidelines. Table 5.4 shows some examples of comparisons of international soil categories with BS 5930 classifications.

Table 5.5 shows the indicative T-values from Gill (2017) and the equivalent K_{fs} ranges calculated using the Hydrus model trendline. Also included are K_{fs} ranges for different jurisdictions. In the sand and gravel range, estimates from the Hydrus model trendline tend to be lower than those from other design standards, which may be in part due to differences in soil classification systems. For example, many lower permeability soil groupings in international standards (such as the clay loam, sandy clay loam, silty clay loam grouping shown in Table 5.4) include the BS 5930 classification of SAND. Low permeability within the BS 5930 SAND classification is possible, particularly when fine particles are present (up to 34%

Table 5.4. Examples of comparisons of US and Canadian standards with BS 5930 soil texture categories for the purposes of comparing indicative K_{fs} ranges

Soil classification in standards (USA, Canada)	BS 5930 classification	Indicative K_{fs} from design standards (cm d^{-1})
British Columbia		
Gravelly, coarse sand	SAND	400–200
Sand, loamy sand	SAND	200–55
Fine sands, loamy fine sands, sandy loams	SAND, SILT	100–30
Loam, silty loam, silt	SILT	55–15
Clay loam, sandy clay loam, silty clay loam	SAND, SILT, CLAY, SILT/CLAY	30–7.5
Sandy clay, silty clay, silt	CLAY, SILT, SILT/CLAY	15–7.5
Georgia		
Sand, loamy sand	SAND	> 19.77[a]
Sandy loam, loam	SAND, SILT	19.77–5.66[a]
Sandy clay loam, silt loam, clay loam, silty clay loam, silt	SAND, SILT, CLAY, SILT/CLAY	5.66–2.83[a]
Sandy clay, silty clay, clay	CLAY, SILT, SILT/CLAY	< 2.83[a]
Canadian Standards		
Gravelly sand	SAND	> 5000
Coarse to medium sand, loamy sand	SAND	5000–150
Fine sand, fine loamy sand	SAND	150–25
Coarse sandy loam, medium sandy loam	SAND, SILT	50–12.5
Fine sandy loam, very fine sandy loam	SAND, SILT	12.5–3
Loam	SILT	25–6
Silt loam, silt	SILT	25–3
Clay loam, sandy clay loam, silty clay loam	SAND, SILT, CLAY, SILT/CLAY	6–1.5
Sandy clay, silty clay, clay	CLAY, SILT, SILT/CLAY	6–0.5

[a] **Calculated using Reynolds (2016) equations from indicative T-values. Applicable to Georgia test conditions only; not universally applicable.**

Table 5.5. Indicative K_{fs} ranges for various soil categories: estimated from Gill (2017), PT values (T-values) for BS 5930 soil categories using Hydrus 2D model trendline, $K_{fs} = 3015 \times \text{T-value}^{-0.98}$, and compared against values cited in various international design standards for on-site wastewater system design

	Indicative PT (T-value) range according to BS 5930 soil texture category	K_{fs} range for BS 5930 soil texture categories calculated from indicative PT using Hydrus trendline: $K_{fs} = 3015 \times \text{T-value}^{-0.98}$	Indicative K_{fs} range provided in various design standards according to soil texture/structure category. Best estimate of corresponding BS 5930 soil category was made to compile values					
BS 5930	Gill (2017), PT (min 25 mm^{-1})	Gill (2017), K_{fs} (cm d^{-1})	CEN (EN 12566-2), K_{fs} (cm d^{-1})	Canada, K_{fs} (cm d^{-1})	British Columbia, K_{fs} (cm d^{-1})	Nova Scotia, K_{fs} (cm d^{-1})	Georgia, K_{fs} (cm d^{-1})	Australia/ New Zealand, K_{fs} (cm d^{-1})
GRAVEL	2–8	39–153	> 1200	> 5000	> 400	> 4320	> 19.77[a]	> 300[b]
SAND	5–18	18–62	50–1200	25–5000	65–400	69–4320	5.66–19.77[a]	50–300[b]
SILT	11–31	10–29	15–50	6–30	7.5–65	26–69	2.83–5.66[a]	12–50[b]
SILT/CLAY	18–43	7.5–18	15	1.5–6	7.5–30	1.7–69	2.83–5.66[a]	6–50[b]
CLAY	> 41	< 7.9	< 15	< 6	< 7.5	< 1.7	< 2.83[a]	< 6

[a] Calculated using Reynolds (2016) equations from indicative T-values. Applicable to Georgia test conditions only; not universally applicable.

