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Raingarden hydraulic conditions and functioning under variable precipitation scenarios

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ABSTRACT

Stormwater can have several serious impacts on public health, infrastructure and landscape of cities. Two of the main negative impacts of urban stormwater are floods and water pollution. Raingardens are bio-retention systems where water and contaminants are retained due to infiltration into a filter media and temporary storage as surface water. The filter medium could be a natural or mixed soil (sandy + natural) that infiltrates and treat the stormwater. The raingarden vegetation will also help retain water and improve the water quality. Hence achieving a combination of the two important local stormwater management objectives peak flow reduction and water quality improvement. This study investigate a raingarden hydraulic conditions and functioning combined with modelling its functionality under variable precipitation scenarios.

The experimental raingarden is situated in the middle of the campus of the Norwegian University of Life Sciences, As, Norway. To quantify the hydrological performance and processes in the raingarden, recharge area was calculated, soil infiltration was measured with double ring infiltrometer before and after planting, and soil samples were collected to perform lab measurements of permeability, grain size distribution, organic carbon content, cation exchange capacity and water retention curve. Based on the physical description of the raingarden, the hydraulic processes were modelled with a numerical model for unsaturated and saturated flow.

The composition of the raingarden mixed soil samples produced a loamy sand texture with saturated hydraulic conductivity values according to the requirements from the different international and national recommendations. The CEC properties of the raingarden allows plant production and indicates the mixed soils have good clay content and OM presence, with high water holding capacity. The original raingarden design was compared with two modified versions under two different flow scenarios. Results suggest a good performance in terms of the retention time of potential pollutants, and in fluid mass reduction.

- **KEY WORDS:** Raingarden, modelling, hydraulic properties, stormwater runoff.

PREFACE & ACKNOWLEDGEMENTS

This thesis was submitted in fulfilment of the requirements for the degree of Master of Science (MSc) in Environment & Natural Resources, with specialization in Sustainable Water, Sanitation, Health and Development.

Many people have contributed to complete this thesis and I would like to thank every one of them:

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- But above all, thanks to God, to my wife and my little son. Thanks for your love, your support and for be always there. You are the reason of my life, that motivates me to be a better person and a blessing for others. I love you with everlasting love.

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LIST OF ABBREVIATIONS

- LID low impact development
- SUDS Sustainable urban drainage systems
- WSUD water sensitive urban design
- BMPs best management practices
- NO_3 nitrate
- N_20 nitrous oxide
- N_2 nitrogen gas
- TSS Total Suspended Solids
- SUTRA saturated-unsaturated transport
- NMBU Norwegian University of Life Sciences

- DRI double ring infiltrometer
- TOC total organic carbon
- OM organic matter
- BD bulk density
- DM dry matter
- MS mineral soil
- WRC water retention curve
- ET evapotranspiration
- CEC cation exchange capacity
- IDF curve of intensity, duration and frequency
- RT retention time

1. INTRODUCTION

1.1. Background

Stormwater is a term used to describe water that originates during precipitation events and snow/ice melt (USEPA, 2012). Stormwater surface runoff is the fraction of the stormwater that “runs off” across the land instead of infiltrating into the ground. In natural ground cover environments, the soil absorbs much of the stormwater, some fraction is evapotranspirated and another becomes runoff that usually flows into the nearest stream, river, or other water bodies (IWA, 2010). However, in urban areas, impervious cover surfaces (e.g. roads, parking lots, and building rooftops and compacted soils) prevent precipitation events and snow melting from naturally evapotranspiration and infiltration into the ground. Instead, most of the water become runoff that and runs rapidly into storm drains, sewer systems, and drainage ditches (IWA, 2010; USEPA, 2012) (Figure 1).

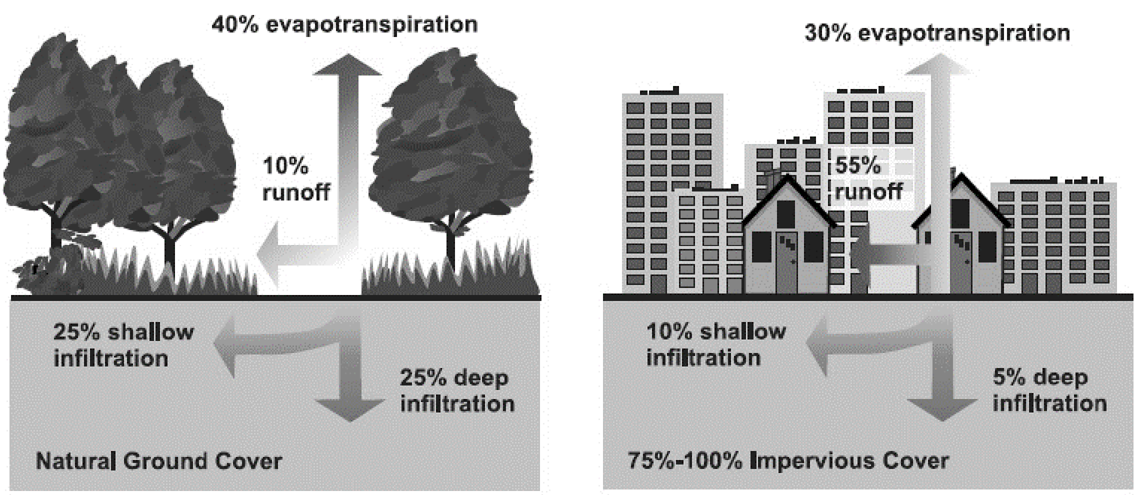


Figure 1. Natural & impervious cover. (USEPA, 2012)

The storm water has some serious impacts on public health, water ecosystems, infrastructure and landscape of the cities if it is not properly treated and managed. The severity of the damages depends on stormwater constituents and the flow rate. The two main issues related with unmanaged stormwater surface runoff are floods and water pollution. The first one due to the increase of the volume and timing of runoff water, and the second one, due to potential contaminants that the water is carrying (IWA, 2010; Paus, 2015; USEPA, 2012)

Floods. The stormwater surface runoff can cause flooding after the stormwater collection system is overloaded by the additional flow. The amount of stormwater runoff is therefore related to the amount of rainfall precipitation, and the nature of surfaces, with impervious surfaces producing more run-off. As the figure 2 shows, during a storm event the peak flow is higher and duration shorter with an impervious surface, while the peak flow is lower and duration longer with a natural surface. For many parts of the world, including Norway, these challenges become even more severe as the outcomes of climate change is expected to result in greater rainfall amounts and higher intensities (Kundzewicz et al., 2007; Paus, 2015; Stocker et al., 2013).

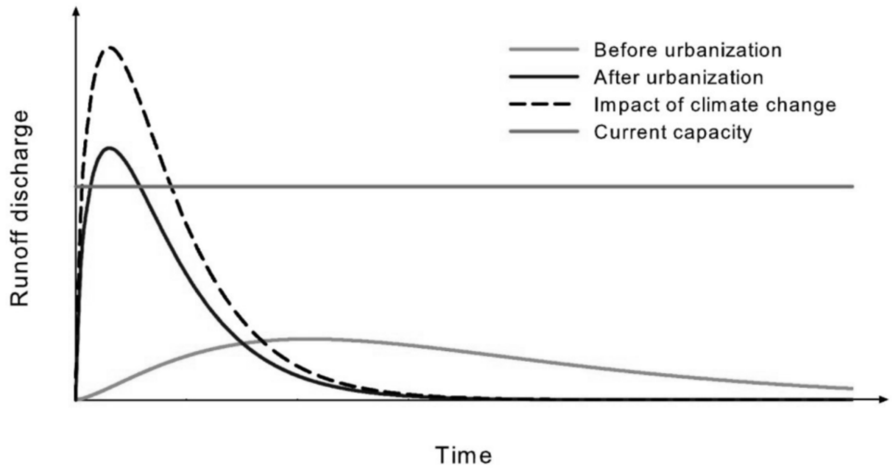


Figure 2. Effects of urbanization and expected outcomes of climate change on the runoff hydrographs (Paus, 2015).

Water pollution. Daily human activities result in deposition of pollutants on roads, lawns, roofs, farm fields, etc. On its way, stormwater surface runoff can pick up and carry many substance and ultimately makes its way to a surface or ground waterbody, polluting the water. While there is some attenuation of these pollutants before entering the receiving waters, the quantity of human activity, results in large quantities of pollutants affecting these receiving waters (Davis, Hunt, Traver, & Clar, 2009; IWA, 2010). A first flush is the initial runoff of a rainstorm. During this phase, polluted water entering storm drains in areas with high proportions of impervious surfaces is typically more concentrated compared to the remainder of the storm. Consequently these high concentrations of urban runoff result in high levels of pollutants discharged from storm sewers to surface waters (Maestre & Pitt, 2005; Metcalf & Eddy, 1935). The stormwater surface runoff, especially in urban areas, constitutes with different types of pollutants like nitrogen, phosphorous, oil and grease, heavy metals, total suspended solids and pathogens among others (Davis et al., 2009).

Other impacts related with storm water surface runoff are: Streambank erosion, increased turbidity from erosion, habitat destruction, changes in the stream flow hydrograph, combined sewer overflows and infrastructure damage (USEPA, 2012).

Given the increase in urbanization worldwide, climate change and the impact of urban stormwater (surface runoff) on both humans and aquatic ecosystems, the management of urban drainage is a critically important challenge (Fletcher et al., 2015). During the last decades, there have been developed different terms that address the urban stormwater management (Fletcher et al., 2015). Some of these terms are “low impact development (LID)”, “sustainable urban drainage systems (SUDS)”, “water sensitive urban design (WSUD)” and “best management practices (BMPs)” (Fletcher et al., 2015). Some of the different techniques or practices used are rain gardens (bioretention facilities), curb and gutter elimination, grassed swales, green parking design, infiltration trenches, inlet protection devices, permeable pavement, permeable pavers, rain barrels and cisterns, riparian buffers, sand and organic filters, soil amendments, stormwater planters, tree box filters, vegetated filter strips and vegetated roofs (USEPA, 2012).

Raingardens, also called biorretention cells or biofilters, are vegetative infiltration based stormwater practices that seek to control stormwater quantity and quality locally at the source where the stormwater originates (Paus, 2015). By imitating a pre-developed hydrological regime, and by utilizing the innate physical, chemical and biological processes in soils and vegetation to remove pollutants, raingardens represent a shift in philosophy from conventional stormwater management (Paus, 2015). The main objectives of a raingarden are peak flow reduction by retain stormwater surface runoff, improve the surface and groundwater quality by pollutants removal, channel protection (erosion control) and increase groundwater recharge and baseflow (Davis et al., 2009; Dietz & Clausen, 2006; Hunt, Davis, & Traver, 2011).

1.2. Problem statement

According to research conducted over the past years, both through laboratory and field studies, findings demonstrate that raingardens can decrease stormwater runoff volumes, reduce and delay discharge peaks via storage and infiltration (Davis, 2008; Li, Sharkey, Hunt, & Davis, 2009), and remove stormwater pollutants and thereby protect water quality (Davis, Shokouhian, Sharma, Minami, & Winogradoff, 2003; Davis et al., 2009; Roy-Poirier, Champagne, & Filion, 2010).

These results are very significant, however uncertainty surrounding different challenges are identified, especially, limited modelling work has been performed on raingardens and there is a need for a comprehensive model including both hydrologic and water quality processes. A need for a modelling tool that can compare and validate the appropriateness of current design guidelines is identified (Davis et al., 2009; Paus, 2015).

1.3. Objectives and research questions

In the campus of the Norwegian University of Life Sciences (Ås, Akershus, Norway), an experimental Raingarden, has been constructed in order to be the object of study of different departments and research groups.

The *main objective* of this study is to investigate the hydraulic conditions and functioning of a rain garden, combined with the modelling of its functionality under variable precipitation scenarios.

The *specific objectives* are:
- Quantify the hydraulic properties of the rain garden and processes performance
- Evaluate in the raingarden functioning in terms of saturation and concentration performance, the retention time of potential pollutants, and water mass balance under different flow scenarios.

The following are the *research questions* of this study:
- Are the raingarden hydrogeological properties according to the international recommendations or this kind of systems?
- Is the infiltration rate higher after the plantation than before it?
- What is the potential retention time for contaminants under different flow scenarios?
- What is the flow mass balance in the system?
- Which design adjustments can be done in the rain garden in order to improve its performance?

1.4. Structure of the Thesis

The "Introduction" presents a general description of the topic, the problem statement the aim of the study, and the structure of the thesis. The "Theoretical & Conceptual Framework" reviews the literature about raingardens facilities, main hydrogeological and treatment properties and processes, and modelling of the transport of flow and solutes in this kind of systems. The "Materials & Methods" presents the field work setup, lab experiments and modelling conducted. Then the "Results" are compared and discussed in relation to the objectives of the thesis. Finally, the main "Conclusions" based upon the major findings in the work are presented and also recommendations for future work.

2. THEORETICAL & CONCEPTUAL FRAMEWORK

2.1. Raingardens overview

Raingardens has rapidly become one of the most versatile and widely used techniques in stormwater management in many parts of the world (figure 3). The raingarden integrates different disciplines such as engineering, hydrology and hydraulics, surface and groundwater flow, soil science, horticulture and landscape architecture (Davis et al., 2009; Paus, 2015).

Figure 3. Rain Gardens in the world: a) Leominster, United States (USEPA, 2016). b) Oslo, Norway (Paus & BrasKerud, 2014). c) London, England (Bob, Gedge, Grant, & Leuthvilay, 2010). d) Melbourne, Australia (Melbourne Water, 2009).

Raingarden (figures 3 & 4) is a depression or a hole, with porous backfill, with a filter media normally consisting of sand, topsoil and leaf compost, under a vegetated surface, with robust plants capable of surviving both dry and wet conditions, that allows rainwater runoff the opportunity to be retained and treated; being an effective solution, especially in impervious urban areas where green space or natural ground cover is limited (Davis et al., 2009; Hunt et al., 2011). E.g. along roads, streets, parking lots, parks, private gardens, etc.

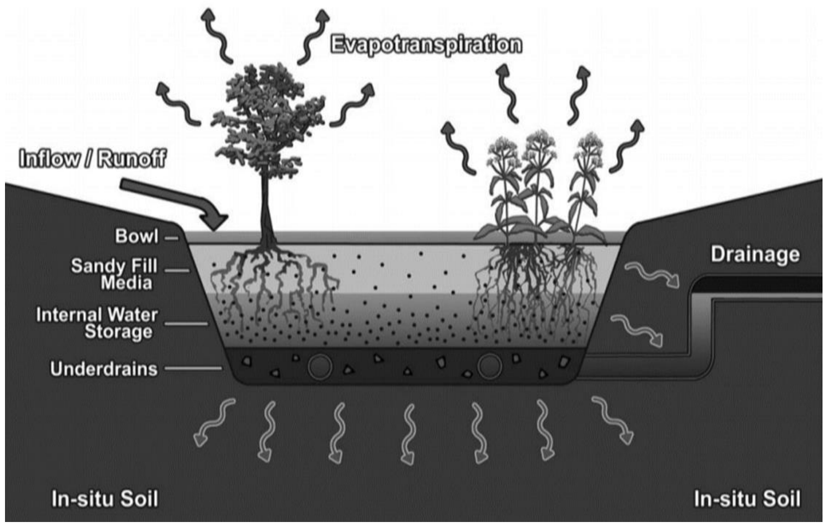


Figure 4. Cross section of raingarden. Adapted from Hunt, et al. *(2011)*

2.2. Raingardens design parameters

Raingardens can be placed, in small catchments. Based on design guidelines from the U.S. (The Prince George's County, 2007) it is recommended that the catchment area should not be greater than 0.8 ha., the slope of the terrain in close proximity to the cell is not too steep (5 %), and to be located at a proper distance from basements (8m) and from building foundations (1.5m) to prevent water damage on constructions below ground.

Bioretention guidelines recommend that the raingarden area should be between 5-10% of the size of the catchment area (Minnesota Stormwater Steering Committee, 2008). This ratio is considered somewhat conservative, therefore in some cases, according to Paus & BrasKerud (2014), it may be desirable to design the area with respect to specific requirements such as the size of the catchment area, the average runoff coefficient of the catchment area, the amount of precipitation that the cell must be able to manage, the maximum water level at the cell surface, the saturated hydraulic conductivity of the bioretention media and the duration of stormwater flow into the cell. Figure 5 illustrates the general design principles of a raingarden.

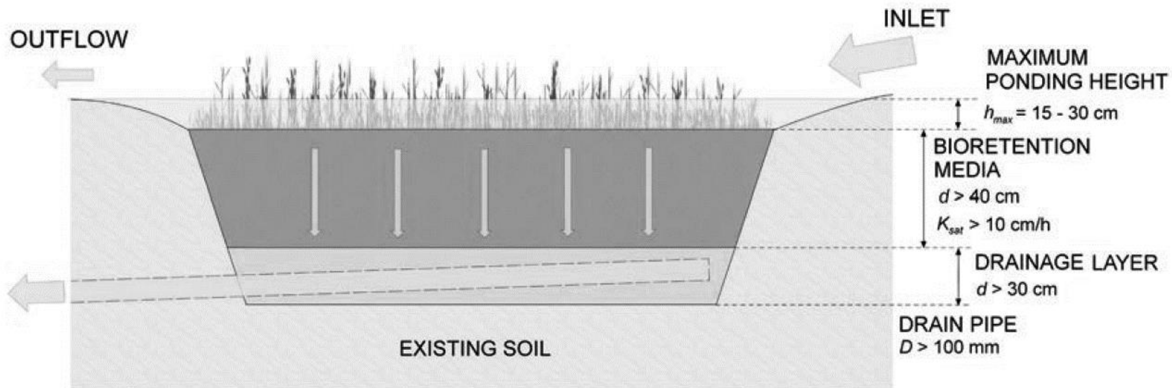


Figure 5. Principles of raingarden design (Paus & BrasKerud, 2014).

General features in the design of a raingarden include maximum ponding height depth, depth and composition of the bioretention media, a surface mulch layer, various forms of vegetation and associated appurtenances for inlet, outlet, and overflow. Depth of the media selection (0.7-1.2m) is according to the vegetation and to the type of pollutants to be treated (Davis et al., 2009).

Different design manuals (Lucas, 2005; Schueler & Claytor, 2000) allows maximum pounding depths of 30 or 45cm. Provided the fill media does not clog, deeper ponding depths may be reasonable, however as deeper pond depths are allowed, the need for bioretention maintenance increases (Davis et al., 2009).

The composition of soil of a raingarden is an important part to determine prior to its construction. Initial bioretention design specifications envisioned the use of natural soils with high permeability (Clar & Green, 1993). However, because of high clay content in these soils, several alternatives have been recommended, usually specifying mixes with high infiltration rates. E.g. in North Carolina, the media specified is 85–88% sand; 8–12% fines (clay+silt); and 3–5% organic material (Hunt & Lord, 2006).

Infiltration characteristics in the local soils determine if the raingarden must be drained and/or if the local soil can be used as bioretention media. It is recommended to use one or more perforated drain pipes with a minimum diameter of 100 mm. If the ground is well drained and has a high infiltration capacity (e.g., > 10 cm/h) infiltrated water will leave the cell through exfiltration, will recharge the groundwater and the existing soil may be used as bioretention media (Paus & BrasKerud, 2014). But if existing soils have a low infiltration capacity, drain pipes and a drainage layer (>30cm) are needed to drain the cell sufficiently between the storms. The drain pipes convey treated water to downstream stormwater systems or into receiving water bodies. If the inflowing runoff exceeds the hydraulic capacity of the cell, excessive runoff will leave the cell at the surface level.

Furthermore, the composition of soil affect the conditions for vegetation growth and the removal of pollutants in the water (Davis et al., 2009; Paus & BrasKerud, 2014).

Before the planting, the selection of the vegetation is an important decision. There are two possible planting strategies. First, it is using ornamental plants and garden plants which require maintenance or secondly, using local vegetation adapted to local conditions and climate (Paus & BrasKerud, 2014).

2.3. Raingarden treatment processes

Raingardens are generally well suited to handle the first runoff after rainfall (i.e., first flush) and will typically retain a wide range of contaminants from the water (Davis et al., 2009; LeFevre et al., 2014; Muthanna, 2007). Much of the literature available to manage the flow of the stormwater but less focus is on pollutants removal (Davis et al., 2009). In raingardens systems the polluted stormwater is treated through different types of processes (table 1) (Hatt, Fletcher, & Deletic, 2009; The Prince George's County, 2007).

Table 1. Major treatment processes that occur in Raingardens (The Prince George's County, 2007)

Process	Description
Settling/ Sedimentation	As the runoff slows and ponds within the raingarden area, particles and suspended solids will settle out. This process occurs on the surface of the raingarden, providing pretreatment before entering the filter medium.
Filtration	Particles are filtered from runoff as it moves through mulch and soil. In raingardens, filtration removes most particulates from runoff.
Assimilation	Plants taking in nutrients and using them for growth and other biological processes. Designers can select plants used in raingarden for their ability to assimilate certain kinds of pollutants.
Adsorption	The ionic attraction holding a liquid, gaseous, or dissolved substance to a solid’s surface. Humus, which can be found in raingardens with the breakdown of mulch and plant matter, adsorbs metals and nitrates.
Nitrification	Bacteria oxidize ammonia and ammonium ions to form nitrate (NO_3) a highly soluble form of nitrogen that is readily used by plants.
Denitrification	When soil oxygen is low, temperatures are high, and organic matter is plentiful, microorganisms reduce nitrate (NO_3) to volatile forms such as nitrous oxide (N_20) and Nitrogen gas (N_2), which return to the atmosphere.