[b] Sand and silt particle sizes are classified differently in the Australia and New Zealand soil classification system: silt, 0.002–0.02 mm; sand, 0.02–2 mm.

fine particles (CLAY, SILT) can be present in sand, as well as finer sand particles of 0.06 mm). In fact, using the bulk descriptors SAND, SILT or GRAVEL to help classify the permeability of soils may be of very limited use (MacDonald *et al.*, 2012; Fogg *et al.*, 1998), and more attention should be given to the presence of silt or clay, as permeability is strongly related to the finest soil fraction (MacDonald *et al.*, 2012). Of particular importance in the Irish context are low permeability soils below approximately 10 cm d^{-1}. In this range, the indicative values shown in the trendline are comparable to those in the international standards. In the international design standards, soils with K_{fs} values below those indicated as the upper threshold for clay soils are generally not considered suitable for standard septic tank systems but may be suitable for secondary systems subject to suitable engineering design and recommendations.

The European CEN standard's (EN 12566-2) lower threshold for direct infiltration of effluent to clay soils is 15 cm d^{-1}. This is out of step with the findings from the Hydrus modelling and parallel in-situ tests and also with other international standards. It equates to a T-value of approximately only 20 min 25 mm^{-1}, according to the research findings, which is in the K_{fs} range for silty soils rather than clay soils. It is unclear from where the CEN saturated hydraulic conductivity ranges have been derived. It should be noted that, in general, the correlation between K_{fs} as measured using a constant head permeameter in the Irish context and T-values (according to the Irish CoP test) obtained in this research gives conservative design estimates in the lower permeability range (see Table 5.7).

The K_{fs} ranges obtained using the Hydrus trendline were also compared with pedotransfer function estimates presented in the literature by Bormann (2010) and Saxton and Rawls (2006). Bormann (2010) developed a soil triangle outlining ranges of various soil hydrological parameters, including K_{sat} (Figure 5.15). The K_{sat} ranges in the triangle are in line with those predicted by the Hydrus trendline, as well as with the international ranges in Table 5.5. For example, in the Bormann triangle, according to BS 5930, CLAY (clay > 35%) has K_{sat} < 10 cm d^{-1}, SILT (silt > 35%) has K_{sat} < 10 cm d^{-1}, and SAND (silt and clay < 35%) has K_{sat} > approximately 50–100 cm d^{-1}, values that are in line with the ranges listed in Table 5.5.

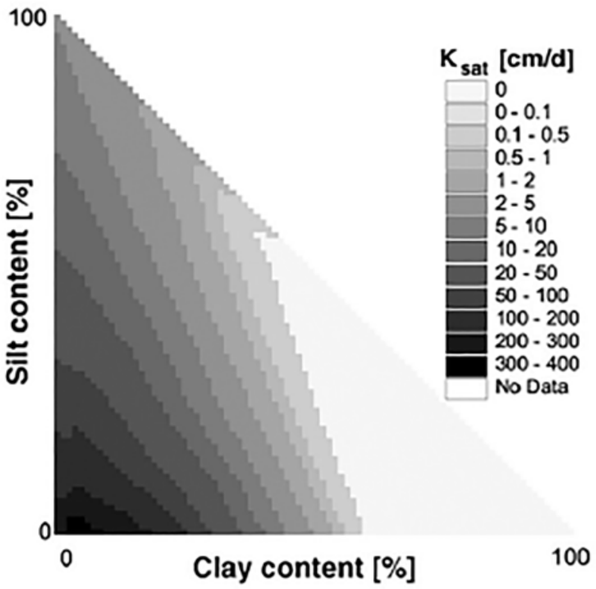


Figure 5.15. Spatial patterns of saturated hydraulic conductivity (K_{sat}) in a defined soil grid (showing % silt and clay) covering all soil texture classes. For each 1% grid point, a virtual soil column was defined and K_{sat} was calculated by applying the pedotransfer function of Rawls and Brakensiek (1985) (Bormann, 2010).

Saxton and Rawls (2006) predicted saturated hydraulic conductivities for the USDA soil texture classes as outlined in Table 5.6, and the equivalent BS 5930 soil texture categories have been added. These K_{fs} ranges are similar to those predicted by the Hydrus model trendline from estimated T-values for the SILT, SILT/CLAY and CLAY categories. For sandy loam, which is at the lower limit of sand content required for SAND under BS 5930 (i.e. 65% sand), the estimated K_{sat} is 120.7 cm d^{-1} compared with approximately 62 cm d^{-1} predicted by the Hydrus model for the upper limit of SAND using the Gill (2017) T-value estimate. The value of 120.7 cm d^{-1} for 65% sand is closer, however, to K_{sat} obtained when the Hydrus model trendline is used to convert the T-value threshold of 3 min 25 mm^{-1} in the Irish CoP (2021) to give 102.7 cm d^{-1} (see Table 5.7).

It is important to note that soil texture alone is not enough to predict saturated hydraulic conductivity, and other factors, such as the density or degree of consolidation of the soil and the soil structure indicative of pore space between soil peds, have a very significant impact on permeability (e.g. Pachepsky and Park, 2015; MacDonald *et al*. 2012; Saxton and Rawls, 2006). In addition, it should be noted that where international standards provide both K_{fs} and T-value ranges for soil categories, these are presented not as equivalent values but as estimated K_{fs} and T-value ranges based on field experience and pedotransfer function estimations (which take numerous soil properties into account for K_{sat} estimation purposes).

Finally, Table 5.7 shows the K_{fs} values calculated by the Hydrus model using the current T-value thresholds (now called percolation values (PVs)) in the new Irish CoP (2021) to provide more context to the important ranges, particularly at lower permeability. These K_{fs} values can be determined in the field using

Table 5.6. K_{sat} (cm d^{-1}) estimated for various USDA soil categories, with sand and clay content defined and equivalent BS 5930 soil texture categories included (adapted from Saxton and Rawls, 2006)

USDA category	K_{sat} (cm d^{-1})	Sand (%)	Clay (%)	BS 5930 category
Sand	259.4	88	5	SAND
Loamy sand	232.1	80	5	SAND
Sandy loam	120.7	65	10	SAND
Loam	37.2	40	20	SILT
Silt loam	38.6	20	15	SILT
Silt	52.8	10	5	SILT
Sandy clay loam	27.1	60	25	SILT/CLAY
Clay loam	10.3	30	35	CLAY, SILT, SILT/CLAY
Silt clay loam	13.7	10	35	SILT, SILT/CLAY
Silt clay	8.9	10	45	CLAY, SILT, SILT/CLAY
Sandy clay	3.4	50	40	CLAY
Clay	2.6	25	50	CLAY

Table 5.7. New percolation value (PV) ranges in the CoP (2021) and corresponding K_{fs} with respect to on-site assessment