Degradation	The breaking down of chemical compounds by microorganisms in the soil medium
Decomposition	The breakdown of organic compounds by the soil fauna and fungi.

The urban stormwater constitutes with different types of common pollutants like nitrogen, phosphorous, oil and grease, heavy metals, total suspended solids and pathogens (Davis et al., 2009). These pollutants are removed in raingardens by different treatment processes:

- Suspended Solids. The availability of suspended solids in the stormwater is one of the health indicators for the presence of organic matter, nutrients, heavy metals and other pollutants (Roy-Poirier et al., 2010). As a common practice, sedimentation and filtration are two methods to mechanically remove particulate matters and Total Suspended Solids (TSS) in raingardens (Hunt et al., 2011). A study from New Hampshire University demonstrate that 97% of TTS are removed through raingardens (Center, 2007).

- Nitrogen and Phosphorus. For the removal of nutrients the results have been variable, likely because of the complexity of the chemistry of these. In some instances very good removal has been documented, but in others, the treatment efficiency has been low (Davis et al., 2009). Generally, in the raingardens phosphorous is removed through the filtration of particulate bound P and the chemical sorption of dissolved P reaction (Hunt et al., 2011). For phosphorus removal, studies have shown 70–85% of phosphorus removal (Davis, Shokouhian, Sharma, & Minami, 2006; Davis, 2007). Nitrogen is removed through biological nitrification and denitrification. Total Kjeldahl nitrogen removal in box studies was good, at 55–65% (Davis et al., 2006). Since nitrate is an anion, it is generally not held back by soil and is generally quite mobile in soil-water systems. It appears, however, that biological nitrification and denitrification processes can take place in bioretention media, depending on design and operating conditions (Davis et al., 2009).

- Heavy Metals. Both dissolved and particulate bound metals appear to be very efficiently removed by raingardens (Davis et al., 2009). Through both filtration of particulate metals and adsorption of dissolved forms, most of the metal removal appears to occur in the upper surface layers of the media (Li & Davis, 2008). Laboratory and field data are available for copper, lead, and zinc, and some cadmium. Total metal concentrations exiting in raingardens are generally in the low µg/L (ppb) levels (Davis et al., 2003; Davis, 2007).

- Oil and Grease. The mulch lay in raingarden system is a sustainable hydrocarbon pollutants management resource. Laboratory studies have indicated that motor oil and two petroleum hydrocarbons, specifically, toluene and naphthalene, can be readily sorbed from incoming simulated stormwater flows by a layer of composted leaf mulch (Hong, Seagren, & Davis, 2006). The available bacteria can easily biodegrade the captured hydrocarbon pollutants in few days (Davis et al., 2009). Moreover, used motor oil was completely removed (96%) from stormwater runoff using bioretention columns with several mixes of media (Center, 2007; Hsieh, Davis, & Needelman, 2007).

- Pathogenic Bacteria. Filtration media is the primary mechanism that has been used in the raingardens through which microbes are strongly sorb to organic component and soil (Hunt et al., 2011). The raingardens removes most species of the bacteria due to its design to collect and filter water, and then dry out, exposing bacteria to dry conditions and sunlight. Initial studies in Charlotte, N.C., show significant reduction of indicator species. Fecal coliform and *E. coli* removal rates were approximately 70% (Hunt, Smith, Jadlocki, Hathaway, & Eubanks, 2008).

2.4. Raingarden modelling

Raingarden can be understood as a small scale groundwater system with saturated and unsaturated flow and with transport of solutes and energy.

Models are tools that represent or describe an approximation of a field situation, real system or natural phenomena. In hydrogeology, models can be classified based on their typical applications in a groundwater system (e.g. raingarden): groundwater flow models, solute transport models, heat transport models and deformation models (Igboekwe & Amos-Uhegbu, 2011). Groundwater flow models simulates the hydraulic behavior of the system such as the flow of water, changes in volume of water storage and changes in water levels or head (pressure). Solute transport models simulate the fate and transport of dissolved constituents (salts and contaminants) in groundwater (Maliva & Missimer, 2012).

Modelling begins with a conceptual understanding of the physical problem. In unsaturated groundwater flow processes are in general complicated and difficult to describe quantitatively since they often entail changes in the state and content of soil water during flow. The formulation and solution of these flow problems require the use of indirect methods of analysis, based on approximations or numerical techniques (numerical models). This is not an exact descriptions of the system but are mathematically representing a simplified version of it. This mathematical solution or calculation is referred to as simulations (Igboekwe & Amos-Uhegbu, 2011).

The governing groundwater flow equations define a mathematical or a numerical model. The entire model has usually the form of a set of partial differential equations, together with auxiliary conditions. The auxiliary conditions describe the system's geometry, the system parameters, the boundary conditions and also the initial conditions (Kumar, 2002).

The numerical simulation models are by far the most applied ones. Numerical methods are based on subdividing the flow region into finite segments bounded and represented by a series of nodal points at which a solution is obtained. This solution depends on the solution of the surroundings segments and on an appropriate set of auxiliary conditions. The methods most appropriate to the problem of soil water dynamics are finite different method, finite element method and boundary element method (Kumar, 2002).

Mathematical and numerical models consist of a governing equations and of initial and boundary conditions.

2.4.1. Raingarden governing flow equations

The water mass balance equation is:

$$\frac{(\varepsilon S_w)}{\partial t} + \nabla q = 0 \quad (1)$$

where ε is porosity [-], S_w is water saturation [-], t is time [T] and q is the specific flow or Darcy's velocity [L/T] (Domenico & Schwartz, 1998).

Darcy's law defines q as:

$$q = -\frac{k}{\mu}(\nabla p - \rho g) \quad (2)$$

where k is permeability [L^2], μ is liquid viscosity [M/LT], p is the liquid phase pressure [M/LT^2], ρ is liquid density [M/L^3] and g is gravity [L/T^2] (Domenico & Schwartz, 1998).

If $\left(\frac{k\rho g}{\mu} = K\right)$, then:

$$q = Q.A = -K * i \qquad \text{or} \qquad q = -K * \nabla H \quad (3,4)$$

where K is the saturated hydraulic conductivity [L/T] and i is the hydraulic gradient [], that is the change of the hydraulic head (Δh) along the distance (x), and ∇H represents the hydraulic gradient in three dimensions. Water will flow in the direction of the highest hydraulic gradient (Domenico & Schwartz, 1998).

Darcy's law can also be generalized in the case of an unsaturated (or partially saturated) flow, becoming the Richard's law. Unsaturated hydraulic conductivity *[$K_{unsat} = K(S_w) = K(\psi)$]* of a soil is a function of the degree of water saturation *(S_w),* which is itself a function of the pore pressure, matric potential or *(ψ)* or suction. The Richard's law generalizes the Darcy's law to the case of a partially saturated medium (Domenico & Schwartz, 1998). Therefore can be written:

$$q = -K(\psi) * \nabla H \tag{5}$$

Capillary pressure p^c is defined as:

$$p^c = p^a - p \tag{6}$$

where p^a is the air pressure, which is assumed to be constant and atmospheric.

The function which describes the variation of the volumetric content (S_w) with the suction (ψ) is the *Water Retention Curve (WRC*) (Domenico & Schwartz, 1998). To measure WRC several descriptive models exist in the literature to fit continuous functions on discrete experimental points. The most used and common models are the Brooks & Corey (1964) model, Gardner (1958) model, van Genuchten (1980) model and Fredlund & Xing (1994) model.

The dependency of capillary pressure and permeability on water saturation is taken from van Genuchten (1980) with the addition of a scaling parameter, a, to account for the heterogeneity of the hydraulic conductivities:

$$\frac{S_w - S_r}{1 - S_r} = \left[1 + \left(\frac{-ap^c}{\alpha}\right)^n\right]^{\frac{1-n}{n}} \tag{7}$$

and

$$k = \alpha^2 k_s \sqrt{\frac{S_w - S_r}{1 - S_r}} \left[1 - \left(1 - \left(\frac{S_w - S_r}{1 - S_r}\right)^{\frac{n}{n-1}}\right)^{\frac{n-1}{n}}\right]^2 \tag{8}$$

where k_s is saturated permeability, S_r is the residual water saturation [-], n and a are parameters [-], and α is a scaling parameter [-] (Warrick and Amoozegar-Fard, 1977).

2.4.2. Raingarden initial and boundary conditions

Initial conditions must be defined when transient soil water flow is modelled. Initial condition provides hydraulic head everywhere within the domain of interest before simulation begins. Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain. Three types of boundary conditions can be defined: Dirichlet, Neumann and Cauchy boundary conditions (Kumar, 2002; Maliva & Missimer, 2012).

In raingardens the main boundary conditions are Neumann. There it is possible to find recharge from the stormwater runoff and from precipitation, discharge from exfiltration, evapotranspiration and also through drainage on the bottom layer, and finally no-flow if the system is built over a membrane.

2.4.3. SUTRA Code

There are numerous computer codes for groundwater modelling available, such as MODFLOW (Harbaugh, 2005), SUTRA (Voss & Provost, 2010), MIKE-SHE (Refshaard, Storm, & Singh, 1995), FEFLOW (Diersch, 2005), COMSOL (COMSOL, 2012) and different graphical user interfaces (GUI) mess generators, such as GMSH (Geuzaine & Remacle, 2008), ModelMuse (Winston, 2009), ArgusOne (Voss, Boldt, & Shapiro, 1997).

SUTRA (Saturated-Unsaturated Transport) is a computer program that simulates fluid movement and the transport of either energy or dissolved substances in a subsurface environment. The code employs a 2D or 3D finite-element and finite-difference method to approximate the governing equations that describe the two interdependent processes that are simulated (Voss & Provost, 2010):

- Fluid-density-dependent saturated or unsaturated groundwater flow
- Transport of a solute or energy in the ground water
    - Transport of solute, in which the solute may be subject to equilibrium. Adsorption on the porous matrix, and both first-order and zero-order production or decay.
    - Transport of thermal energy in the ground water and solid matrix of the aquifer.

Specifically on raingardens, limited modelling work has been performed and there is a need for a comprehensive model including both hydrologic and water quality processes. A need for a modelling tool that can compare and validate the appropriateness of current design guidelines is identified (Davis et al., 2009; Paus, 2015).

3. METHODS

3.1. Study Design

This is a study with an experimental, descriptive and scenario modelling design. Where physical properties and hydraulic processes of an experimental raingarden are described, analysed and then modelled with a numerical model for unsaturated and saturated flow with the purpose to evaluate the raingarden functioning in terms saturation and concentration performance, the retention time (RT) of potential pollutants, and water mass balance under different flow scenarios.

3.2. Study Site

The experimental raingarden is situated in the municipality of Ås, Akershus county, Norway; right in the middle of the campus of the Norwegian University of Life Sciences (NMBU), behind the Tivoli building (NORAGRIC, Department of International Environment and Development Studies) (Figure 6).

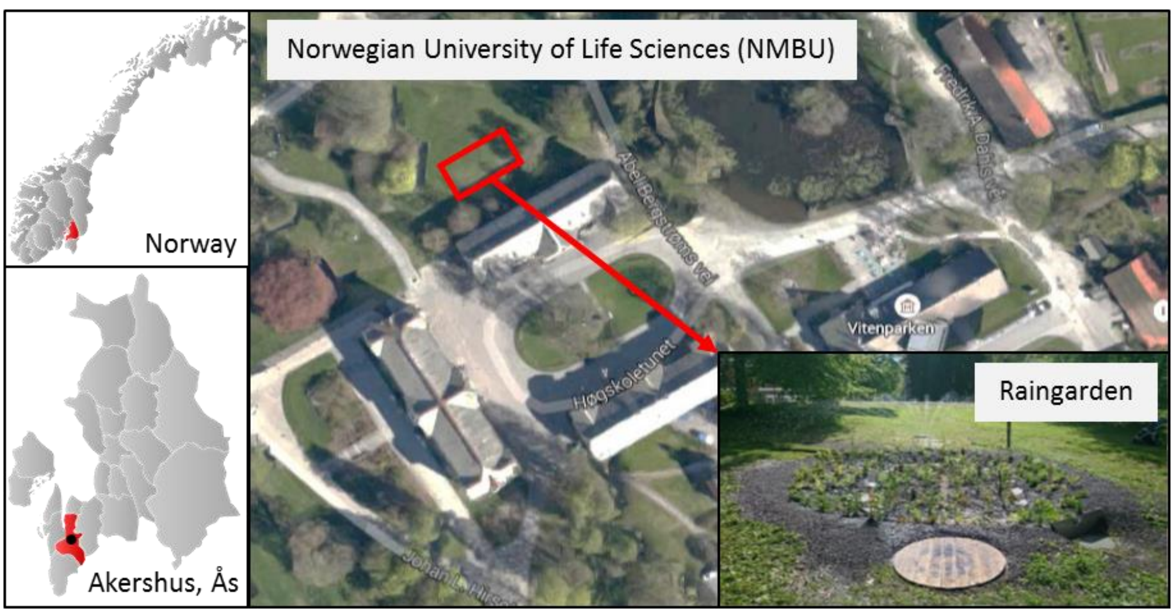


Figure 6. Location of the raingarden in NMBU, Ås, Akershus, Norway

Ås is located 35km south from Oslo, and is the largest agricultural municipality of Akershus, providing the region with grain, vegetables, and dairy products. Of the 100 km^2 of land in the municipality, about 39 km^2 are farmed and about 46 km^2 are forested (Ås Kommune, 2016). However, Ås is one of the fastest growing municipalities in Akershus, with a population of 18,503 in 2015, and a growth of 489 in 2016 (Statistisk sentralbyrå, 2016). The Norwegian Statistical bureau predicts a doubling of the number of inhabitants in Ås to over 30,000 residents in 2040, aiming to focus 75% of the growth in the central area, which in turn implies an increase in impervious surfaces (Ås Kommune, 2015).

3.2.1. NMBU Raingarden Background

The raingarden is part of a research project where four NMBU academic departments (Environmental Sciences, Plant Sciences, Mathematical Sciences and Technology, Landscape Architecture and Spatial Planning) and the technical section managing the university campus are collaborating together.

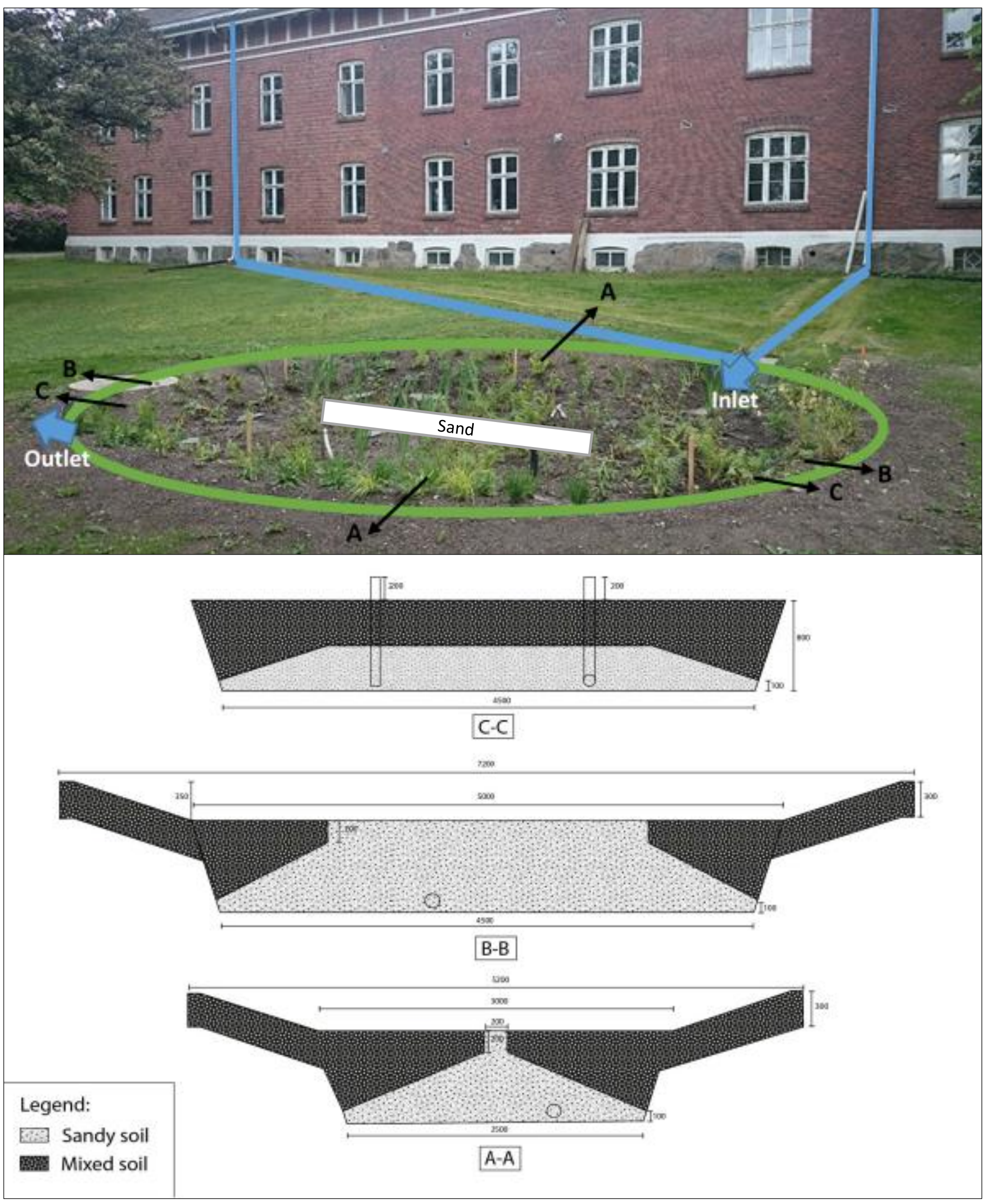


Figure 7. NMBU Raingarden Design: Area, roof drainage pipes and water inlet & outlet. Raingarden dimensions and type of media (Mixed soil and sandy soil). Cross sections: A-A, B-B and C-C

In the area, the infiltration capacity of the exiting soil was very low because of high clay content, so it was necessary to replace the existing soil. Two type of soils where located in the raingarden, a mixed soil (local soil, sand and compost) and a sandy soil (figure 7).

The dimension of the raingarden area is 35m^2, which is the 5% of the catchment area. The catchment area corresponds to one side of the Tivoli building roof plus the area between the roof drains. Other design parameters were 50 years of precipitation data, an estimated flow of 1.4 l/s, a standing water of less than 24 h. Additionally, stormwater runs through two roof open drainage pipes, with the following parameters:

- Total width of the gutter in meters = 0.24
- Depth in the trough in meters = 0.04
- Fall longitudinally m/m = 0.02
- The flow of water in the trough: 2.38 l/s

A membrane was included below this open drains in order not to lose too much of the roof water to deeper percolation.

The design of the NMBU raingarden is somehow different to other raingardens (figure 7). In this one, there is a sandy part along the entire base of the raingarden, as a drain layer, the sandy part is also extended to the surface in the central part of the raingarden area, this feature of the raingarden has been included to increase the infiltration conditions also during frozen conditions. The hypothesis is that the sandy part will help drain meltwater when the soil is frozen, because that larger grain and pore size will reduce the influence of ice in the winter season with frost, hence soil surface may be blocked by ice. Because full control of water in and out of the system is required, the outlet of the drain water runs through a manhole where the discharge can be measured over a V-notch.

Drainage pipe lines (diameter of pipe 8 cm) with some negative gradient are laid in the middle of the rain garden bed area (thickness of 10 cm) at an elevation of 90cm below ground surface level (figure 7).

The use of local vegetation expected to be able to adapt to the local conditions and climate were selected. The choice of plants in the raingarden should tolerate the cold conditions. Norwegian species such as *Athyrium Filix-femina, Filipendula Ulmaria, Iris Pseudacourus* and *Lysimachia Vulgaris* were planted (Appendix A).

3.3. Meteorological data

The Ås (NMBU) meteorological station is located in Ås municipality, 92m.a.s.l. It is the closest official weather station, 0.9 km away from Ås. The station was established in January 1874. The station measures precipitation, temperature and snow depths.

According to an online report from the Norwegian Meteorological Institute and the Norwegian Broadcasting Corporation (2016), of the weather statistics for Ås, in the 13 full months (Mar. 2015 – Mar. 2016) the highest temperature was 25.8 °C (5. Jul. 2015) and the lowest -22.1 °C (15. Jan. 2016); the highest daily precipitation was 76.4 mm (9. Jul. 2015), and the maximum snow depth was 24 cm (11. Jan. 2016)

Additionally, a curve of intensity, duration and frequency (IDF curve) from the precipitation data of NMBU weather station, has been plotted (figure 8) by Buhler (2013).