Percolation test result at point of infiltration, PV	Corresponding K_{fs} (cm d^{-1}) calculated from $K_{fs} = 3015 \times \text{T-value}^{-0.98}$	Implication for DWWTS design
$PV < 3$	$K_{fs} > 102.7$	The retention time in the soil and/or subsoil is too short to provide satisfactory treatment Site improvement works comprising importation of soil and/or subsoil with a slower percolation rate and installation of a suitable DWWTS could be considered Discharge to surface water may be an alternative but requires a Water Pollution Act licence from the local authority
$3 \leq PV \leq 50$	$6.5 \leq K_{fs} \leq 102.7$	Suitable for a septic tank and percolation area and all secondary/tertiary treatment systems with soil percolation
$50 \leq PV \leq 75$ (if installed at the surface, the subsurface PV must be 3–90)	$4.4 \leq K_{fs} \leq 6.5$ (if installed at the surface, the subsurface K_{fs} must be 102.7–3.7)	Not suitable for a septic tank and percolation area Secondary treatment system and soil polishing filter: pumped or underlying gravity discharge (options 1 and 2) or gravity discharge, 500-mm-wide trenches (option 3) or low-pressure pipe (option 4) or drip-dispersal systems (option 5) Tertiary treatment system and infiltration area
$75 \leq PV \leq 90$	$3.7 \leq K_{fs} \leq 4.4$	Secondary treatment system and soil polishing filter: low-pressure pipe, 300-mm-wide trenches (option 4) or drip-dispersal system (option 5).
$90 \leq PV \leq 120$	$2.8 \leq K_{fs} \leq 3.7$	Secondary treatment system and soil polishing filter: drip-dispersal system (option 5)
$PV > 120$	$K_{fs} < 2.8$	Site is unsuitable for a DWWTS discharging to ground Discharge to surface water may be an alternative but requires a Water Pollution Act licence from the local authority

a constant head percolation test with the Reynolds (2008) equation (see section 3.3). The parallel field tests are placed into the CoP assessment categories in Table 5.8, which shows that the K_{fs} thresholds are more conservative than the T-value categories in the lower permeability range.

Mulqueen and Rodgers (2001) estimated that the K_{fs} range for soils suitable for a septic tank absorption system in Ireland could be in the range 8–200 cm d^{-1} (80–2000 mm d^{-1}) but that further research was required to confirm this. This is not far off the range suggested from the combination of field testing and modelling set out in this report (6.5–103 cm d^{-1}), although the upper permeability limit estimated by the Hydrus model is lower.

Finally, the two main weaknesses of the model are the limited accuracy of conversion between USDA soil texture classifications (used in Hydrus software) and BS 5930 soil texture categories, and the difficulty in carrying out parallel falling head and constant head field tests across the full range of soil textures and permeabilities in the context of CoP thresholds (Table 5.7). However, despite these limitations, positive conclusions can be drawn from the efforts to validate the Hydrus 2D model trendline as a method for comparing K_{fs} and T-value in the Irish context. When comparing the model trendline with (1) parallel constant head and falling head field tests, (2) other PT–K_{fs} correlations and (3) international ranges for K_{fs} according to soil texture category, the model did not deviate widely in any of these categories and in most cases was within range. Across the lower K_{fs} (lower permeability) range, which is generally of most concern for site assessment, the model appears to be within expected limits. It should also be highlighted that the K_{fs} and T-value ranges in many international standards are often based on a combination of field experience and PTF estimates due to the difficulty in carrying out in-situ tests across the range of soil textures and structures.

Table 5.8. Parallel field test results placed into CoP assessment categories (as shown in Table 5.7) based on measured T-values and K_{fs}

Site location	Reynolds (2008) a., K_{fs} (cm d^{-1})	Standard T-test, T-value (min 25 mm^{-1})	Modified T-test, T-value (min 25 mm^{-1})	T-test result placed in CoP assessment ranges	K_{fs} results placed in CoP assessment ranges as outlined in Table 5.7
Cork 1 (2015)	21.9	15.0	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Dublin 1 (2016)	0.9	Fail	Fail	Unsuitable for DWWTSs	Unsuitable for DWWTSs
Dublin 2 (2016)	2.6	Fail	Fail	Unsuitable for DWWTSs	Unsuitable for DWWTSs
Dublin 3 (2021)	20.9	12.6	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Dublin 4 (2021)	2.8	–	84.5	Secondary treatment system and soil polishing filter: low-pressure pipe, 300-mm-wide trenches (option 4)	Secondary treatment system and soil polishing filter: drip-dispersal system (option 5)
Kildare 1 (2017)	5.0	54.0	–	Suitable for a septic tank and percolation area	Secondary treatment system and soil polishing filter: pumped or underlying gravity discharge (options 1 and 2) Gravity discharge, 500-mm-wide trenches (option 3) Tertiary treatment system and infiltration area
Kildare 2 (2020)	3.8	62.0	–	Secondary treatment system and soil polishing filter: pumped or underlying gravity discharge (options 1 and 2) Gravity discharge, 500-mm-wide trenches (option 3) Tertiary treatment system and infiltration area	Secondary treatment system and soil polishing filter: low-pressure pipe, 300-mm-wide trenches (option 4)
Limerick 1 (2015)	8.7	35.9	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Limerick 2 (2015)	13.1	13.3	12.6	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Limerick 3 (2016)	21.1	13.3	12.6	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Limerick 4 (2016)	13.6	13.3	12.6	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Limerick 5 (2021)	4.6	74.9	–	Suitable for a septic tank and percolation area	Secondary treatment system and soil polishing filter: pumped or underlying gravity discharge (options 1 and 2) Gravity discharge, 500-mm-wide trenches (option 3) Tertiary treatment system and infiltration area
Limerick 6 (2021)	2.2	92.6	–	Secondary treatment system and soil polishing filter: drip-dispersal system (option 5)	Unsuitable for DWWTSs
Louth 1 (2016)	0.4	Fail	Fail	Unsuitable for DWWTS	Unsuitable for DWWTSs
Meath 1 (2017)	7.5	41.0	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Meath 2 (2017)	12.3	46.0	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area
Wicklow 1 (2020)	15.4	6.6	–	Suitable for a septic tank and percolation area	Suitable for a septic tank and percolation area

6 Conclusions and Recommendations

6.1 Conclusions

The findings of this research identify a need to revise or at least augment the options currently available in the Irish CoP for estimating soil permeability for on-site wastewater system design. This is based on the difficulty currently encountered in Ireland when conducting falling head percolation tests in less permeable soils (specifically the length of tests and the number of tests that fail at T-values > 90) and also the need to consider significant progress made in the area of soil science theory and permeability estimation internationally over the past several decades.

The main advantages of the falling head percolation test are its simplicity and the fact that valuable experience and expertise have been accumulated over years of carrying out these tests in Ireland. While these are very important considerations, a review of literature and design standards internationally, particularly in regions where significant research has been conducted into the area of STU performance and testing over a number of decades, shows that this test has significant limitations. At best, it can provide a useful complement to other, more rigorous permeability estimation methods, but it should not be used as the only criterion for site suitability. This is mainly due to the result being tied to specific hole dimensions, the varying test (hydraulic head) conditions and the lack of standardisation of test methodology across jurisdictions and the result metric, making the T-value obtained difficult to place in the context of international design thresholds.

The constant head well permeameter test is considered a better alternative internationally for in-situ testing because it gives a field saturated hydraulic conductivity value, K_{fs}, from inherently more controlled test conditions (than the falling head test), is independent with regard to hole dimensions and is the standard international method for measuring water transmission through soil. The constant head test is included in the Canadian Standards (2012), Australian/New Zealand Standard (2012) and European (EN 12566-2) Standard (2005). An important consideration, however, is that many design manuals and standards (USEPA, 2002; Australian/New Zealand Standard, 2012; Canadian Standards, 2012) now indicate that in-situ permeability tests should be used only as a complement to detailed site assessments, particularly for morphology analysis of soil texture, structure and consistency. This adds weight to the fact that in-situ tests should not be the only determining factor of site suitability and should not be used to override conclusions drawn from soil and site assessments. This is in part because of the variability observed from the results of such tests, particularly in more heterogeneous soils. Increasing the number of tests carried out can enhance accuracy and is a feasible option when using the constant head well permeameter test, as this is generally quicker to perform than the falling head test.