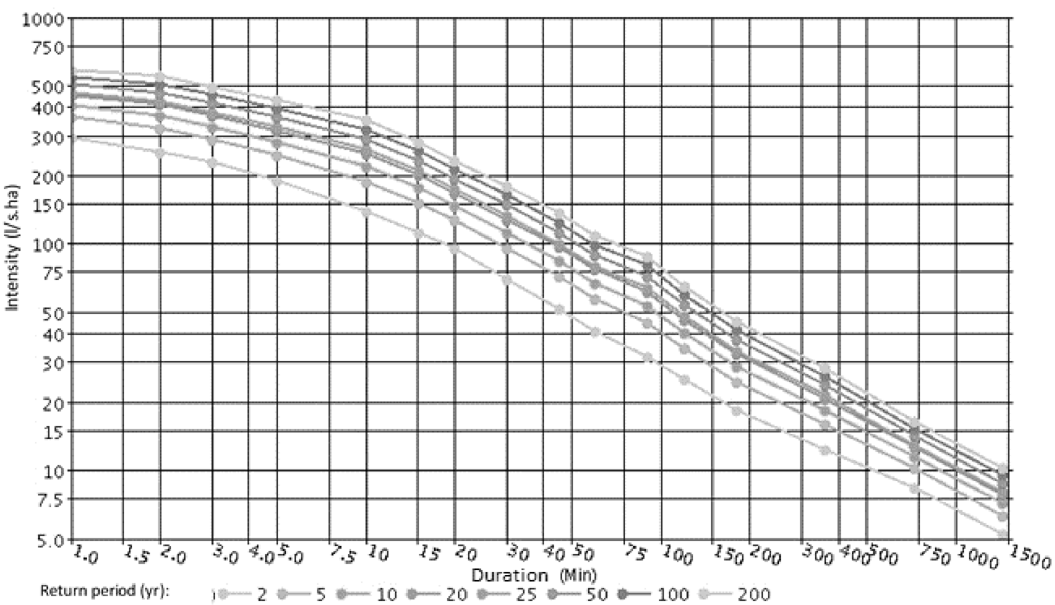


Figure 8. IDF curve from Ås weather station. Period: 1974 – 2013 (Buhler, 2013)

3.4. Field and Laboratory Methods

Laboratory and field methods will be used to map the hydrogeological properties of the NMBU Rain-garden. Based on the physical description of the raingarden, the hydraulic processes will be modeled with SUTRA v2.2. (Voss and Provost, 2010) a numerical model for unsaturated and saturated flow.

3.4.1. Soil Sampling & Field methods

3.4.1.1. Soil sampling

Different soil samples, both undisturbed and disturbed, were taken (figure 9) to make different lab measurements. The samples were taken before the planting of the raingarden.

Figure 9. Collection equipment and techniques of soil sampling

In the mixed soil, 35 samples were taken; 32 for the pF analysis and 3 (R0, R1 & R2) for the other analysis. In the sandy soil, 7 samples were taken; 4 for the pF analysis and 3 for other analysis (S1, S2 & S3) (Table 2 & Figures 10 & 11).

Table 2. Type of media, number of samples and lab analysis

Type of media	**Number of samples**	**Lab analysis**	**References**
Mixed Soil	3 samples	Permeameter - Orcanic Carbon - Grain Size Distribution (Dry sieving & Wet sieving methods) - CEC measurement	Van Reeuwijk, L. P. (1993); Richards (1947; 1948), Torstensson & Eriksson (1936); Schollenberger & Simon (1945)
	32 samples	pF analysis	
Sandy Soil	3 samples	Permeameter – Grain Size Distribution (Dry sieving method)	
	4 samples	pF analysis	

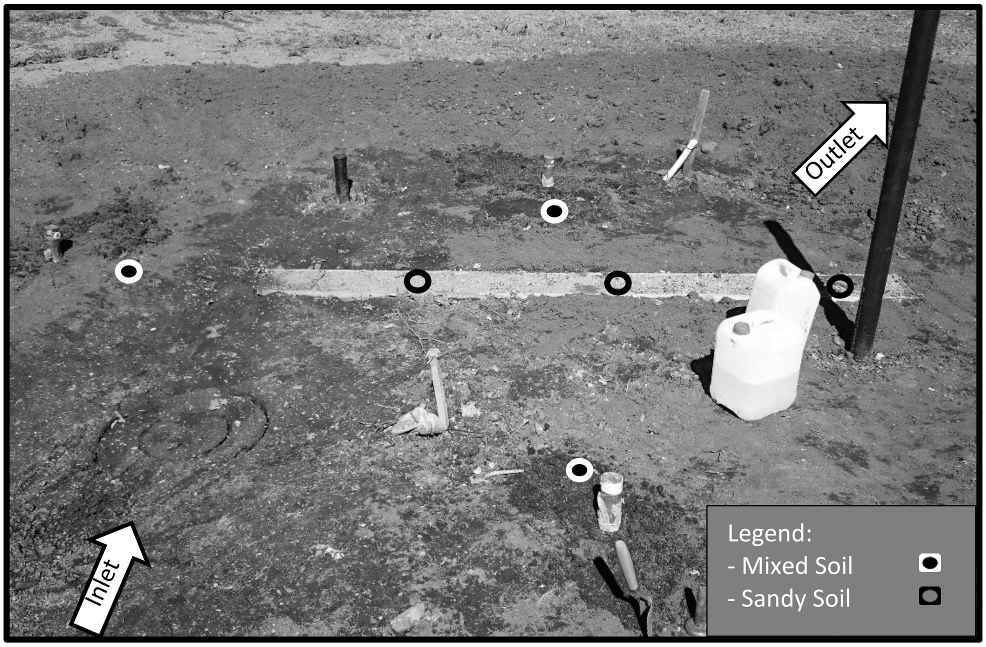


Figure 10. Locations of the collect of mixed soil samples (R0, R2 and R3) and sandy soil (S1, S2 and S3)

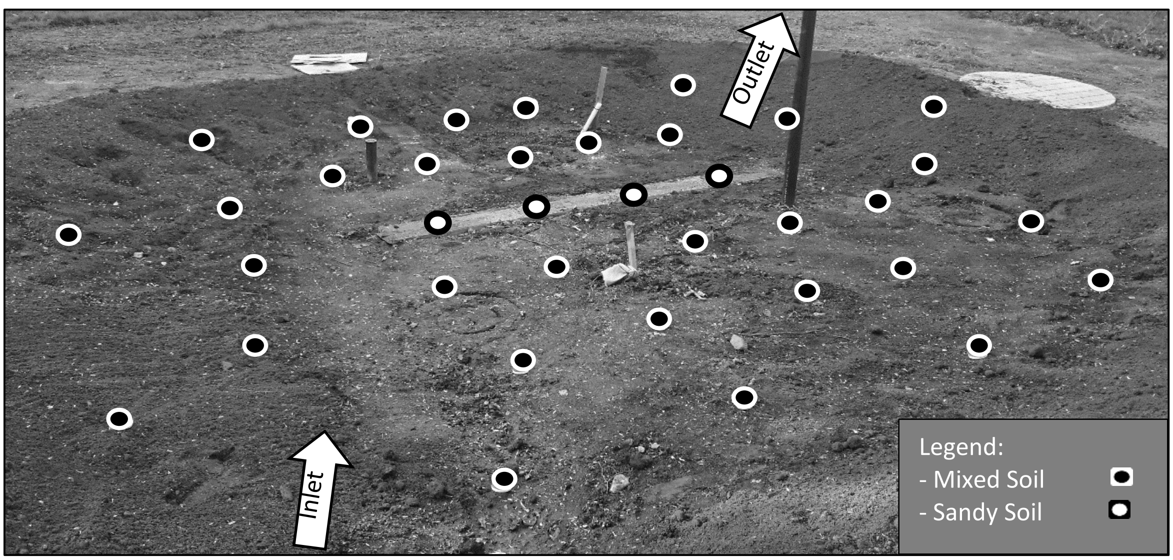


Figure 11. Locations of the collect of mixed soil and sand samples (n=36) for the pF analysis

3.4.1.2. Infiltration Tests

Infiltration is the process by which water on the ground surface enters the soil. Infiltration rate is the velocity or speed at which water enters into the soil. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. In dry soil, water infiltrates rapidly, this is called the initial infiltration rate. As more water replaces the air in the pores, the water from the soil surface infiltrates more slowly and eventually reaches a steady rate, this is called the basic infiltration rate or saturated hydraulic conductivity. The infiltration rate depends on soil texture and soil structure (table 3). The maximum rate that water can enter a soil in a given condition is the infiltration capacity (Brouwer, Prins, Kay, & Heibloem, 1988).

Table 3. Basic infiltration rates for various soil types (Brouwer et al., 1988)

Soil Type	**Basic infiltration rate**
	(mm/h)
Sand	< 30
Sandy loam	20 - 30
Loam	10 - 20
Clay loam	5 - 10
Clay	1 - 5

The most common method to measure the infiltration rate is by a field test using a cylinder or ring infiltrometer. Double ring infiltrometer (DRI) method (Figure 12) was used to measure the infiltration capacity of the mixed soil in the raingarden. DRI gives a measure of the onsite infiltration capacity. The principle of this method is to measure how fast a standing water table on the soil surface infiltrates the soil. This is done by measuring the water level at regular time intervals. With these data, the volume infiltrated (Δh) versus time (Δt) can be plotted hydraulic conductivity calculated. Normally this method should carried out when the soil is dry (Brouwer et al., 1988).

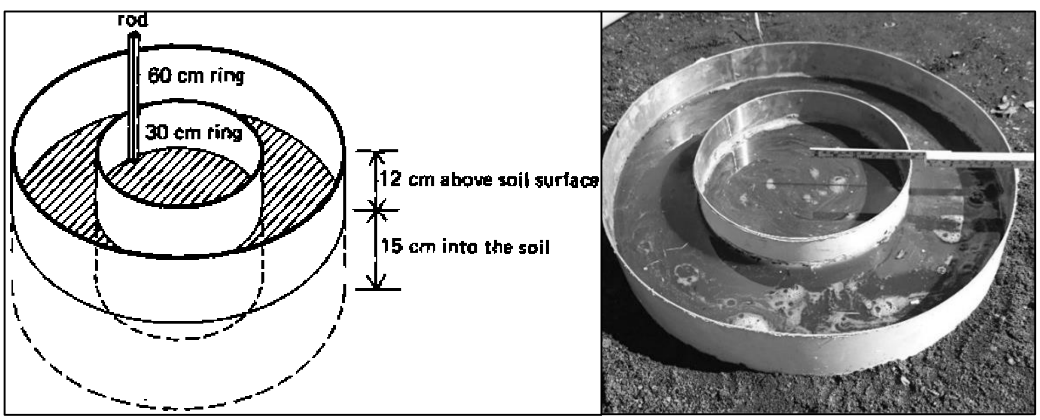


Figure 12. Diagram of the "Double ring infiltrometer" method (Brouwer et al., 1988).

Through this method it's possible to calculate the K_{sat}, using Darcy's law (equation 1):

$$K = \frac{Q}{A*i} = \frac{\cancel{A*}v}{\cancel{A*}i} = \frac{v}{\cancel{i}} \rightarrow \qquad K = v = \frac{\Delta h}{\Delta t} \tag{1}$$

where *v* is infiltration rate (speed of infiltration [L/T], I the hydraulic gradient (*i* = 1, between the rings) [], Δh is the cumulative infiltration [L], and Δt cumulative time [T]

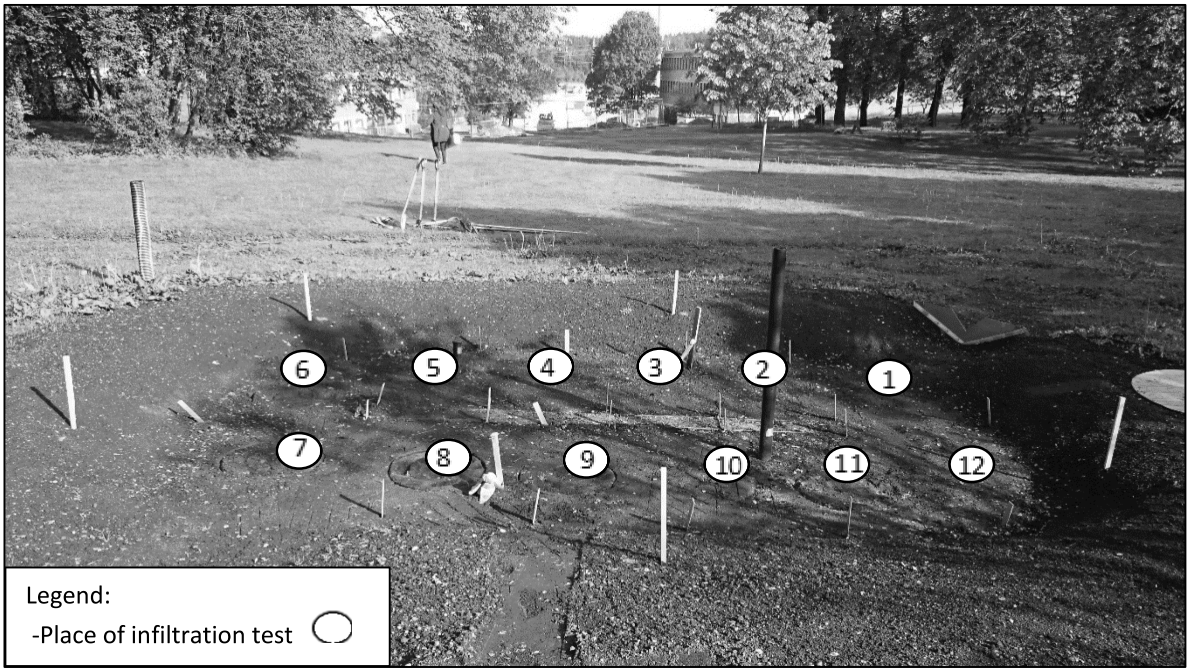


Figure 13. Places of infiltration test in the raingarden

The surface area of the raingarden was divided in 12 different plots, 4 different plant species were planted in the different plots, hence 3 replica for each plant. Twelve infiltration tests were carried out before the planting (Figure 13) and 12 before the planting.

3.4.2. Laboratory methods

3.4.2.1. Permeability tests

Permeability is a measure of a soil's or rock's ability to transmit a fluid, usually water. Soil permeability is determined by grain or pore size distribution, shape of grains or pores, tortuosity, specific surface and porosity. Water can permeate between granular void or pore spaces, and fractures between rocks (Fetter, 2000; Miller & Donahue, 1990).

Saturated hydraulic conductivity *(K_{sat})* simply assumes that water is the fluid moving through a soil or rock type. The size of pore space and interconnectivity of the spaces help determine K_{sat}. The larger the pore space, the more permeable the material. However, the more poorly sorted a sample (mixed grain sizes), the lower the permeability because the smaller grains fill the openings created by the larger grains (Fetter, 2000; Miller & Donahue, 1990). Table 4 show the soil permeability classification based on values of K_{sat}.

Table 4. Soil permeability classification (Btkov, Matula, & Mihlikov, 2013)

Permeability	K_{sat} (m/s)
Highly impermeable	> 10^{-10}
Impermeable	10^{-8} - 10^{-10}
Lowly (poorly) permeable	10^{-6} - 10^{-8}
Permeable	10^{-4} - 10^{-6}
Highly permeable	< 10^{-4}

The hydraulic conductivity of "undisturbed" soil can be measured with a permeameter. The box-permeameter (constant head) method (figure 14), used to characterize the top layer of the rain-garden, is a quick method for the determining the K_{sat}. By creating a difference in water pressure on both ends of a saturated soil sample and measuring the resulting flow of water, the K_{sat} was determined. For this method, six samples from the rain-garden were analyzed (figure 12); three sand samples (S1, S2 and S3) and three samples from the mixed soil (R0, R2, R3). For each sample, the same test was done twice.

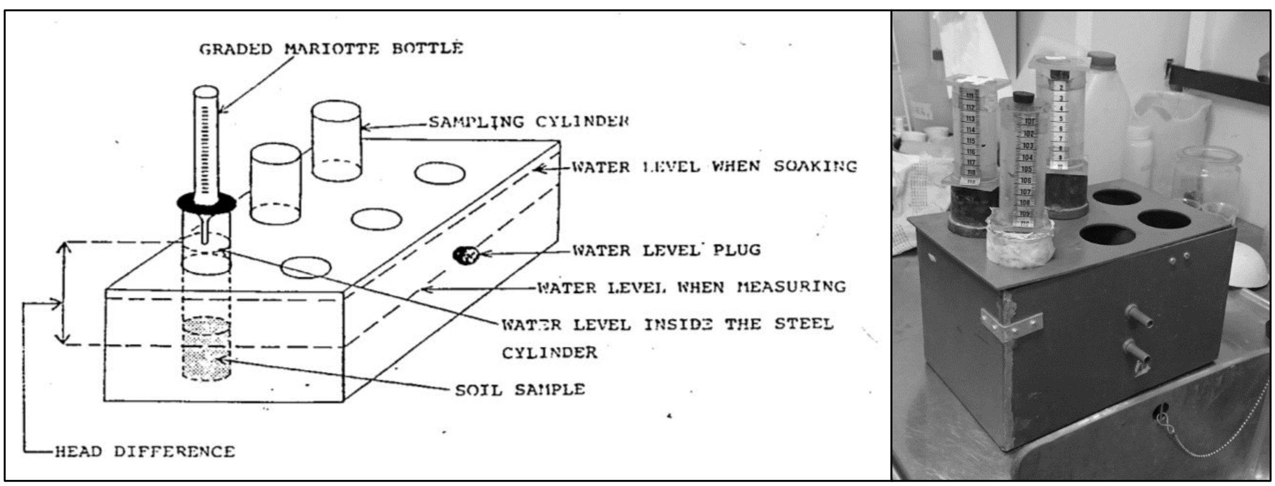


Figure 14. Diagram of "Box-permeameter" method

The flow volume (Q) is calculated through soil volume with constant head applied over the column, to find the K_{sat}. Darcy law (equation 1) has been used (ref):

$$K_{sat} = Q \Big/ A * \left(\frac{h_{top} - h_{bot}}{L}\right) \qquad (2)$$

Where Q is the water flow volume / time measured in the Mariotte cylinder [L^3/T], A is the flow area L^2], h_{top} is the height of water level in the tube [L] (Constant), h_{bot} is the height of water level in the container [L] (Constant), and L is the length of sample [L]

3.4.2.2. Particle size analysis

The aim of particle-size analysis is to separate the different size fractions (table 1) of the mineral soil and to determine the percentage of each fraction (Van Reeuwijk, 1993).

For this method, six samples from the rain-garden were analyzed (figure 10); three sand samples (S1, S2 and S3) and three samples from the mixed soil (R0, R2, R3). Two methods to determine particle-size was used. For particles larger than 2 mm dry sieving was carried out, and for particles smaller than 2 mm, the pipette method (wet sieving) was used (Figure 15) (Reynolds, Carter, & Gregorich, 1993; Van Reeuwijk, 1993).

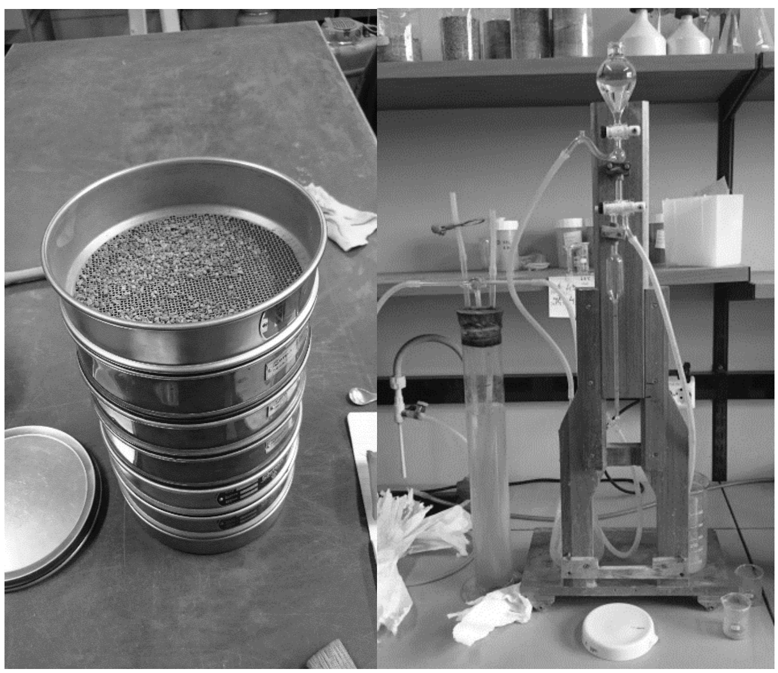


Figure 15. Equipment for dry sieving of the soil sample for the grain-size distribution (Left) and Equipment of pipette method / wet sieving (Right)

In the dry sieving, the soil sample is separated on sieves of different sizes. In the wet sieving (by pipette method), before the procedure for particle-size separation, different procedures of pretreatments such as removal of carbonates, removal of organic matter, removal and soluble salts and finally removal of iron oxides were carried out. The different steps in the procedure for particle-size separation by wet sieving were dispersion of sample, separation of sand fractions, determination of clay (0 - 0.002 mm) and determination of fine clay (< 0.002 mm) (Reynolds et al., 1993; Van Reeuwijk, 1993).