Design standards which emphasise soil texture and structure categorisation provide design hydraulic loadings for different soil categories. Indicative K_{sat} values may also be provided if comparison with an in-situ test is encouraged. The use of both an in-situ permeability test and a detailed soil assessment to determine soil permeability gives protection against inconsistent results from either method and is the approach taken in many jurisdictions (e.g. British Columbia, North Carolina). This point underlines the fact that no perfect method exists for soil permeability estimation and so results must always be placed in the context of wider site assessment, as well as local knowledge of soil behaviour where possible.

Hydrus 2D modelling in conjunction with a database of over 900 field tests carried out according to the falling head percolation test procedure outlined in the Irish CoP, as well as soil texture categorisation according to the BS 5930, was used to develop a correlation between K_{fs} and percolation time for the Irish context. The Hydrus 2D simulations produced a correlation of K_{fs} and T-values across a full range of Irish soil texture data, and the model trendline was found to fit with parallel falling head and constant head permeameter test results to a large degree, when K_{fs} was solved using the Reynolds (2008) solution with parameter values (i.e. α^*, Z_1, Z_2, Z_3) recommended for most soils. In addition, K_{fs} ranges predicted by the model based on T-values for GRAVEL, SAND, SILT, SILT/CLAY and CLAY, as suggested by Gill (2017), are within international ranges for low permeability soils (SILT, CLAY), but the model tends to predict lower K_{fs} for sands and gravels. This discrepancy may be due to differences in soil classification systems, particularly with the inclusion of SAND as defined by BS 5930 in some lower permeability groupings internationally.

The modelling process showed that the broad categories of the BS 5930 soil texture classification system (particularly GRAVEL, SAND and SILT) may be of limited use in predicting K_{fs}, as can be seen in comparison with other soil classification systems; international groupings of soils that are similar in hydraulic conductivity can, in some cases, include all BS 5930 soil texture categories. Focusing in particular on the fraction of fines present in soil is an important aspect of verifying K_{fs} measurements for SANDs and SILTs, as there is a high fines content in the Irish context.

At low permeabilities, the Hydrus 2D model trendline falls within international ranges for K_{fs}, as shown in Table 5.5. The choice of solution for K_{fs} is particularly important in this range of values, however, and Reynolds (2008) with parameter values (i.e. α^*, Z_1, Z_2, Z_3) recommended for most soils appears to agree best with model predictions. At very high permeabilities, the Reynolds parameters for coarse sands also give good results. In addition, the K_{fs} ranges predicted by the Hydrus model trendline are in good agreement with those estimated by applying PTFs across the range of soil textures (Bormann, 2010; Saxton and Rawls, 2006).

Given the range of comparisons conducted on the T-value–K_{fs} correlation produced from Hydrus modelling, it was concluded that the trendline can be used with a high degree of confidence to provide comparisons between T-values and K_{fs}, particularly for low permeability soils in the Irish context, and comparative threshold results for the constant head percolation test have been developed for the main limit falling head PVs, as specified in the current CoP.

6.2 Recommendations

Based on the findings of this research, the constant head permeameter test should be phased in initially as an additional option to the falling head test, particularly for low permeability soils, and, following a period of implementation, assessments could be made of whether the former should replace the latter. The constant head permeameter test is considered to be the most suitable in-situ test for on-site wastewater system design internationally. Workshops and/or training videos could assist site assessors to become comfortable with the operation of permeameters and specifically with important elements such as establishing the required borehole water depth and diameter and avoiding the effects of smearing when preparing the borehole. Comparison tables showing equivalent T-values for measured K_{fs} (based on the Hydrus modelling correlation) can provide context for the new hydraulic conductivity measurement scale and facilitate transition from the T-value scale to the more universal K_{fs} scale.

The findings of the project indicate that further research is needed on:

- The emphasis of soil categorisation assessment as a critical element of site assessment. This has become the primary recommended method for determining suitable hydraulic loading rates for STUs in many regions (USA, Canada, Australia/New Zealand), and in-situ permeability or percolation tests are considered to be a secondary check. While soil categorisation is already included in the Irish CoP (according to BS 5930), it is recommended that research be carried out to make this the critical determining factor in the conclusions of a site assessment, as opposed to the results of the falling head percolation test, as is current practice.