With the accumulative grain size distribution a curve is plotted to calculate the K_{sat} of the different samples, using the Hazen´s pedotransfer equation (Domenico & Schwartz, 1998):

$$K = C \times (d_{10})^2 \qquad (3)$$

Where K_{sat} is the Saturated Hydraulic conductivity [L/T], C is the Hazen's empirical coefficient [], d_{10} is the soil particle diameter [L] such as 10% of all soil particles is smaller by weight. If, $d_{60}/d_{10} \leq 5$

$$K = {(d_{10})^2}/{100} \qquad (4)$$

If, d60/d10 ≥ 5, grain-size distribution curve must be re plotted in a double logarithmic paper.

3.4.2.3. Total Organic Carbon determination

The Total Organic Carbon (TOC) measurements gives the percentage of Organic Matter (OM) in the soil and the bulk density (BD) value.

Bulk density is the weight of dry soil divided by the total soil volume. The total soil volume is the combined volume of solids and pores which may contain air or water, or both. The soil bulk density and porosity, which is the amount of air space or void space between soil particles, reflects the size, shape and arrangement of particles and voids (soil structure). Both, give a good indication of the suitability for root growth and soil permeability and are vitally important for the soil-plant-atmosphere system (McKenzie, Coughlan, & Cresswell, 2002; McKenzie, Jacquier, Isbell, & Brown, 2004).

Organic Matter is a fraction of Total Carbon. It serves as a reservoir of nutrients and water in the soil, aids in reducing compaction and surface crusting, takes part in the adsorption processes in the soil, and increases water infiltration and retention into the soil. OM allows aeration of the soil, is stable in it, is a reservoir of nutrients that can be released to the soil, improves the ability of plant roots penetrate dense soils and has a good water-holding capacity; with the advantage that the matter will release most of the water that it absorbs to plants, in contrast, clay holds great quantities of water. OM causes soil to clump and form soil aggregates, which improves soil structure. With better soil structure, permeability improves, in turn improving the soil's ability to take up and hold water (Brady, 1974; Jones, 1983).

Before the determination of the percentage of OM, the percentage of dry matter and mineral matter was determined. TOC was measured in three samples (R0, R2 and R3) (Van Reeuwijk, 1993).

- Determination of dry matter

Dry matter (DM) is the soil that remains after all the water has been removed (Schnitzer, 1982). The DM was determined by drying the soil in an oven at 105 ˚C for 16 hours. The samples were weighed before and after drying the samples in the oven at a temperature of 105 ˚C (figure 16).

Figure 16. Weighing of samples before and after before and after drying

DM was calculated with the following equation:

$$\%DM = \frac{(m2-m0)}{(m1-m0)} * 100 \quad (5)$$

where *%DM* is the percentage of dry matter in the sample, *m0* is the weight of soil tray [M], *m1*, is the weight of soil tray and the sample before drying [M], and *m2* is the weight of soil tray and the sample after drying [M]

- Determination bulk density

The bulk density is calculated from the dry matter. Bulk density was calculated with the following equation:

$$\rho = m2V \quad (6)$$

where ρ is the bulk density [M/L^3], $m2$ is bulk of the sample after it has been dried in the oven at 105 ˚C [M], and V Volume of the sample [L^3]

- Determination of mineral soil

The mineral soil (MS) component is the matter which remains after the OM has been removed by combustion (Schnitzer, 1982). The dry soil sample was left in an oven at 505 ˚C for 7 hours. Before, particles larger than 2 mm were removed by screening (in the sieves) and weighed. The samples were weighed before and after the combustion process (Figure 17).

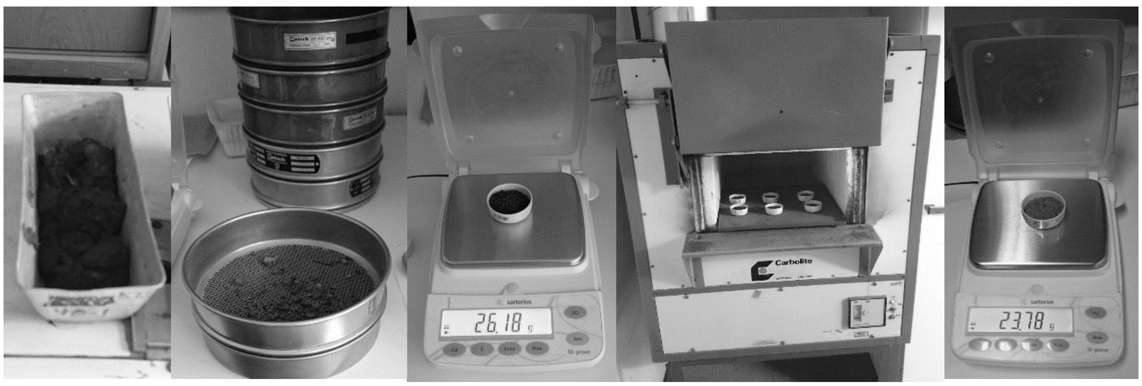


Figure 17. Weighing of samples before and after before and after the combustion process

MS (particles smaller than 2 mm) was calculated with the following equation:

$$\%MS = \frac{(m2\prime - m0\prime)}{(m1\prime - m0\prime)} * 100 \quad (7)$$

where *%MS* is the percentage of mineral soil in the sample, *m0'* is the weight of soil tray [M], *m1'*, is the weight of soil tray and the sample before combustion [M], and *m2'* is the weight of soil tray and the sample after combustion [M]

- Determination of organic matter

OM was calculated with the following equation:

$$\%OM = 100 - \%MS \quad (8)$$

where *%OM* is the percentage of organic matter in the sample

3.4.2.4. Water retention (pF) curve measurement

In unsaturated conditions, the flow is biphasic (liquid and gas). Depending on the relative water and air content, the flow is different. In order to assess the water flow and water content in a partially saturated medium, its hydraulic characteristics are required. The function which describes the variation of the volumetric content (S_w) with the suction (ψ) is the Water Retention Curve *(WRC)*. The suction, or pressure, is equivalent to some cm of water column, the values are usually log transformed (pF) (Domenico & Schwartz, 1998).

WRC is an important hydraulic property related to size and connectedness of pore spaces; hence strongly affected by soil texture and structure, and by other constituents including OM. Several methods exist to measure the WRC, in the laboratory and in the field, such as the pressure plate/cells, the sandbox, the triaxial cell, the paper filter method, tensiometers, psychrometers, column test, etc. These tests give several points on the WRC, based on which the complete curve can be defined mathematically (Domenico & Schwartz, 1998). Figure 18 depicts representative WRC curves for soils of different textures, demonstrating the effects of porosity (saturated water content) and the varied slopes of the relationships resulting from variable pore size distributions (Tuller & Or, 2004).

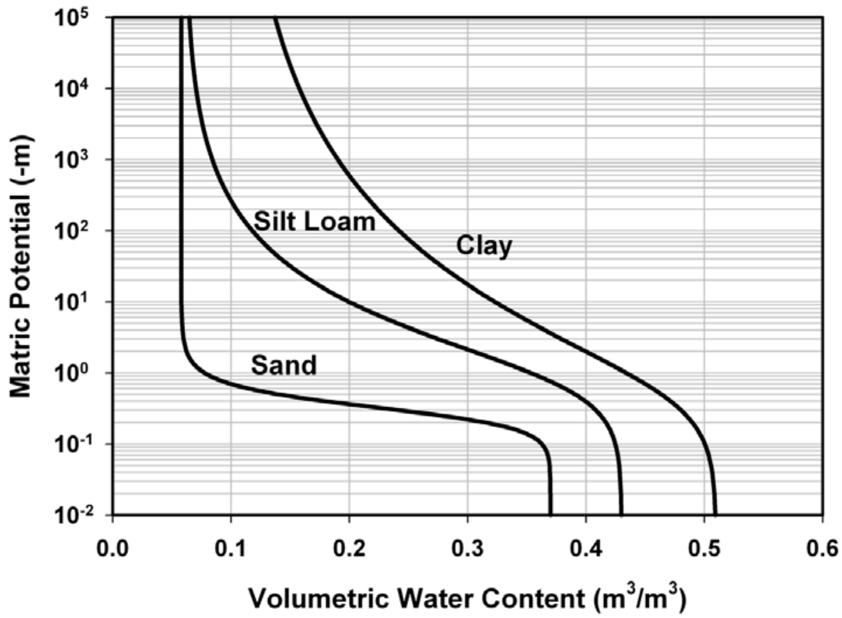


Figure 18. Typical WRC for soils of different textures (Tuller & Or, 2004)

In this study, the 36 intact soil cores (of 100cm^3 each one) collected were used for measurements of total porosity, air porosity, pore size distribution, bulk density, volumetric water content, air permeability and modulus of rupture. These were taken in 2-7 cm depth with four samples per plot on two replicates on each experiment. Moisture tension was measured thorough a Sandbox. Measurements of bulk density and volumetric water content were made on cores dried at 105°C.

Pore size distribution in soil was measured using ceramic pressure plates (Richards, 1947; 1948). Air porosity at -10 kPa matric potential was determined with an air pycnometer (Torstensson & Eriksson, 1936), the total porosity was calculated as the sum of air porosity and volumetric water content at -10 kPa matric potential Air permeability was measured at -10 kPa matric potential as described by (Green & Fordham, 1975).

- Water retention (pf) curve and the van Genuchten model parameters

The soil hydraulic parameters for analysing water movement in variably saturated soil can be determined by fitting soil hydraulic model to a soil water retention curve. SWRC Fit web interface program (Seki, 2007) was used to perform nonlinear fitting of van Genuchten (VG) model (Tuller & Or, 2004) to measured soil water retention curve; the relationship between the soil water potential and volumetric water content. The program is written in numerical calculation language GNU Octave, and initial estimate of parameters is automatically determined by the program (Seki, 2007).

3.4.2.5. CEC measurements

Cationic Exchange Capacity (CEC) is a measure of the soil's ability to hold positively charged ions. It is a very important soil property influencing soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilizers. CEC is an inherent soil characteristic and is difficult to alter significantly. It influences the soil's ability to hold onto essential nutrients and provides a buffer against soil acidification. Soils with a higher clay fraction tend to have a higher CEC. Organic matter has a very high CEC. Sandy soils rely heavily on the high CEC of organic matter for the retention of nutrients in the topsoil (Cornell University Cooperative Extension, 2007; Hazelton & Murphy, 2007).

In this study, the method used to determine CEC was by saturating the soil complex with an index cation, washing out the excess and determining the amount of cation retained. The method is based on ammonium acetate extraction on pH 7. Quantity of Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} were determined by ICP-OES spectrometry and $H^{+}_{(ex)}$ concentration by titration with 0,05M NaOH to pH 7 (Schollenberger & Simon, 1945).

3.5. Modelling

3.5.1. Purpose of the modelling

Based on the physical description of the raingarden, the hydraulic processes is modelled with a numerical model for unsaturated and saturated flow. It is intended to describe and evaluate in the raingarden the saturation, concentration and retention time of potential pollutants, and water balance under different flow scenarios.

3.5.2. Conceptual Model

Three models are designed, ran and compared under different flow scenarios.

The first model (figure 19) describes the original design of the raingarden. The second model (figure 20) is the modification of the original design, which is filled with mixed soil with a layer of sand in the bottom and a column of sand close to the inlet section from the top to the bottom of the garden. The third model (figure 21) is also a modification of the original design, which is filled with mixed soil with one layer of sand in the bottom. In all figures, the blue layer represents the air, the white layer the mixed soil, the grease layer the sand and the black points the observation wells.

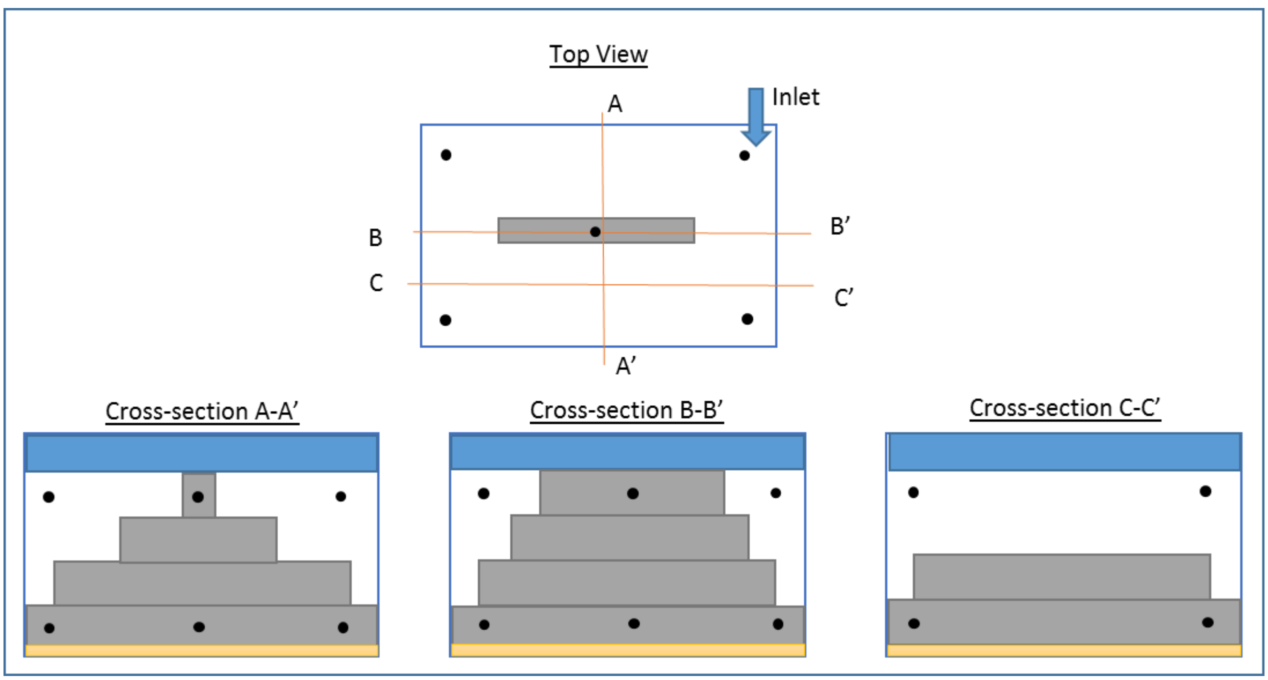


Figure 19. Model No. 1

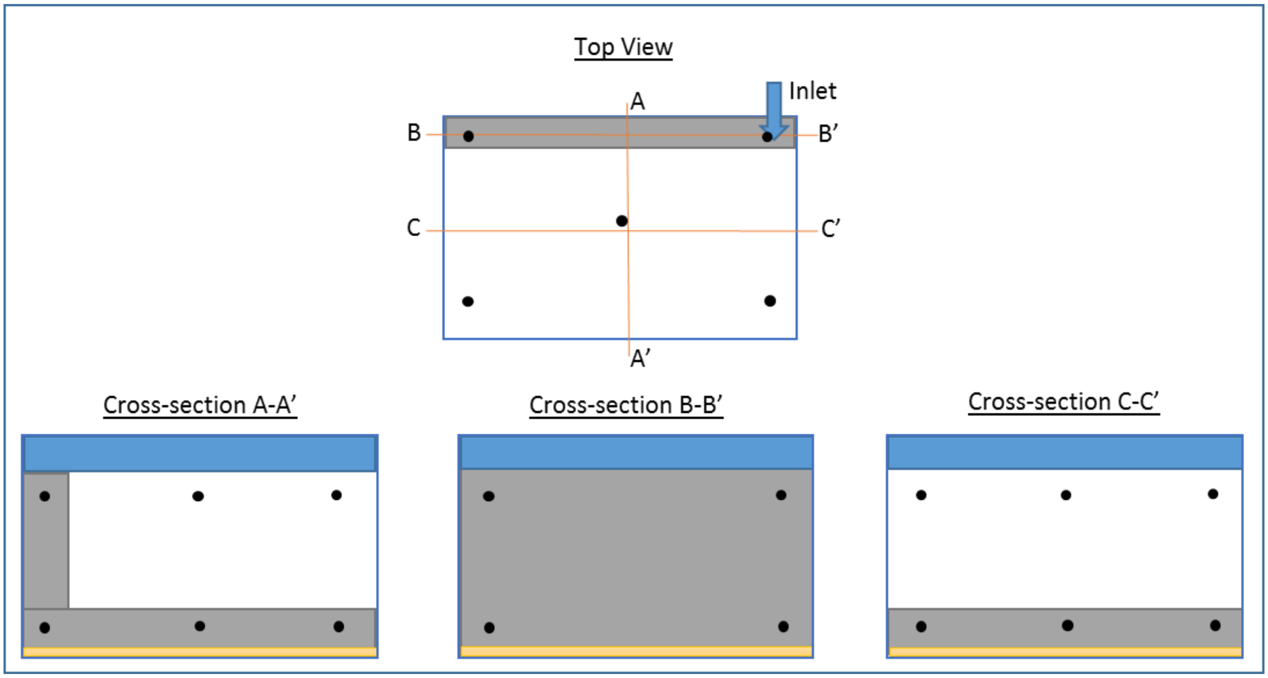


Figure 20. Model No. 2

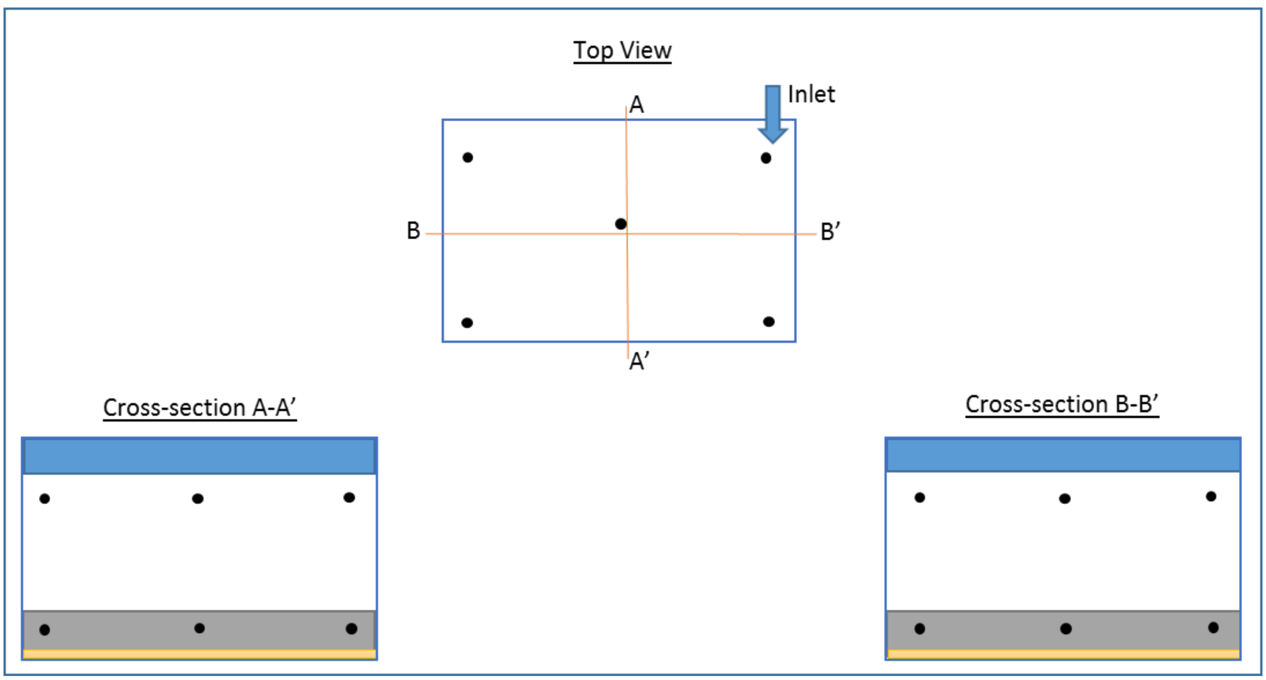


Figure 21. Model No. 3

3.5.2.1. Information about the Computer Code

Simulations were performed using the flow and transport model SUTRA v.2 (Voss & Provost, 2010), which is a semi-finite element model for flow and transport in the saturated and unsaturated zone (see section 2.4.3. Sutra Code). SUTRA code was chosen because its ability to simulate modeling of saturated and unsaturated water flow and modeling of pollutants transport including processes of solute sorption, production and decay; process that occur in a raingarden system.

3.5.2.2. Description of modelled systems

Three rain garden models was designed with a grid of 5m length, 3m width and 0.8m depth. The depth was divided into eight (8) layers. The finite element grid of 16500 elements and 18972 nodes.

In the three models (figures 19-21), the top layer (n.1) is an imaginary layer that represents the volume of air; layers 2 to 7 are filled with sand and a composition of mixed soil, and the bottom layer (n.8) is filled only with sand. Air layer only participate in the redistribution of flow when the influx is higher than K_{sat}.

The layers are made up of three different materials, which are the same for the three models. Soil properties values, such as K_{sat} porosity and VG parameters, for the imaginary air layer and for each type of soil (sandy and mixed soil) are presented in results section (table 12).

To give to the models the option to work for unsaturated flow conditions, VG result parameters (table 12) where used to change the default soil parameters of the SUTRA code and recompile it, making new and appropriate executables able to run the models according to the rain garden flow conditions. The program used to recompile the code was "Simple-fortran 2.25" (Approximatrix, 2013).

Infiltrating water flows vertically through model, from the top to the bottom layers, reaching the drain layer (n.8) which is entirely filled with sandy soil and then discharged out of the system via drainage lines.

The major source of recharge is from rain runoff which is collected from one side of the roof of Tivoli, then delivered to the rain garden through the pipelined gut (figures 19-21). This recharge occurs on the upper 5cm of layer 2. The other recharge comes from an atmospheric boundary (the precipitation that falls directly over the raingarden). This recharge occurs between the air layer and the ground surface layer.
The groundwater discharge occurs through evapotranspiration (ET) which mainly takes place on the surface area of the system and also through drainage on the bottom layer, but if the system

is overloaded the water can also runoff through the weir at the surface. Evapotranspiration was not taken in account due to the small amount that this contributes in a storm-event.

Ten (10) observation wells (figures 22) are measuring the pressure, concentration and saturation by each time measure by the models, at different nodes locations, in the middle and the 4 corners of the system, and at different depths, layer 2 (top) & 7 (bottom).

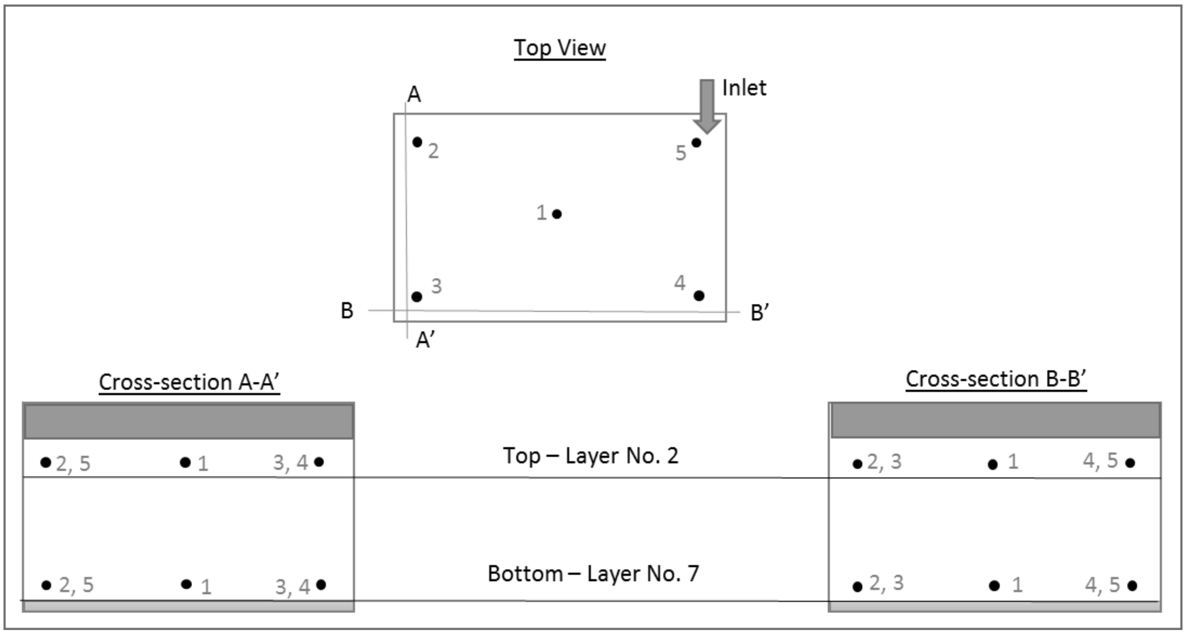


Figure 22. Observation wells locations in the 3 models: Top view and Cross-sections A-A' and B-B'

Mixed soil properties where define by default in the data sets description of the model. To define sand, air, drain and flux-in (runoff and atmospheric flow) objects, it was assigned rectangles to define their "soil" properties.

The units used in the models for different parameters are: length (m), K_{sat} (m/s), recharge (m^3/s), time (s), mass (g) concentration (g/m^3). The type of the flow is unsaturated transient and heterogeneous flow

3.5.2.3. Initial and Boundary conditions

Initial and boundary conditions were defined according to 2 flow scenarios modelled by the 3 model designs. Simulations were performed for transient flow.

The first flow scenario was described by 3 dry hours; this gave a steady state system which served as the initial conditions for the storm event, followed by an storm event with an intensity of 88 l/ha.s (0.53 mm/min) with a duration of 60min (1 hour) and a return period of 50 years, and finally 20 observation hours without precipitation. The precipitation intensity of the storm-event was calculated from the IDF curve (figure 8). The second scenario was described by 3 dry days (without precipitation), followed by 3 wet days with an average precipitation intensity of 7mm/d, and finally 8 observation days without precipitation.

The initial and boundary conditions parameters defined for all models were no flow boundary, in the bottom of the system, and flow boundary recharge by the stormwater runoff, by direct precipitation, and by pressure in the drain layer. The drain layer had an assigned pressure of -1000 pascal (kg.m/s^2), because in that point the system is close to saturation completely saturated. The recharge from stormwater runoff flow and from direct precipitation was calculated with the “Rational Method” equation (9), which is the simplest method to determine peak discharge from drainage basin runoff (Thompson, 2007).

$$Q = CiA \tag{9}$$

where Q is the runoff flow [V/T], C is the rational method runoff coefficient, which describes the ration of the water going to runoff and what infiltrates [-], i is the precipitation intensity (V/A.T) and A is the Drainage area [L^2]

Recharge from direct precipitation, runoff coefficient (C) is not taking in account in the calculation. In dry initial conditions the runoff flow (Q) tracer concentration is 0 g/l. For wet initial or boundary conditions, the runoff flow (Q) pollutant normalized concentration of 100 g/m^3 was defined, assuming there is no density effect in the model.

Finally, after run the 3 models under the 2 flow scenarios, results from the simulations presented in the 10 observation wells were analyzed and compared regarding pressure, saturation, concentration, retention time, and flow mass balance.

3. RESULTS & DISCUSSIONS

3.1. Soil Properties of the Raingarden

3.1.1. Particle-size analysis

According to the "Soil Survey Manual" form the U.S. Department of Agriculture (Soil Survey Division Staff, 1993) the particle sizes in the mixed soil are between clay and gravel, with highest percentages of particles between 0.063 mm and 2mm (table 5). For the sandy media the particle sizes are between silt and gravel, with highest percentages of particles size between 0.5 mm and 2 mm (table 6).

Table 5. Results Grain-size distribution for the raingarden "mixed soil" media

Type of soil	Particle size (mm)	RO			R2			R3		
		Weight (g)	%	Cumulative (%)	Weight (g)	%	Cumulative (%)	Weight (g)	%	Cumulative %
Clay	< 0,002	12.51	3%	3%	11.00	3%	3%	11.47	3%	3%
Silt	0,002-0,006	10.84	3%	6%	15.72	4%	7%	8.19	2%	5%
	0,006-0,02	6.67	2%	7%	14.15	4%	10%	13.11	3%	8%
	0,02-0,063	29.20	7%	14%	23.58	6%	16%	23.75	6%	14%
Sand	0,063-0,2	71.61	17%	32%	67.54	17%	33%	64.13	15%	29%
	0,2-0,6	161.41	39%	71%	155.24	38%	71%	157.84	38%	67%
	0,6-2,0	78.66	19%	90%	67.43	17%	88%	85.18	21%	88%
Gravel	2,0-4,0	22.20	5%	95%	20.30	5%	93%	22.40	5%	93%
	4,0-6,0	11.70	3%	98%	11.10	3%	96%	12.70	3%	96%
	>6,0	7.90	2%	100%	17.50	4%	100%	15.90	4%	100%

Table 6. Results Grain-size distribution for the raingarden "sandy soil" media

Type of soil	Particle size (mm)	S1			S2			S3		
		Weight (g)	%	Cumulative (%)	Weight (g)	%	Cumulative %	Weight	%	Cumulative %
Silt	< 0.0063	3.4	1%	1%	5.5	1%	1%	4.9	1%	1%
	0,125 -0.0063	8.9	2%	3%	6.8	2%	3%	6.4	2%	3%
Sand	0,25 -0.125	33.7	8%	11%	33.4	8%	11%	33.2	8%	11%
	0,5 -0.25	79.9	19%	30%	86.2	21%	32%	84.1	21%	32%
	1 -0. 5	123.2	29%	59%	118.9	29%	60%	114	28%	61%
	2 -1	69.6	17%	76%	64.7	16%	76%	66.2	17%	77%
Gravel	4 -2	47.3	11%	87%	48.2	12%	88%	48.8	12%	89%
	6,3 -4	27.4	7%	93%	26.5	6%	94%	19.7	5%	94%
	>6,3	28.1	7%	100%	25.3	6%	100%	23.5	6%	100%

The composition of the raingarden sandy soil samples is more than 95% sand; for the mixed soil samples is 3.23 % clay, 13.27 % silt and 84.43 % sand (table 7) with a "loamy sand" texture according to different guidelines for soil description (Jahn, Blume, Asio, Spaargaren, & Schad, 2006; Soil Survey Division Staff, 1993). These values and texture meet the requirements for a raingarden media, according to the "Minnesota Stormwater Manual, (2008)", who recommend in the soil a mix of 50-85% of sand and 15-50 % of leaf compost, and according to the "Prince George's County Biorretention manual, (2007)", who recommend a sandy loam, loamy sand or loam soils for bio-retention systems. Although the percentage of clay is lower here at NMBU than the minimum 5% recommended by Prince George's County (2007).

Table 7. Soil composition and texture classification of the raingarden media

Type of Soil	**Samples**	**Clay**	**Silt**	**Sand**	**Soil Texture**
Sandy soil	S1	0%	4%	96%	Sand
	S2	0%	4%	96%	
	S3	0%	4%	96%	
	Average	0%	4%	96%	
Mixed soil	R0	3.4%	12.6%	84.0%	Loamy sand
	R2	3.1%	15.1%	81.8%	
	R3	3.2%	12.4%	84.5%	
	Average	3.2%	13.3%	83.4%	

Appendix B, shows the results of the grainsize distribution for the mixed soil (samples R0, R2 & R3) and for the sandy soil (samples S1, S2 & S3) media in the NMBU raingarden.

3.1.2. Total Organic Carbon

The determination of the soil organic matter (OM) and bulk density (BD) was carried out before planting. Table 8 shows that the percentage of DM, BD, MS, and OM of the mixed soil media (samples R0, R2 & R3) in the NMBU raingarden.

Table 8. Results of the determination of Dry Matter (DM), mineral soil (MS), Organic matter (OM) and bulk density (ρ)

Type of Soil	**Samples**	**DM (%)**	**ρ (g/cm^3)**	**MS (%)**	**OM (%)**
Mixed soil	R3	74.03	1.33	91.35	8.65
	R2	72.64	1.18	89.53	10.47
	R0	74.05	1.12	89.65	10.35
	Average	73.57	1.21	90.18	9.82

For the three samples, OM values are between 8.65 % and 10.47 %, these values are similar and even greater than other raingardens studied by Paus & Braskerud (2014) and by Muthanna, Viklander, & Thorolfsson (2008). These authors reinforce the importance of OM content to facilitate vegetation and microbial activity and the importance of OM high content to promote vegetation growth as well as a high infiltration capacity.
BD of soil are between 1.12 g/cm^3 and 1.33 g/cm^3. According to Jones (1983), under the critical BD value of 1.4 g/cm^3, it is easy for the roots of the plants to penetrate in the soil. So, before the planting, the soil was correct for the root penetration. The OM reduces the bulk density by increasing the micropores, so the more OM, the lower the BD, the better the root penetration (Anderson, 2011). OM is also a factor that affect the chemical processes in the biorretention system. According to Hunt, Davis & Traver (2011), it gives a high adsorption capacity to the soil, and have the potential to provide a carbon source for the nitrifying and denitrifying bacteria.

Appendix C, shows all the calculations of the mixed soil media (samples R0, R2 & R3) properties in the NMBU raingarden.

3.1.3. Cation Exchange Capacity

Cation Exchange Capacity (CEC) of the raingarden mixed soil has an average of 25.45 meq/100g (table 9). According to McLaren and Cameron (1990), a CEC above 10 meq/100g is preferred for plant production and a CEC greater than 20 meq/100g indicates soils with high clay and OM presence, and with high nutrient and water holding capacity. Key considerations for robust plant establishment and stormwater treatment by plants and soil include soil pH between 5.5 and 7.5,3 and CEC greater than 5 meq/100g (Emanuel, Godwin, & Stoughton, 2010).

Table 9. CEC *values from the raingarden mixed soil media*

Type of soil	Samples	Cations					CEC (meq/100g)
		Ca (meq/100g)	K (meq/100g)	Mg (meq/100g)	Na (meq/100g)	H+ (meq/100g)	
Mixed soil	R0	21.0	0.48	2.3	0.18	0	23.96
	R2	24.0	0.60	2.4	0.19	0	27.19
	R3	22.0	0.51	2.5	0.18	0	25.19
	Average	22.3	0.53	2.4	0.18	0	25.45

CEC value in the NMBU raingarden is greater than the values reported by Paus (2015) and by Muthanna et al. (2008) in other raingardens, which reported values were between 10 – 22 meq/100g. One reason of this value could be the high OM content in the soil. CEC allows adsorption processes with some nutrients and metals. Cation exchange describes the process in which metals are exchanged on the surface of negatively charged soil particles with positively charged cations.

3.1.4. Saturated Hydraulic Conductivity

Table 10 presents the Saturated Hydraulic Conductivity (K_{sat}) results from the permeability and grainsize analysis, for the two type of soils (mixed and sandy) in the NMBU raingarden. These tests were conducted before planting.

K_{sat} in the soils were between 10^{-4} - 10^{-5}m/s, with an average of 1.35*10^{-4}m/s for the sandy soil and an average of 8.09*10^{-5}m/s for the mixed soil. According these results and to Btkov et al. (2013) the soil in the raingarden is sufficiently permeable because the K_{sat} is between 10^{-4} at 10^{-6}m/s. There were not results for mixed soil from grain-size distribution test, because in calculations, d60/d10 were d60/d10 ≥ 5, so it was decided to use K_{sat} values from the box-permeameter and the infiltration test (table 10).

Table 10. Results of K_{sat}, from the permeability and grainsize analysis, for the mixed soil and sandy soil in NMBU raingarden, before planting

Method	Soil Samples					
	Mixed (m/s)			Sandy (m/s)		
	R0	R2	R3	S1	S2	S3
Grain Size Distribution	-	-	-	1.44E-04	1.21E-04	1.21E-04
	-			1.29E-04		
Box Permeameter	2.50E-05	2.03E-04	1.48E-05	2.78E-04	9.33E-05	4.76E-05
	8.09E-05			1.40E-04		

Table 11 shows the different values of K_{sat} for the different infiltration tests in the rain-garden. Infiltration tests were carried out before and after planting and with different humidity and saturation soil conditions. Before the planting, the hydraulic conductivity values vary between 10^{-5} and 10^{-7} m/s. After the planting (8 weeks), the hydraulic conductivity values vary between 10^{-4} and 10^{-6} m/s.

The average K_{sat} values of the soil before and after planting was 8.28*10^{-6} m/s 6.18*10-5m/s respectively. According to a soil classification based on values of saturated hydraulic conductivity (table 3), this soil was poorly permeable and permeable before and after plantation respectively.

K_{sat} values, also understood as infiltration rate in this test, are higher than the minimum infiltration rate recommended by the Prince George's County Biorretention Manual (2007) and by Paus et al. (2014) of 7*10^{-6} m/s for a texture class of loamy sand.

Table 11. Results of double ring infiltration tests in the rain-garden mixed soil before and 8 weeks after the planting

Tests	Before Planting		After planting	
	Soil	K (m/s)	Soil	K (m/s)
1	Dry	2.36E-05	wet	9.74E-05
2	Dry	3.01E-05	wet	1.33E-04
3	Dry	1.13E-05	wet	1.719E-04
4	Dry	1.49E-06	wet	1.02E-05
5	Wet	1.82E-05	wet	1.17E-04
6	Wet	8.89E-07	wet	1.13E-05
7	Wet	4.00E-07	wet	7.08E-06
8	Wet	1.96E-06	wet	2.44E-05
9	Wet	3.71E-06	wet	2.19E-05
10	Dry	5.09E-06	wet	3.29E-05
11	Dry	1.67E-06	wet	6.53E-05
12	Dry	1.03E-06	wet	4.94E-05
Average	8.28E-06		6.18E-05	

The difference between the K_{sat} values or infiltration rates before and after planting, could be explained by, first, because of the wet condition of the soil during the tests; the values were lower when the soil was wet and with the presence of plants, and second, because the plant roots increase the pore space and connectivity of soil, so the water can infiltrate faster.

Appendix D, shows all the K_{sat} calculations of the mixed and the sandy soil in the NMBU raingarden.

3.1.5. WRC & the VG model parameters

The WRC (Figure 23) and the VG model parameters (Table 12) presents the availability of the media (mixed soil and sandy soil to retain water in unsaturated conditions. According to Tuller & Or (2004) the mixed soil media in NMBU rain garden is classified as a “sandy loam clay” which has a good capacity to retain water. The sandy media is poor in its capacity to retain water and the mixed soil media.

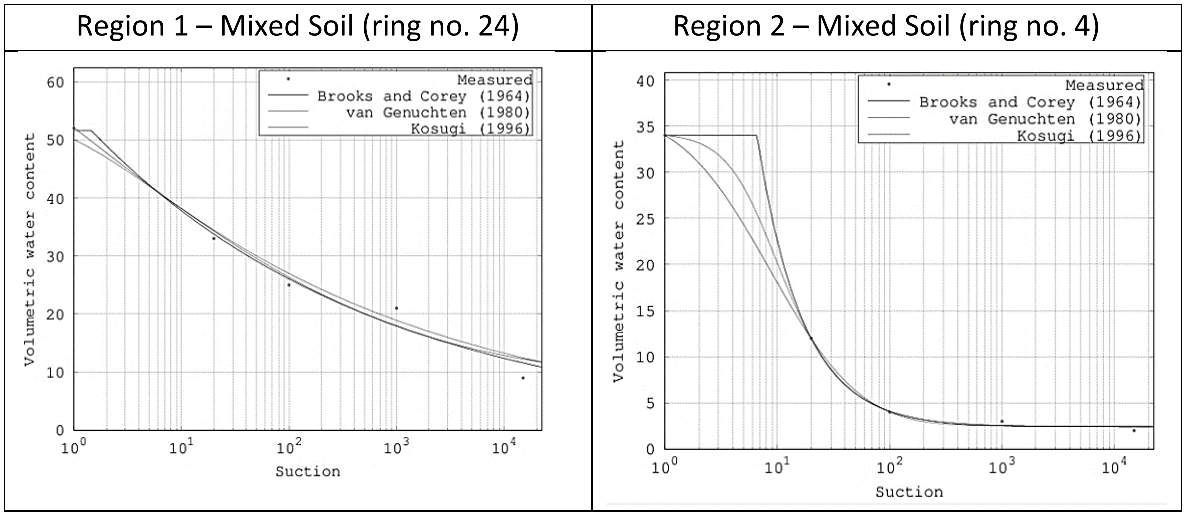


Figure 23. Water retention (pF) Curve for Sandy and Mixed Soil
*[*SWRC Fit web interface program (Seki, 2007)*]*

The VG parameters registered in the table (no.12) were used to change the default soil parameters on the SUTRA code and recompile it, making new and appropriate executables able to run the models, and thereby used to define the layer properties of the different layers and regions in the 3 developed models (figure 19-21). Region 1 corresponds to the mixed soil, region 2 corresponds to the sandy soil and region 3 corresponds to air (imaginary material).

Table 12. The VG model parameters and K_{sat}

VG Parameters	Region 1	Region 2	Region 3
	Mixed Soil	Sandy Soil	Air
Ss (porosity)	0.54822	0.34261	0.5
Sr	1.202E-06	2.393E-02	0
Alpha (α)	1.00E-04	1.43E-05	1.02E-03
n	1.15	2.11	2
m	0.134	0.526425459	0.5
K_{sat}	6.18E-05	1.35E-4	0.01

Appendix E, shows all the WRC (PF curve) and VG parameters calculation of the mixed the sandy soil medias in the NMBU raingarden.

3.2. Modelling

3.2.1. Recharge

Table 13 presents the different recharge calculations for the 2 flow scenarios, according to the flux boundary time line conditions, the precipitation intensity data, the runoff coefficients and the drainage area. For the flow scenario no. 1, that correspond to an extreme storm event, the total influx was 3.49 l/s, and for the flow scenario no. 2, that correspond to a normal rainy week conditions, the total influx is $3.2*10^{-5}$ l/s.

Table 13. Flow scenarios: Flux boundary Time-line conditions, Precipitation, Flux-In from roof & drainage area, Flux-in from direct precipitation, and Total flux-in.