  In this regard, the BS 5930 soil texture classification (i.e. GRAVEL, SAND, SILT, CLAY, SILT/CLAY) currently used in the CoP is considered to provide insufficient refinement in terms of K_{fs} estimation. Further amendment of these categories in the CoP would be beneficial, particularly to catch soil categories with significant fines content (e.g. silty or clayey SAND), as well as including soil structure and consistency in the assessment. The possibility of switching to the USDA soil categorisation system (USDA, 2017) should be assessed, as this would provide more finely tuned and flexible categorisation of soil permeability. Furthermore, it is recommended that more research is carried out to evaluate a combined approach looking at texture, structure and density, which is considered the best method for K_{fs} estimation. Details of indicative K_{fs} values by soil category should be provided in the CoP, alongside indicative T-values.

- Establishment of a database and mapping of K_{fs} results from in-situ constant head permeameter tests across different Irish soil types. Many international standards use local soil maps as a further check in addition to in-situ tests and site assessments, and this is a feature which should be considered in the long term, as it would be very useful for both site assessors and local authority personnel. Further work to establish typical K_{fs} ranges in Irish soil categories is recommended; this could form part of long-term projects aimed at establishing comprehensive databases of soil types and associated K_{fs} ranges according to location (using geographical information system (GIS)), as has been done in many countries.

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Abbreviations

CoP	Code of Practice
dH/dz	Hydraulic gradient
DWWTS	Domestic wastewater treatment system
h	Pressure potential
H	Hydraulic head
K	Unsaturated hydraulic conductivity
K_{fs}	Field-saturated hydraulic conductivity
K_{sat}	Saturated hydraulic conductivity
LTAR	Long-term acceptance rate
PT	Percolation time (US/Canada)
PTF	Pedotransfer function
PV	Percolation value
q	Flux density
Q	Volumetric flow
r	Radius
S	Soil water storage
STU	Soil treatment unit
T-value	T-value (Ireland)
USDA	US Department of Agriculture
z	Gravitational potential
ψ_m	Matric potential
Θ_g	Gravimetric moisture content
Θ_v	Volumetric moisture content

Appendix 1 Constant Head Permeameter Test Procedure

A number of brands of constant head permeameter (also called borehole permeameter) are available commercially. These permeameters generally consist of a Mariotte siphon or pressure regulator valve that maintains water at a constant level in a borehole and a water reservoir that allows measurement of the rate of water discharge into the soil. Each permeameter comes with specific instructions for its use which must be followed closely. A generic guide to constant head permeameter application in the field follows, but this must be used in conjunction with the permeameter's operating manual.

Preparing the Borehole

1. At least three percolation tests should be carried out in soil representative of the site, adjacent to but not within the proposed percolation area.
2. The boreholes should be augered to a depth in the soil horizon at which K_{fs} is to be measured, which should represent the base of the proposed percolation trenches. It is important to locate the measurement zone in the soil horizon of interest; measuring at soil horizon transitions could lead to inaccurate measurements and improper interpretations.
3. The borehole should be constructed to the required diameter using a screw-type or bucket auger as recommended by the permeameter manufacturer, ensuring minimal compaction or sidewall smearing when creating the borehole and removing the auger.
4. A nylon bottle brush (or similar tool) with a diameter similar to that of the hole should be used to gently brush the sides and bottom of the borehole to mitigate disturbance effects. Extract the minor debris created by brushing, taking care not to touch the sidewall.
5. Dry to moist soil is required for representative results (i.e. the soil should be at field capacity or drier). Measurements should not be conducted under saturated or nearly saturated conditions, which introduce unaccounted water volume into the test and increase compaction and smearing.