Flow Scenarios		**No. 1**	**No. 2**
Flux Boundary Timeline	Dry initial conditions	3 hours	3 days
	Rain event conditions*	1 hour	3 days
	Post-rain event dry conditions	20 hours	14 days
***Precipitation** (Rain event conditions)	Precipitation Intensity	88 (l/ha.s)	7 (mm/d)
	P. Intensity in (l/m2.s)	8.80E-03	8.10E-05
	P. Intensity in (m/s)	0.00001	8.1019E-08
Flux-In from the Roof + drainage area	Area of the roof (m2)	697.5	697.5
	Runoff coefficient (c)	1	1
	Area between drains (m2)	93.75	93.75
	Runoff coefficient (c)	0.5	0.5
	Q (l/s)	3.185E+00	2.932E-02
	Q (m/s)	3.185E-03	2.932E-05
Flux-In from direct precipitation	Raingarden Area (m2)	35	35
	Runoff coefficient (c)	1	1
	Q (l/s)	3.080E-01	2.836E-03
	Q (m/s)	3.080E-04	2.836E-06
Total Flux-In	Q (l/s)	3.493E+00	3.215E-02
	Q (m/s)	3.493E-03	3.215E-05

3.2.2. Saturation

The systems appear to be always in a saturation state with saturation ranges between 80 to 100%, top layers (92%-100%) more saturated than bottom layer (80-100%).

For flow scenario no. 1 (figure 24), observations wells in models no. 1 & 3 behaves similar with saturation decreases during time (hours 5 to 8) where the tracer is added with a reduction of 6-8 percentage points. Model no. 2 has a lower saturation reduction (1-3%) during the same time. Saturation in wells located at top layer (no. 2) were lower (10-20%) than the wells located at bottom layer (no.7). For flow scenario no. 2(figure 24), observation wells in all 3 models behaves similar, with saturation between 98 – 100% in bottom layer (no. 7) and saturation in top layer (no. 2) up to 92%.

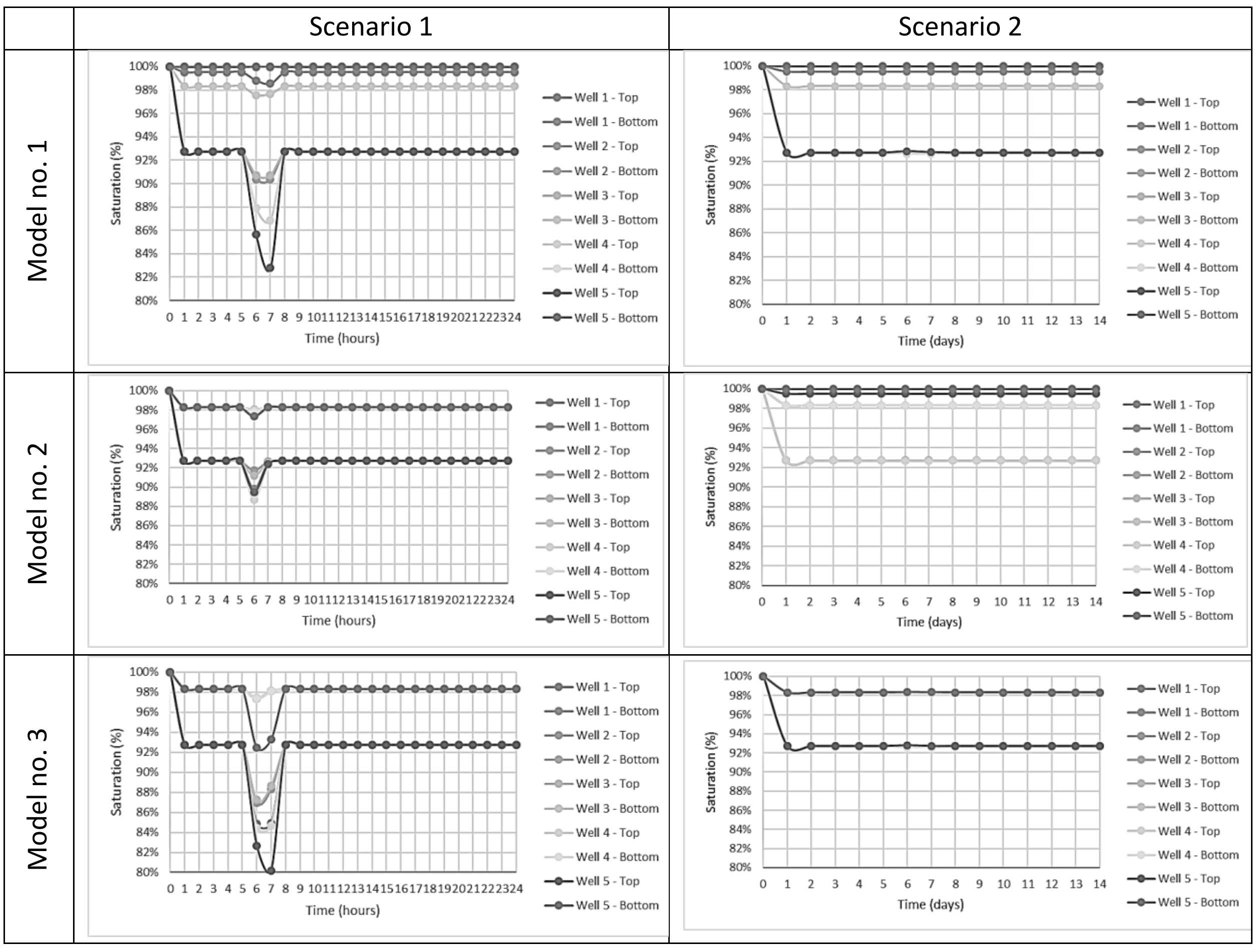


Figure 24. Saturation for Scenario 1 & 2 (Models 1-3)

3.2.3. Concentration

Under both flow scenarios (No. 1 & 2), all the design models (No. 1, 2 & 3) shows and increase in the concentration of the tracer (pollutant with normalized concentration) during the time-steps 4 to 7, whether they are hours (scenario 1) or days (scenario 2). That could mean that the transport of the tracer in the different systems (models) is very fast, related with the good permeability of the NMBU raingarden.

In both, scenario 1 and scenario 2 (figure 25), models number 1 & 3 behaves very similar with relative high concentration of the tracer near to the inlet (Well no. 5), followed by a concentration decrease in the middle of the system and finally very low concentration in the corners. For model no. 2, the tracer concentration is lower than in the others models. It could be because of the column of sand close to the inlet section from the top to the bottom of the garden (figure 20).

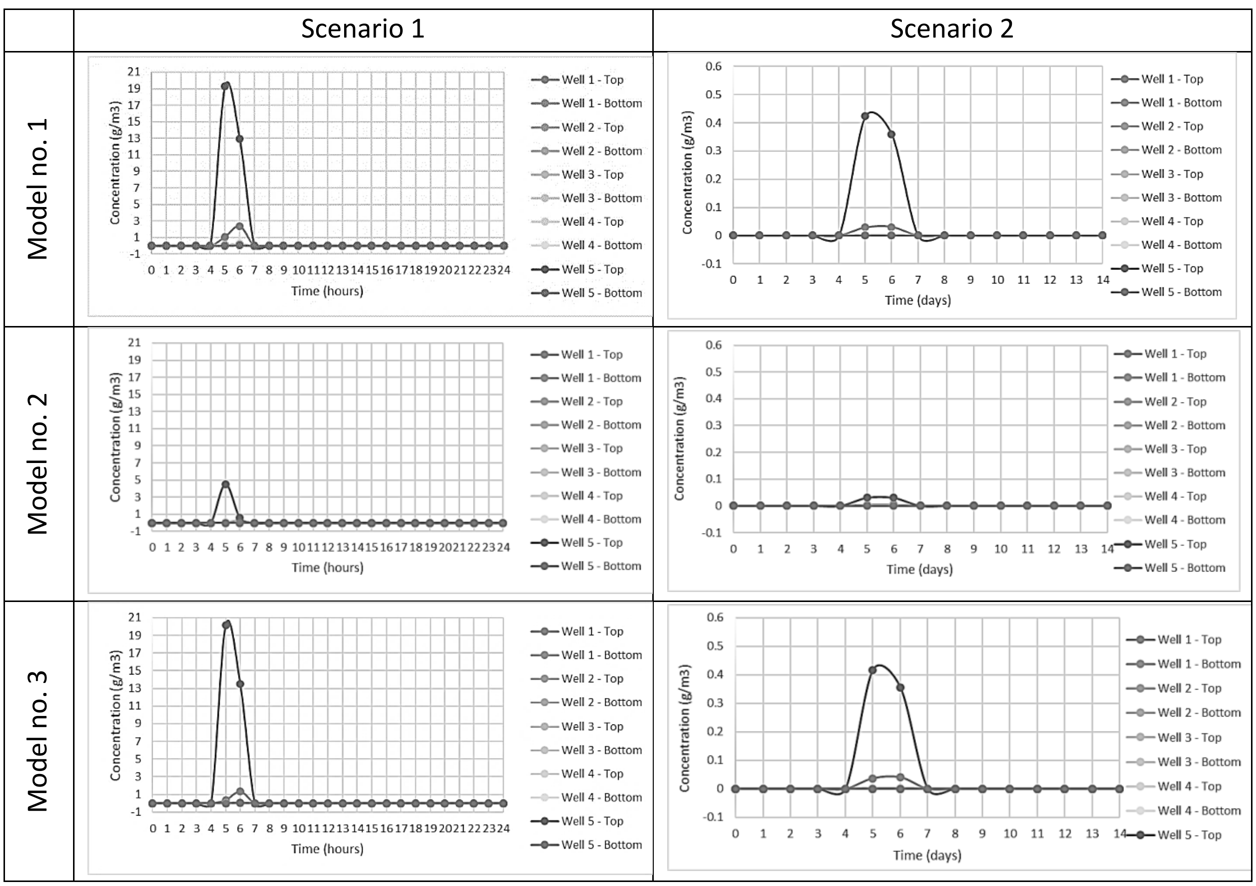


Figure 25. Tracer concentration for Scenario 1 & 2 (Models 1-3)

- Tracer flow path

In all scenarios, except in scenario no. 2 (design model no. 2) it is possible to observe tracer flow activity during the time-steps 4 to 7.

Models No. 1 and 3 behaves very similar in both flow scenarios (figure 26 & 27), but with more intensity in scenario no. 1 because a higher flux from the roof, the drainage area and from direct precipitation (table 13). There it is possible to observe the movement of the tracer from the inlet to beyond the middle of the garden and toward the outlet (extreme right corner).

In model no. 2 (figures 26 & 27), the concentration transported along the system is lower than in models No. 1 & 3, and lower between the scenario no. 1 and the scenario no. 2. An explanation to the above, is associated to the column of sand close to the inlet section from the top to the bottom of the garden (figure 20), working as a sink of the tracer, but possibly without further removal capacity, because of the sands properties.

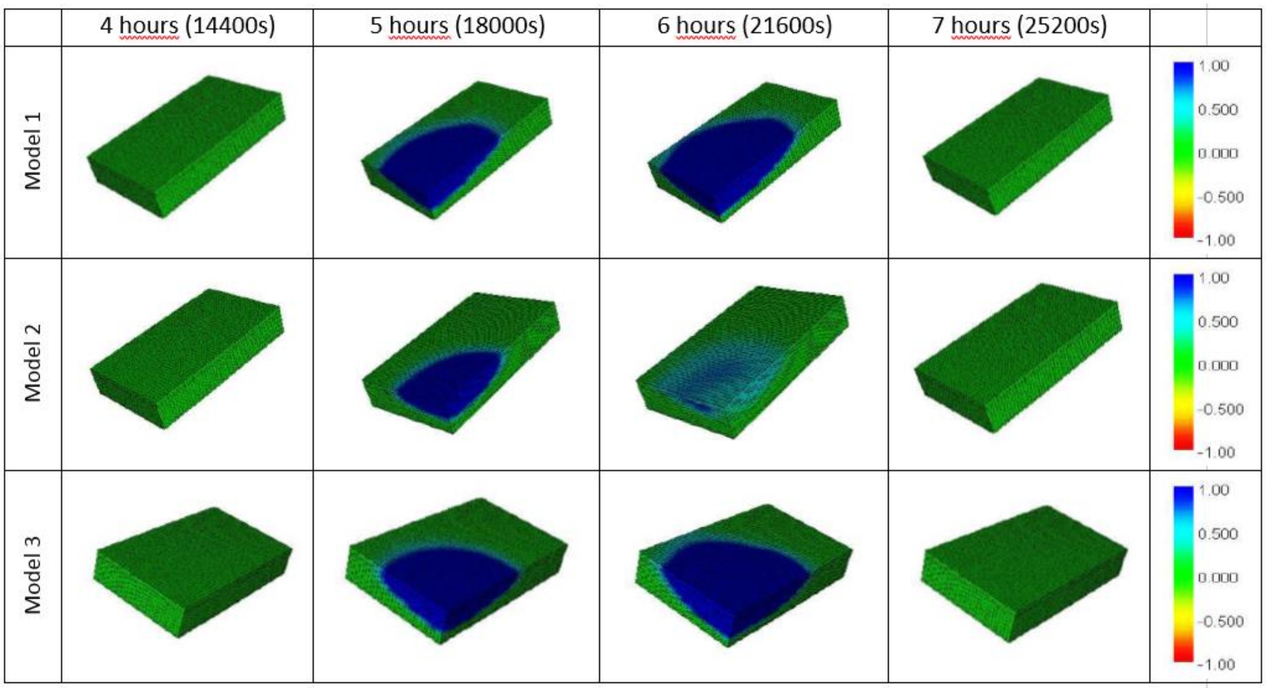


Figure 26. Tracer flow path for Scenario 1 (Models 1-3)

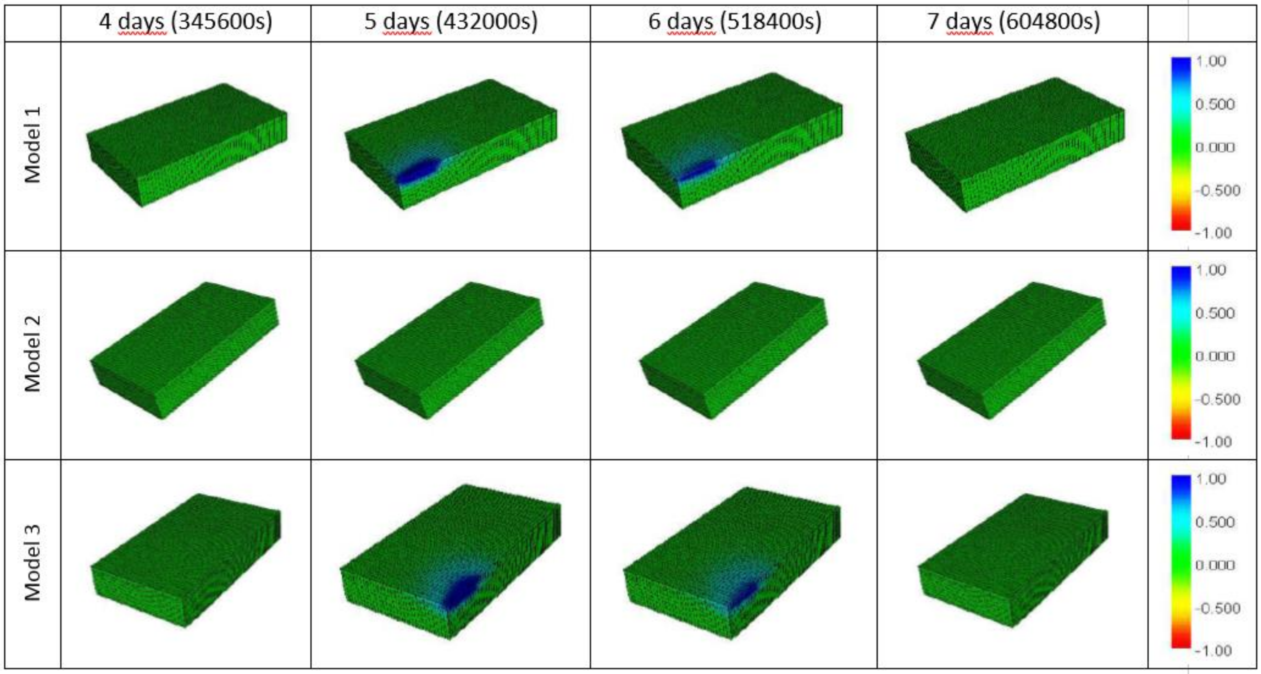
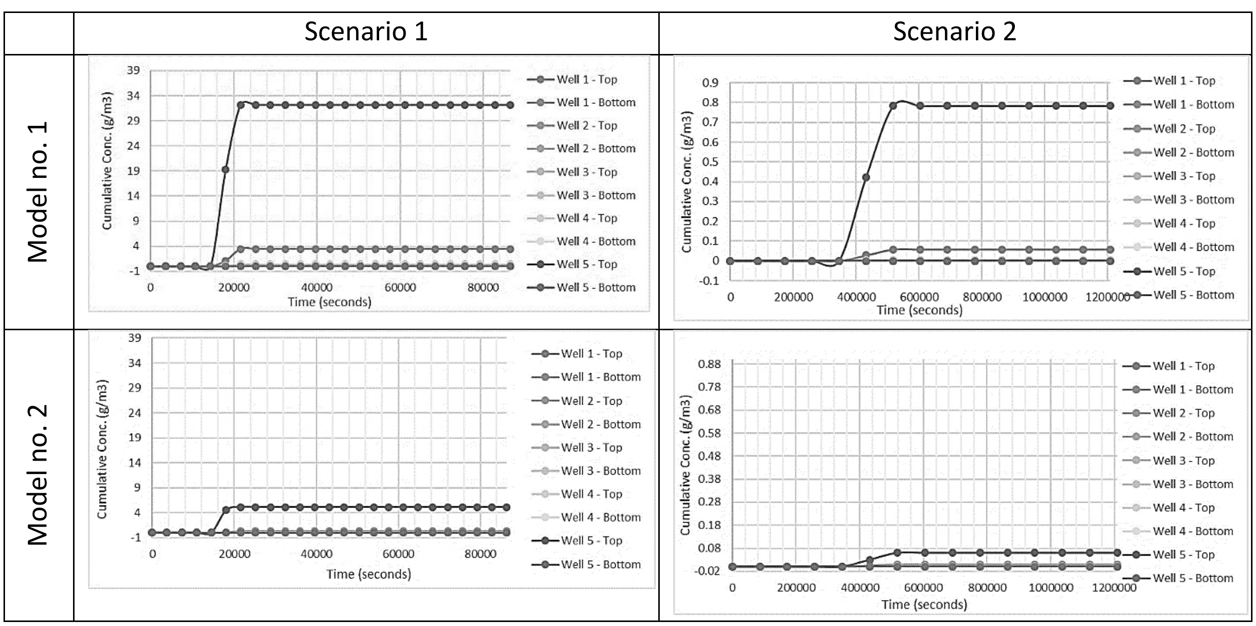


Figure 27. Tracer flow path for Scenario 2 (Models 1-3)

- Breakthrough Curve & Tracer Retention Time

Scenarios 1 and 2, shows that the breakthrough of the tracer concentration in the 3 models occurs close to the 6 hour. One hour after the beginning recharge. The high breakthrough values occur in the top of the observation well no. 5 (near to the inlet), being even bigger in models no. 1 & 3 than in model no. 2 (figure 28).



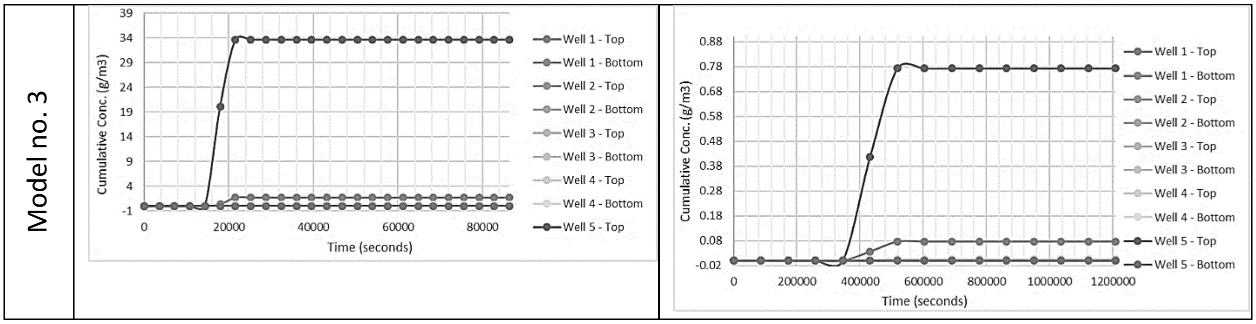


Figure 28. Breakthrough Curve for Scenario 1 & 2 (Models 1-3)

Table 14, shows the tracer retention time (RT) from the top of the observation well no. 5 (Well_5_Top) to the bottom of the observation well no. 3 (Well_3_Bottom), in the 3 design models and under the 2 flow scenarios. All model designs (1-3) presented similar tracer RT according to the flow scenario. In scenario no. 1, RT were around 5.8 to 7.5 hours, and in scenario no. 2, RT were around 12.2 to 12.8.