Steady State Measurements

6. Set up the permeameter in the borehole in accordance with the manufacturer's instructions.
7. Record the depth and diameter of the borehole, as well as all required water reservoir measurements in accordance with the manufacturer's instructions.
8. Open the reservoir valve to allow water to flow into the borehole and establish a constant head of water. Depending on the borehole dimensions and the soil permeability, it may take between under one minute and several minutes until a constant water head is established.
9. Start to record the rate of discharge from the water reservoir into the borehole at the time intervals outlined in the manufacturer's instructions. In general, measure and record at intervals of 15 minutes (or when at least 100 cm^3 of water has flowed into the soil) for a minimum run time of one hour or until steady state is achieved. The achievement of steady state may take longer (1–2 hours) in higher permeability soils.
10. Steady state equilibrium is achieved when the change in discharge rate is less than 10% of the median value for three consecutive discharge readings. Alternatively, the flow rate should reach a quasi-steady state condition during which it varies around an average value. To determine this average, plot the rate of water flow (or the calculated K_{fs} values) against the time and pass a smooth curve through them using a manually or mathematically best-fitting curve. Steady state flow is reached if the tail end of this curve is nearly horizontal and does not indicate an upwards or downwards trend.
11. The geometric mean infiltration volume for the last three to five measurements after steady state has been reached is used to calculate K_{fs}. (K_{fs} is not normally distributed and so the geometric mean of steady state flow rate measurements must be used for calculations. For example, the geometric mean of the number set {1,2,3,4,5} would be as follows: $\sqrt[5]{1 \times 2 \times 3 \times 4 \times 5} = 2.61$.)

Table A1.1. Texture–structure classifications with corresponding α* and Z-constants. Soil sorptive number (α* in cm^{-1}) and borehole shape function (C) parameters (Z_1, Z_2, Z_3) are for a range of normally consolidated soils where the ratio of steady ponding depth (H) to borehole radius (r) is ≤20 (Reynolds *et al.*, 2015)

Soil group	Soil texture/structure category	α*(cm^{-1})	Z_1 (-)	Z_2 (-)	Z_3 (-)
I	This group includes soils which are both fine textured (clayey) and unstructured. This includes very low permeability clay soils	0.04	1.992	0.091	0.683
II	This group is the first choice for most soils. It includes structured clays and silts and unstructured medium and fine sands	0.12	2.074	0.093	0.754
III	This group includes coarse and gravelly sands; it may also include some highly structured fine soils with large cracks and/or macropores	0.36	2.074	0.093	0.754

Converting Borehole Discharge Rate to Field-Saturated Hydraulic Conductivity

The saturated conductivity of a soil under steady flow from a borehole can be described using the following equation (Reynolds, 2008):

$$K_{fs} = \frac{CQ}{(2\pi H^2 + C\pi r^2 + 2\pi H\alpha^{*-1})} \qquad \text{(A1.1)}$$

where Q is the steady discharge out of the borehole and into the soil (cm^3 minute^{-1}),

α* is the soil sorptive number for ponded infiltration (cm^{-1}),

H is the steady water head (ponding depth) in the borehole (cm),

r is the borehole radius (cm), and

C is a borehole shape function (-).

C is defined as (Reynolds, 2008; Zhang *et al.*, 1998):

$$C = \left[\frac{(H/r)}{Z_1 + Z_2(H/r)}\right]^{Z_3} \qquad \text{(A1.2)}$$

where Z_1, Z_2 and Z_3 are dimensionless empirical constants obtained for specified soil capillarity as shown in Table A.1. The value of α* can be estimated using the texture–structure classifications shown in Table A.1, provided that the soil is at field capacity or drier.

Placing K_{fs} within CoP Design Thresholds

The calculated K_{fs} (and associated PV) can be placed within existing CoP PV thresholds using the values in Table 5.7 (in main report). For example, a soil with $K_{fs} = 3.52\,\text{cm}\,\text{d}^{-1}$ would be considered suitable only for a secondary treatment system discharging via a tertiary drip dispersal system ($2.8 \leq K_{fs} \leq 3.7$).

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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