Table 14. Tracer RT in the 3 design models and under the 2 flow scenarios

Retention Time		*From Well_5_Top to Well_3_Bottom*		
		sec	min	hour
Scenario 1	Design 1	23000.0	383.3	6.4
	Design 2	21000.0	350.0	5.8
	Design 3	27000.0	450.0	7.5
Scenario 2	Design 1	44500.0	741.7	12.4
	Design 2	46000.0	766.7	12.8
	Design 3	44000.0	733.3	12.2

Appendix G, shows the RT calculations of the tracers in the 3 design models under the 2 flow scenarios

3.2.4. Fluid Mass Balance

In all design models and flow scenarios (figures 29 & 30) it is possible to observe a drainage of the system at the start of the modulation. Then, in the time steps 5 to 7, an increase of the fluid mass up to 1.5g/s, in flow scenario no. 1, and up to 0.002g/s, in flow scenario no. 2; followed by a decrease of the fluid mass, in time steps 7 to 9, about -2g/s, in flow scenario no. 1, and -0.004, in flow scenario no. 2. Finally the system is It is levelled to zero, between time steps no. 10 to 24 in the case of scenario 1 and to 14 in the case of scenario no. 2.

The increase and decrease of the fluid mass was higher in designs models no. 1 & 3 than in the model no. 2.

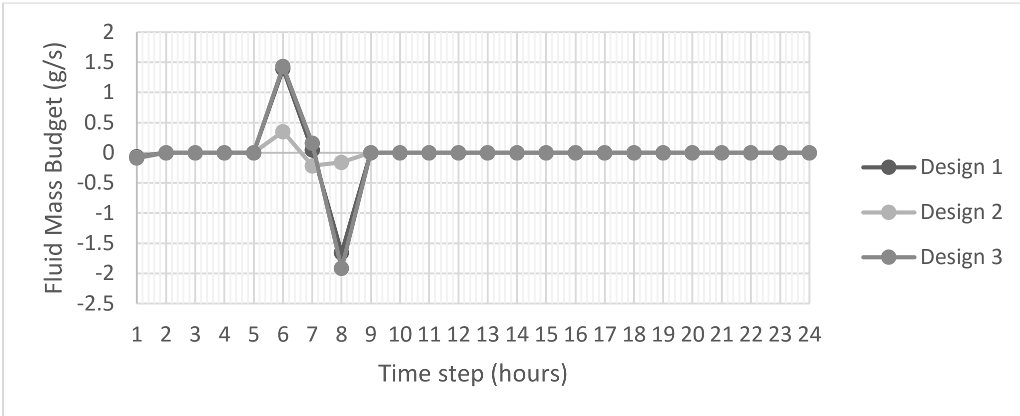


Figure 29. Scenario 1 - Total rate of change in stored fluid (mass/second) by time step

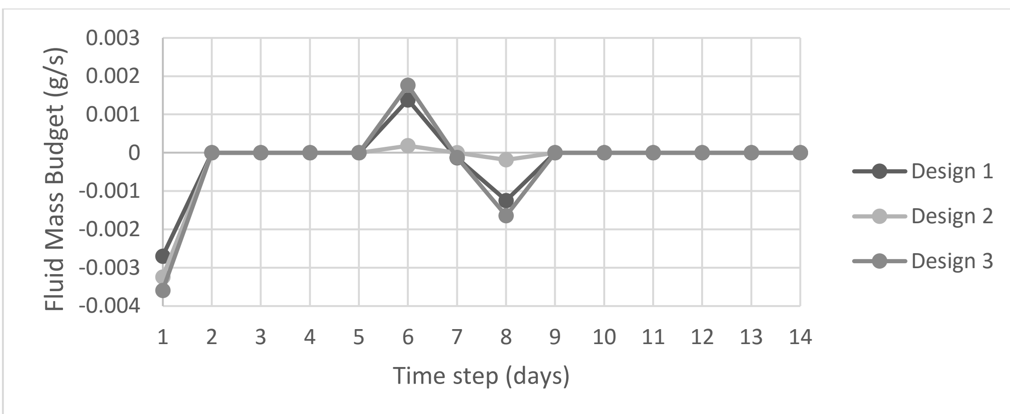


Figure 30. Scenario 2 - Total rate of change in stored fluid (mass/second) by time step

In the flow scenario no. 1, it is possible to observe a fluid mass reduction, between 81 – 87% and in the flow scenario no. 2 a fluid mass reduction between 6 to 35%; being the designs model no. 1 & 3 better in performance, than the design model no. 2 (table 5).

Table 15. Raingarden (Models 1-3) fluid mass reduction or storage capacity under the flow scenarios (1-2)

Total rate of change in stored fluid			Amounts (g/s)	Fluid mass reduction (%)
Scenario 1	Design 1	Sum of increases (+)	1.891311671	87%
		Sum of decreases (-)	2.17272712	
		Net Change	-0.281415449	
	Design 2	Sum of increases (+)	0.459841248	81%
		Sum of decreases (-)	0.567080689	
		Net Change	-0.107239441	
	Design 3	Sum of increases (+)	2.179858393	84%
		Sum of decreases (-)	2.596300132	
		Net Change	-0.416441739	
Scenario 1	Design 1	Sum of increases (+)	0.001436316	35%
		Sum of decreases (-)	0.004135647	
		Net Change	-0.002699331	
	Design 2	Sum of increases (+)	0.000196606	6%
		Sum of decreases (-)	0.003439443	
		Net Change	-0.003242837	
	Design 3	Sum of increases (+)	0.001885546	34%
		Sum of decreases (-)	0.005479884	
		Net Change	-0.003594338	

Appendix H, shows fluid mass budget/balance in the 3 design models under the 2 flow scenarios

4. CONCLUSIONS

In this project, several laboratory and field methods were used to quantify the hydrogeological properties of the NMBU raingarden. Infiltration tests were done before and after the planting, all the other tests were carried out before it.

The composition of the raingarden mixed soil samples produce a “loamy sand” texture meeting the requirements for a raingarden media, according to the different international and national recommendations. The Organic Matter content in the raingarden reinforce the importance of this to facilitate vegetation and microbial activity and to promote vegetation growth as well as a high infiltration capacity. Cation Exchange Capacity of the raingarden allows the plant production and indicates the mixed soils have good clay and OM presence, with high water holding capacity.

Saturated hydraulic conductivity values were higher than the minimum requirements, also according to the different international and national recommendations; being higher after than before planting. The difference, could be explained, first, because of the wet condition of the soil during the tests; the values were lower when the soil was wet and with the presence of plants, and second, because the plant roots increase the pore space and connectivity of soil, so the water can infiltrate faster.

The mixed soil media in NMBU rain garden had a good capacity to retain water at different pressures according to the water retention (pf) curve. The van Genuchten calculated parameters were used to change the default soil parameters on the SUTRA code and to recompile it, making new and appropriate executables able to run the models, and thereby used to define the layer properties of the different layers and regions in the 3 developed models. The fact that the SUTRA code has to be recompiled every time the VG parameters are changed was a weakness for the modelling system, in addition that this code is not constructed particularly for rain gardens hence, it is not perfect for studying the effect on flow peaks.

Under different designs and flow scenarios, raingarden functioning was evaluated in terms of saturation and concentration performance, the retention time of potential pollutants, and water mass balance.

In terms of saturation, the systems appear to be always in a saturation state, that could be explain because it was simulated a situation where there was already water ponding on the surface, while it had to be dry. Therefore, it can be a good idea to drain the top 'air' layer more specifically to create a more appropriate initial conditions. The above is one of the challenges with using a classical soil/groundwater model for these type of systems.

The modelling results and comparison between the 3 models, suggest design model no. 1 (original raingarden design) and no. 3 are better than design model no. 2. It could be because of the column of sand close to the inlet section from the top to the bottom of the garden, which worsen the system capacity to retain the stormwater flow and its dispersion for the mixed soil, that potentially is able to works and provides adsorption processes for the different pollutants. In model no. 2, the concentration transport along the system was lower than the concentration transport in models no. 1 & 3. Besides that, there were not found significant difference between the tracer retention times between the different design models.

The design of the NMBU raingarden (design no. 1) with a sandy part along the entire base of the raingarden and extended to the surface in the central part of the system, with the idea to increase the infiltration conditions, is not making a difference in comparison to the design model no. 3, which only have a sand (drain) layer below the mixed soil layers.

As a future and next part of this research it is recommendable to evaluate the NMBU raingarden performance under different climatic conditions in terms of temperature (warm and cold conditions).

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APPENDIXES

Appendix A. Different plants Latin names and pictures in the rain-garden

Athyrium filix-femina	*Caltha palustris*	*Dryopteris filix-mas*	*Filipendula ulmaria*
			
Geranium sylvaticum "Amy Doucastes"	*Iris pseudacorus*	*Luzula sylvatica*	*Lysimadria vulgaris*
			
Molinia caerulea	*Polygonatum multiflorum*	*Smilacina racemosa*	*Succisa pratensis*
			

Appendix B. Results Grain-size distribution for the raingarden "mixed soil" and "sandy soil" media

- Sandy soil media (samples)

Type of soil	Particle size (mm)	S1			S2			S3		
		Weight (g)	%	Cumulative (%)	Weight (g)	%	Cumulative %	Weight (g)	%	Cumulative %
Silt	< 0.0063	3.4	1%	1%	5.5	1%	1%	4.9	1%	1%
	0,125 - 0.0063	8.9	2%	3%	6.8	2%	3%	6.4	2%	3%
Sand	0,25 - 0.125	33.7	8%	11%	33.4	8%	11%	33.2	8%	11%
	0,5 -0.25	79.9	19%	30%	86.2	21%	32%	84.1	21%	32%
	1 -0.5	123.2	29%	59%	118.9	29%	60%	114	28%	61%
	2 -1	69.6	17%	76%	64.7	16%	76%	66.2	17%	77%
Gravel	4 -2	47.3	11%	87%	48.2	12%	88%	48.8	12%	89%
	6,3 -4	27.4	7%	93%	26.5	6%	94%	19.7	5%	94%
	>6,3	28.1	7%	100%	25.3	6%	100%	23.5	6%	100%

- Mixed soil media (samples)

Type of soil	Particle size (mm)	RO			R2			R3		
		Weight (g)	%	Cumulative (%)	Weight (g)	%	Cumulative %	Weight (g)	%	Cumulative %
Clay	< 0,002	12.51	3%	3%	11.00	3%	3%	11.47	3%	3%
Silt	0,002-0,006	10.84	3%	6%	15.72	4%	7%	8.19	2%	5%
	0,006-0,02	6.67	2%	7%	14.15	4%	10%	13.11	3%	8%
	0,02-0,063	29.20	7%	14%	23.58	6%	16%	23.75	6%	14%
Sand	0,063-0,2	71.61	17%	32%	67.54	17%	33%	64.13	15%	29%
	0,2-0,6	161.41	39%	71%	155.24	38%	71%	157.84	38%	67%
	0,6-2,0	78.66	19%	90%	67.43	17%	88%	85.18	21%	88%
Gravel	2,0-4,0	22.20	5%	95%	20.30	5%	93%	22.40	5%	93%
	4,0-6,0	11.70	3%	98%	11.10	3%	96%	12.70	3%	96%
	>6,0mm	7.90	2%	100%	17.50	4%	100%	15.90	4%	100%

Appendix C. Total Organic Carbon calculation

- Dry Matter (DM) calculation

Samples	Weight of the recipient (g)	Weight of the sample wet (g)		weight of the sample dry (g)		%DM
		with the recipient	without the recipient	with the recipient	without the recipient	
R3	178.83	618.37	439.54	504.21	325.38	74.03
R2	172.28	569.49	397.21	460.82	288.54	72.64
R0	181.07	611.58	430.51	499.86	318.79	74.05

- Bulk Density calculation

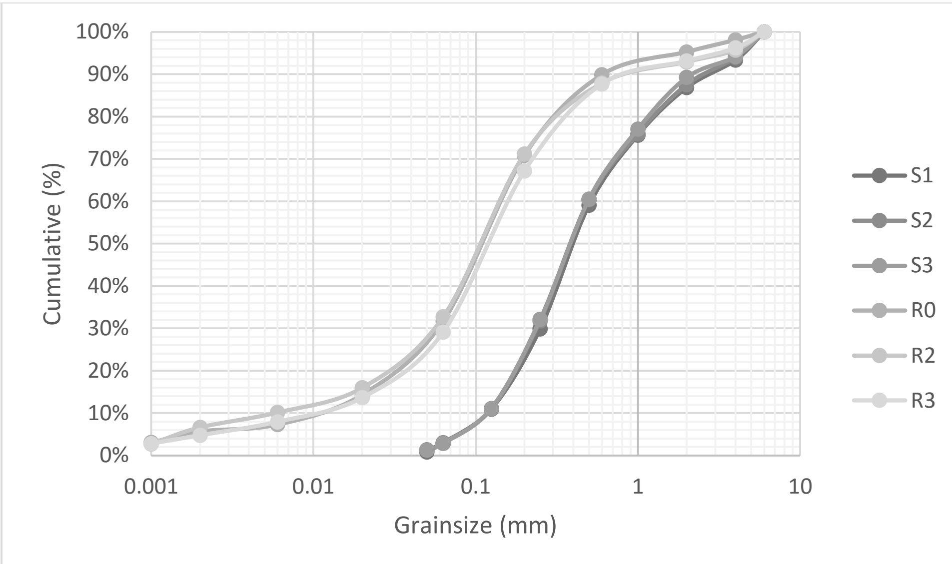
Samples	Weight of the dry sample (g)	Area (m^2)	Volume (m^3)	Bulk density - Concentration of soil (g/cm^3)
R3	325.38	0.0020	0.00024544	1.33
R2	288.54	0.0020	0.00024544	1.18
R0	318.79	0.0024	0.0002851	1.12

- Mineral Soil (MS) and Organic Matter (OM) calculation

Samples	Recipient weight (g)	Weight of the sample before combustion (g)			weight of the sample after combustion (g)			MS (%)	OM (%)
		with recipient	without recipient	Average (g)	with recipient	without recipient	Average (g)		
R3	13.5	27.07	13.57	13.52	25.86	12.36	12.35	91.35	8.65
	12.79	26.26	13.47		25.13	12.34			
R2	12.95	25.42	12.47	12.47	24.15	11.2	11.165	89.53	10.47
	12.65	25.12	12.47		23.78	11.13			
R0	13.06	26.18	13.12	13.235	24.81	11.75	11.865	89.65	10.35
	13.05	26.4	13.35		25.03	11.98			

Appendix D. Ksat calculations

- K_{sat} from grain-size distribution analysis



Type of Soil	Sample	d10	d60	d60/d10	K_{sat}
Sandy	S1	0.12	0.51	4.25	1.44E-04
	S2	0.11	0.50	4.55	1.21E-04
	S3	0.11	0.50	4.55	1.21E-04
Mixed	R0	0.009	0.15	16.67	-
	R2	0.005	0.15	30.00	-
	R3	0.009	0.17	18.89	-

- K_{sat} from Box-Permeameter test

Type of Soil	Mixed			Sandy		
Samples	**R3**	**R2**	**R0**	**S1**	**S2**	**S3**
L samples (cm)	12.5	12.5	12	12.5	12.5	12
L samples (m)	0.125	0.125	0.12	0.125	0.125	0.12
r samples (cm)	2.5	2.5	2.75	2.5	2.5	2.75
r samples (m)	0.025	0.025	0.0275	0.025	0.025	0.0275
A samples (m²)	0.0020	0.0020	0.0024	0.0020	0.0020	0.0024
hA (cm)	18.5	19	18	18	18.5	17
hB (cm)	6.5	6.5	6.5	6.5	6.5	6.5

hA - hB (cm)	12	12.5	11.5	11.5	12	10.5
hA - hB (m)	0.12	0.125	0.115	0.115	0.12	0.105
r mariotte (cm)	2	1.65	1.75	1.65	2	1.65
r mariotte (m)	0.02	0.0165	0.0175	0.0165	0.02	0.0165
h mariotte (cm)	9.8	9.5	8.5	8.5	9.8	8.5
h mariotte (m)	0.098	0.095	0.085	0.085	0.098	0.085
V mariotte (m3)	1.23E-04	8.13E-05	8.18E-05	7.27E-05	1.23E-04	7.27E-05
t1 (min)	75	0.93	15	1.15	3.70	7.48
t2(min)	81	2.62	24	1.72	19.42	12.42
t3 (min)	67	4.83	23.96	2.23	2.83	12.01
t4 (min)	-	-	-	2.62	10.92	-
t5 (min)	-	-	-	-	12.55	
t1 (s)	4500	56	900	69	222	468
t2 (s)	4860	157.2	1440	103	1165	745
t3 (s)	4020	289.8	1437.6	134	170	726
t4 (s)	-	-	-	157	655	-
t5 (s)	-	-	-	-	753	-
Q1 (m3/s)	-	-	-	5.43E-07	1.88E-07	9.76E-08
Q2 (m3/s)	2.53E-08	5.17E-07	5.68E-08	4.63E-07	1.64E-07	1.00E-07
Q3 (m3/s)	3.06E-08	2.80E-07	5.69E-08	-	-	-
K1 (m/s)	-	-	-	3.00E-04	9.97E-05	4.69E-05
K2 (m/s)	1.34E-05	2.63E-04	2.49E-05	2.56E-04	8.68E-05	4.82E-05
K3 (m/s)	1.63E-05	1.43E-04	2.50E-05	-	-	-

- K_{sat} from Double-Ring Infiltrometer Test

  - DRI test **BEFORE** planting

    - No. B1

Water level (mm)		**Time interval**	**Time interval**	**Cumulative time**	**Cumulative time**	**Infiltration**	**Infiltration**	**Cumulative infiltration**	**Infiltration capacity**
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	40								
25	45	5	300	5	300	15	0.015	0.0150	5.00E-05
31	43	5	300	10	600	14	0.014	0.0290	4.67E-05
32	43	5	300	15	900	11	0.011	0.0400	3.67E-05
30	41	5	300	20	1200	13	0.013	0.0530	4.33E-05
31	40	5	300	25	1500	10	0.01	0.0630	3.33E-05
25	43	5	300	30	1800	15	0.015	0.0780	5.00E-05
34	41	5	300	35	2100	9	0.009	0.0870	3.00E-05
33	43	5	300	40	2400	8	0.008	0.0950	2.67E-05
29	42	10	600	50	3000	14	0.014	0.1090	2.33E-05
28	44	10	600	60	3600	14	0.014	0.1230	2.33E-05
31	46	10	600	70	4200	13	0.013	0.1360	2.17E-05
31	40	10	600	80	4800	15	0.015	0.1510	2.50E-05
24	40	15	900	95	5700	16	0.016	0.1670	1.78E-05
20	44	15	900	110	6600	20	0.02	0.1870	2.22E-05
14	44	15	900	125	7500	30	0.03	0.2170	3.33E-05
35	44	15	900	140	8400	9	0.009	0.2260	1.00E-05
18	40	15	900	155	9300	26	0.026	0.2520	2.89E-05
30	45	20	1200	175	10500	10	0.01	0.2620	8.33E-06
24	44	20	1200	195	11700	21	0.021	0.2830	1.75E-05
23	-	20	1200	215	12900	21	0.021	0.3040	1.75E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.3040	12900	2.357E-05	8.484

- No. B2

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	40								
15	42	5	300	5	300	15	0.015	0.0150	5.00E-05
25	40	5	300	10	600	17	0.017	0.0320	5.67E-05
24	40	5	300	15	900	16	0.016	0.0480	5.33E-05
22	40	5	300	20	1200	18	0.018	0.0660	6.00E-05
32	42	5	300	25	1500	8	0.008	0.0740	2.67E-05
34	44	5	300	30	1800	8	0.008	0.0820	2.67E-05
29	40	5	300	35	2100	15	0.015	0.0970	5.00E-05
32	40	5	300	40	2400	8	0.008	0.1050	2.67E-05
27	42	10	600	50	3000	13	0.013	0.1180	2.17E-05
22	40	10	600	60	3600	20	0.02	0.1380	3.33E-05
27	40	10	600	70	4200	13	0.013	0.1510	2.17E-05
26	40	10	600	80	4800	14	0.014	0.1650	2.33E-05
22	42	10	600	90	5400	18	0.018	0.1830	3.00E-05
30	40	10	600	100	6000	12	0.012	0.1950	2.00E-05
29	40	10	600	110	6600	11	0.011	0.2060	1.83E-05
29	-	10	600	120	7200	11	0.011	0.2170	1.83E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.2170	7200	3.014E-05	10.85

- No. B3

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	40								
29	41	5	300	5	300	11	0.011	0.0110	3.67E-05
32	41	5	300	10	600	9	0.009	0.0200	3.00E-05
32	41	10	600	20	1200	9	0.009	0.0290	1.50E-05
25	40	20	1200	40	2400	16	0.016	0.0450	1.33E-05
27	42	20	1200	60	3600	13	0.013	0.0580	1.08E-05
34	42	20	1200	80	4800	8	0.008	0.0660	6.67E-06
30	40	20	1200	100	6000	12	0.012	0.0780	1.00E-05
28	40	20	1200	120	7200	12	0.012	0.0900	1.00E-05
31	40	20	1200	140	8400	12	0.012	0.1020	1.00E-05
28	40	20	1200	160	9600	9	0.009	0.1110	7.50E-06
28	41	20	1200	180	10800	12	0.012	0.1230	1.00E-05
29	-	20	1200	200	12000	12	0.012	0.1350	1.00E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.1350	12000	1.125E-05	4.05

- No. B4

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	42								
35	40	5	300	5	300	7	0.007	0.0070	2.33E-05
38	42	5	300	10	600	2	0.002	0.0090	6.67E-06
38	42	10	600	20	1200	4	0.004	0.0130	6.67E-06

42	42	10	600	30	1800	0	0	0.0130	0.00E+00
42	42	10	600	40	2400	0	0	0.0130	0.00E+00
40	40	30	1800	70	4200	2	0.002	0.0150	1.11E-06
39	45	60	3600	130	7800	1	0.001	0.0160	2.78E-07
44	-	60	3600	190	11400	1	0.001	0.0170	2.78E-07

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0170	11400	1.491E-06	0.54

- No. B5

Water level (mm)		**Time interval**	**Time interval**	**Cumulative time**	**Cumulative time**	**Infiltration**	**Infiltration**	**Cumulative infiltration**	**Infiltration capacity**
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	43								
35	44	5	300	5	300	7	0.007	0.0070	2.33E-05
38	44	5	300	10	600	6	0.006	0.0130	2.00E-05
37	42	5	300	15	900	7	0.007	0.0200	2.33E-05
36	41	5	300	20	1200	6	0.006	0.0260	2.00E-05
30	43	10	600	30	1800	11	0.011	0.0370	1.83E-05
34	44	10	600	40	2400	9	0.009	0.0460	1.50E-05
32	41	10	600	50	3000	12	0.012	0.0580	2.00E-05
30	42	10	600	60	3600	11	0.011	0.0690	1.83E-05
31	41	10	600	70	4200	11	0.011	0.0800	1.83E-05
30	41	10	600	80	4800	11	0.011	0.0910	1.83E-05
21	45	20	1200	100	6000	20	0.02	0.1110	1.67E-05
25	-	20	1200	120	7200	20	0.02	0.1310	1.67E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.1310	7200	1.819E-05	6.55

- No. B6

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	60								
60	60	5	300	5	300	0	0	0.0000	0.00E+00
60	60	5	300	10	600	0	0	0.0000	0.00E+00
59	59	10	600	20	1200	1	0.001	0.0010	1.67E-06
58	58	10	600	30	1800	1	0.001	0.0020	1.67E-06
57	57	20	1200	50	3000	1	0.001	0.0030	8.33E-07
56	60	20	1200	70	4200	1	0.001	0.0040	8.33E-07
58	58	40	2400	110	6600	2	0.002	0.0060	8.33E-07
56	-	40	2400	150	9000	2	0.002	0.0080	8.33E-07

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0080	9000	8.889E-07	0.32

- No. B7

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	60								
58	60	5	300	5	300	2	0.002	0.0020	6.67E-06
60	60	5	300	10	600	0	0	0.0020	0.00E+00
59	59	10	600	20	1200	1	0.001	0.0030	1.67E-06
59	59	10	600	30	1800	0	0	0.0030	0.00E+00
59	59	20	1200	50	3000	0	0	0.0030	0.00E+00
58	58	20	1200	70	4200	1	0.001	0.0040	8.33E-07
58	58	30	1800	100	6000	0	0	0.0040	0.00E+00

58	58	30	1800	130	7800	0	0	0.0040	0.00E+00
57	57	60	3600	190	11400	1	0.001	0.0050	2.78E-07
56	-	60	3600	250	15000	1	0.001	0.0060	2.78E-07

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0060	15000	4.000E-07	0.14

- No. B8

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	60								
58	60	5	300	5	300	2	0.002	0.0020	6.67E-06
58	61	5	300	10	600	2	0.002	0.0040	1.33E-05
59	60	10	600	20	1200	2	0.002	0.0060	1.00E-05
58	60	10	600	30	1800	2	0.002	0.0080	1.33E-05
58	60	20	1200	50	3000	2	0.002	0.0100	8.33E-06
59	59	20	1200	70	4200	1	0.001	0.0110	9.17E-06
54	60	30	1800	100	6000	5	0.005	0.0160	8.89E-06
58	58	30	1800	130	7800	2	0.002	0.0180	1.00E-05
51	61	30	1800	160	9600	7	0.007	0.0250	1.39E-05
54	60	60	3600	220	13200	7	0.007	0.0320	8.89E-06
58	58	60	3600	280	16800	2	0.002	0.0340	9.44E-06
54	54	60	3600	340	20400	4	0.004	0.0380	1.06E-05
45	60	60	3600	400	24000	9	0.009	0.0470	1.31E-05
54	-	60	3600	460	27600	6	0.006	0.0530	1.47E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0470	24000	1.958E-06	0.71

- No. B9

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	70								
60	70	5	300	5	300	10	0.01	0.0100	3.33E-05
68	71	5	300	10	600	2	0.002	0.0120	6.67E-06
67	70	10	600	20	1200	4	0.004	0.0160	6.67E-06
70	70	10	600	30	1800	0	0	0.0160	0.00E+00
64	74	20	1200	50	3000	6	0.006	0.0220	5.00E-06
70	70	20	1200	70	4200	4	0.004	0.0260	3.33E-06
65	72	30	1800	100	6000	5	0.005	0.0310	2.78E-06
66	70	30	1800	130	7800	6	0.006	0.0370	3.33E-06
66	75	30	1800	160	9600	4	0.004	0.0410	2.22E-06
71	71	30	1800	190	11400	4	0.004	0.0450	2.22E-06
67	-	30	1800	220	13200	4	0.004	0.0490	2.22E-06

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0490	13200	3.712E-06	1.34

- No. B10

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	80								
68	70	5	300	5	300	12	0.012	0.0120	4.00E-05

68	71	5	300	10	600	2	0.002	0.0140	6.67E-06
70	70	10	600	20	1200	1	0.001	0.0150	1.67E-06
65	70	10	600	30	1800	5	0.005	0.0200	8.33E-06
64	70	20	1200	50	3000	6	0.006	0.0260	5.00E-06
66	70	20	1200	70	4200	4	0.004	0.0300	3.33E-06
63	72	30	1800	100	6000	7	0.007	0.0370	3.89E-06
63	70	30	1800	130	7800	9	0.009	0.0460	5.00E-06
64	70	30	1800	160	9600	6	0.006	0.0520	3.33E-06
64	-	30	1800	190	11400	6	0.006	0.0580	3.33E-06

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0580	11400	5.088E-06	1.832

- No. 11

Water level (mm)		**Time interval**	**Time interval**	**Cumulative time**	**Cumulative time**	**Infiltration**	**Infiltration**	**Cumulative infiltration**	**Infiltration capacity**
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	70								
65	71	5	300	5	300	5	0.005	0.0050	1.67E-05
70	70	5	300	10	600	1	0.001	0.0060	3.33E-06
70	70	10	600	20	1200	0	0	0.0060	0.00E+00
68	70	10	600	30	1800	2	0.002	0.0080	3.33E-06
70	71	20	1200	50	3000	0	0	0.0080	0.00E+00
70	70	20	1200	70	4200	1	0.001	0.0090	8.33E-07
68	70	30	1800	100	6000	2	0.002	0.0110	1.11E-06
68	-	30	1800	130	7800	2	0.002	0.0130	1.11E-06

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0130	7800	1.667E-06	0.600

- No. 12

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	50								
44	50	5	300	5	300	6	0.006	0.0060	2.00E-05
43	51	5	300	10	600	7	0.007	0.0130	2.33E-05
49	50	20	1200	30	1800	2	0.002	0.0150	1.67E-06
49	50	30	1800	60	3600	1	0.001	0.0160	5.56E-07
49	51	60	3600	120	7200	1	0.001	0.0170	2.78E-07
49	50	60	3600	180	10800	2	0.002	0.0190	5.56E-07
47	52	60	3600	240	14400	3	0.003	0.0220	8.33E-07
52	55	60	3600	300	18000	0	0	0.0220	0.00E+00
53	53	60	3600	360	21600	2	0.002	0.0240	5.56E-07
51	-	60	3600	420	25200	2	0.002	0.0260	5.56E-07

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0260	25200	1.032E-06	0.37

- DRI test after planting

  - No. A1

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	58								
0	58	3	180	3	180	58	0.058	0.0580	3.22E-04
21	61	3	180	6	360	37	0.037	0.0950	2.06E-04
10	62	5	300	11	660	51	0.051	0.1460	1.70E-04
0	63	5	300	16	960	62	0.062	0.2080	2.07E-04
38	60	5	300	21	1260	25	0.025	0.2330	8.33E-05
37	60	5	300	26	1560	23	0.023	0.2560	7.67E-05
38	58	5	300	31	1860	22	0.022	0.2780	7.33E-05
39	58	5	300	36	2160	19	0.019	0.2970	6.33E-05
40	60	5	300	41	2460	18	0.018	0.3150	6.00E-05
40	63	5	300	46	2760	20	0.02	0.3350	6.67E-05
41	66	5	300	51	3060	22	0.022	0.3570	7.33E-05
45	65	5	300	56	3360	21	0.021	0.3780	7.00E-05
47	64	5	300	61	3660	18	0.018	0.3960	6.00E-05
48	64	5	300	66	3960	16	0.016	0.4120	5.33E-05
48	48	5	300	71	4260	16	0.016	0.4280	5.33E-05
32	-	5	300	76	4560	16	0.016	0.4440	5.33E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.4440	4560	9.737E-05	35.053

- No. A2

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	50								
0	50	3	180	3	180	50	0.05	0.0500	2.78E-04
5	50	3	180	6	360	45	0.045	0.0950	2.50E-04
10	50	3	180	9	540	40	0.04	0.1350	2.22E-04
15	50	3	180	12	720	35	0.035	0.1700	1.94E-04
17	51	3	180	15	900	33	0.033	0.2030	1.83E-04
18	51	3	180	18	1080	33	0.033	0.2360	1.83E-04
24	59	3	180	21	1260	27	0.027	0.2630	1.50E-04
5	56	5	300	26	1560	54	0.054	0.3170	1.80E-04
19	50	5	300	31	1860	37	0.037	0.3540	1.23E-04
15	50	5	300	36	2160	35	0.035	0.3890	1.17E-04
50	51	5	300	41	2460	0	0	0.3890	0.00E+00
18	60	5	300	46	2760	33	0.033	0.4220	1.10E-04
23	51	5	300	51	3060	37	0.037	0.4590	1.23E-04
20	51	5	300	56	3360	31	0.031	0.4900	1.03E-04
21	54	5	300	61	3660	30	0.03	0.5200	1.00E-04
23	54	5	300	66	3960	31	0.031	0.5510	1.03E-04
22	44	5	300	71	4260	32	0.032	0.5830	1.07E-04
12	58	5	300	76	4560	32	0.032	0.6150	1.07E-04
26	-	5	300	81	4860	32	0.032	0.6470	1.07E-04

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.6470	4860	1.331E-04	47.93

- No. A3

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	69								
30	64	3	180	3	180	39	0.039	0.0390	2.17E-04
22	69	3	180	6	360	42	0.042	0.0810	2.33E-04
28	85	3	180	9	540	41	0.041	0.1220	2.28E-04
45	83	3	180	12	720	40	0.04	0.1620	2.22E-04
48	78	3	180	15	900	35	0.035	0.1970	1.94E-04
49	84	3	180	18	1080	29	0.029	0.2260	1.61E-04
45	79	3	180	21	1260	39	0.039	0.2650	2.17E-04
45	77	3	180	24	1440	34	0.034	0.2990	1.89E-04
45	84	3	180	27	1620	32	0.032	0.3310	1.78E-04
51	83	3	180	30	1800	33	0.033	0.3640	1.83E-04
30	82	5	300	35	2100	53	0.053	0.4170	1.77E-04
40	79	5	300	40	2400	42	0.042	0.4590	1.40E-04
39	75	5	300	45	2700	40	0.04	0.4990	1.33E-04
35	79	5	300	50	3000	40	0.04	0.5390	1.33E-04
39	70	5	300	55	3300	40	0.04	0.5790	1.33E-04
30	-	5	300	60	3600	40	0.04	0.6190	1.33E-04

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.6190	3600	1.719E-04	61.90

- No. A4

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	60								
55	55	3	180	3	180	5	0.005	0.0050	2.78E-05
54	54	3	180	6	360	1	0.001	0.0060	5.56E-06
50	50	5	300	11	660	4	0.004	0.0100	1.33E-05
48	64	5	300	16	960	2	0.002	0.0120	6.67E-06
58	58	10	600	26	1560	6	0.006	0.0180	1.00E-05
47	47	10	600	36	2160	11	0.011	0.0290	1.83E-05
44	55	10	600	46	2760	3	0.003	0.0320	5.00E-06
42	42	20	1200	66	3960	13	0.013	0.0450	1.08E-05
32	45	20	1200	86	5160	10	0.01	0.0550	8.33E-06
35	-	20	1200	106	6360	10	0.01	0.0650	8.33E-06

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0650	6360	1.022E-05	3.68

- No. A5

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	60								
10	59	3	180	3	180	50	0.05	0.0500	2.78E-04
0	58	3	180	6	360	59	0.059	0.1090	3.28E-04
15	58	3	180	9	540	43	0.043	0.1520	2.39E-04
58	61	5	300	14	840	0	0	0.1520	0.00E+00
17	59	5	300	19	1140	44	0.044	0.1960	1.47E-04

15	55	5	300	24	1440	44	0.044	0.2400	1.47E-04
10	68	5	300	29	1740	45	0.045	0.2850	1.50E-04
34	68	5	300	34	2040	34	0.034	0.3190	1.13E-04
40	74	5	300	39	2340	28	0.028	0.3470	9.33E-05
31	60	8	480	47	2820	43	0.043	0.3900	8.96E-05
24	60	8	480	55	3300	36	0.036	0.4260	7.50E-05
24	40	8	480	63	3780	36	0.036	0.4620	7.50E-05
4	-	8	480	71	4260	36	0.036	0.4980	7.50E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.4980	4260	1.169E-04	42.08

- No. A6

Water level (mm)		**Time interval**	**Time interval**	**Cumulative time**	**Cumulative time**	**Infiltration**	**Infiltration**	**Cumulative infiltration**	**Infiltration capacity**
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	65	0	0	0	0				
50	60	3	180	3	180	15	0.015	0.0150	8.33E-05
58	58	3	180	6	360	2	0.002	0.0170	1.11E-05
52	51	10	600	16	960	6	0.006	0.0230	1.00E-05
46	51	10	600	26	1560	5	0.005	0.0280	8.33E-06
39	58	20	1200	46	2760	12	0.012	0.0400	1.00E-05
48	56	20	1200	66	3960	10	0.01	0.0500	8.33E-06
28	54	40	2400	106	6360	28	0.028	0.0780	1.17E-05
30	52	40	2400	146	8760	24	0.024	0.1020	1.00E-05
28	-	40	2400	186	11160	24	0.024	0.1260	1.00E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.1260	11160	1.129E-05	4.06

- No. A7

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	60	0	0	0	0				
55	54	3	180	3	180	5	0.005	0.0050	2.78E-05
53	52	3	180	6	360	1	0.001	0.0060	5.56E-06
46	62	10	600	16	960	6	0.006	0.0120	1.00E-05
58	61	10	600	26	1560	4	0.004	0.0160	6.67E-06
47	59	30	1800	56	3360	14	0.014	0.0300	7.78E-06
53	60	30	1800	86	5160	6	0.006	0.0360	3.33E-06
47	47	30	1800	116	6960	13	0.013	0.0490	7.22E-06
34	-	30	1800	146	8760	13	0.013	0.0620	7.22E-06

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.0620	8760	7.078E-06	2.55

- No. A8

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	After filling	(min)	(s)	(min)	(s)	(mm)	(m)	(m)	(m/s)
-	65	0	0	0	0				
50	50	3	180	3	180	15	0.015	0.0150	8.33E-05
43	67	3	180	6	360	7	0.007	0.0220	3.89E-05
53	67	10	600	16	960	14	0.014	0.0360	2.33E-05
56	71	10	600	26	1560	11	0.011	0.0470	1.83E-05
30	69	30	1800	56	3360	41	0.041	0.0880	2.28E-05
28	68	30	1800	86	5160	41	0.041	0.1290	2.28E-05
27	-	30	1800	116	6960	41	0.041	0.1700	2.28E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.1700	6960	2.443E-05	8.79

- No. A9

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	69	0	0	0	0				
60	60	3	180	3	180	9	0.009	0.0090	5.00E-05
55	54	3	180	6	360	5	0.005	0.0140	2.78E-05
40	83	10	600	16	960	14	0.014	0.0280	2.33E-05
71	68	10	600	26	1560	12	0.012	0.0400	2.00E-05
30	90	30	1800	56	3360	38	0.038	0.0780	2.11E-05
52	102	30	1800	86	5160	38	0.038	0.1160	2.11E-05
64	64	30	1800	116	6960	38	0.038	0.1540	2.11E-05
26	-	30	1800	146	8760	38	0.038	0.1920	2.11E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.1920	8760	2.192E-05	7.89

- No. A10

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	71	0	0	0	0				
60	60	3	180	3	180	11	0.011	0.0110	6.11E-05
52	81	3	180	6	360	8	0.008	0.0190	4.44E-05
61	60	10	600	16	960	20	0.02	0.0390	3.33E-05

39	88	10	600	26	1560	21	0.021	0.0600	3.50E-05
27	88	30	1800	56	3360	61	0.061	0.1210	3.39E-05
34	93	30	1800	86	5160	54	0.054	0.1750	3.00E-05
39	-	30	1800	116	6960	54	0.054	0.2290	3.00E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.2290	6960	3.290E-05	11.84

- No. A11

Water level (mm)		**Time interval**	**Time interval**	**Cumulative time**	**Cumulative time**	**Infiltration**	**Infiltration**	**Cumulative infiltration**	**Infiltration capacity**
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	54	0	0	0	0				
44	65	3	180	3	180	10	0.01	0.0100	5.56E-05
50	60	3	180	6	360	15	0.015	0.0250	8.33E-05
37	64	5	300	11	660	23	0.023	0.0480	7.67E-05
56	68	5	300	16	960	8	0.008	0.0560	2.67E-05
23	80	10	600	26	1560	45	0.045	0.1010	7.50E-05
44	79	10	600	36	2160	36	0.036	0.1370	6.00E-05
42	88	10	600	46	2760	37	0.037	0.1740	6.17E-05
46	84	10	600	56	3360	42	0.042	0.2160	7.00E-05
42	85	10	600	66	3960	42	0.042	0.2580	7.00E-05
45	84	10	600	76	4560	40	0.04	0.2980	6.67E-05
45	88	10	600	86	5160	39	0.039	0.3370	6.50E-05
49	91	10	600	96	5760	39	0.039	0.3760	6.50E-05
52	-	10	600	106	6360	39	0.039	0.4150	6.50E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.4150	6360	6.525E-05	23.491

- No. A12

Water level (mm)		Time interval	Time interval	Cumulative time	Cumulative time	Infiltration	Infiltration	Cumulative infiltration	Infiltration capacity
Before filling	**After filling**	**(min)**	**(s)**	**(min)**	**(s)**	**(mm)**	**(m)**	**(m)**	**(m/s)**
-	78	0	0	0	0				
65	65	3	180	3	180	13	0.013	0.0130	7.22E-05
49	88	3	180	6	360	16	0.016	0.0290	8.89E-05
68	66	5	300	11	660	20	0.02	0.0490	6.67E-05
48	80	5	300	16	960	18	0.018	0.0670	6.00E-05
58	86	10	600	26	1560	22	0.022	0.0890	3.67E-05
52	111	10	600	36	2160	34	0.034	0.1230	5.67E-05
82	82	10	600	46	2760	29	0.029	0.1520	4.83E-05
48	90	10	600	56	3360	34	0.034	0.1860	5.67E-05
60	88	10	600	66	3960	30	0.03	0.2160	5.00E-05
64	90	10	600	76	4560	24	0.024	0.2400	4.00E-05
64	84	10	600	86	5160	26	0.026	0.2660	4.33E-05
58	90	10	600	96	5760	26	0.026	0.2920	4.33E-05
64	86	10	600	106	6360	26	0.026	0.3180	4.33E-05
60	-	10	600	116	6960	26	0.026	0.3440	4.33E-05

Q = Δh / Δt ->	Δh (m)	Δt (s)	Q = K (m/s)	Q = K (cm/h)
	0.3440	6960	4.943E-05	17.79

Appendix E. Water Retention (pF) Curve calculations

- Pf test calculations

Type of Soil Sample	Ring no.	Cylinder no.	Soil Density	Pore Volume	Porosity	Air (100hPa)	Water Withdrawal	Saturation Volume (Water 1hPa)	Water 20hPa	Water 100hPa	Water 1000hPa	Water 15000hPa	Usable water	Material density	Air permeability
			g/cm3	vol%	(%)	vol%	vol%	vol%	vol%	vol%	vol%	vol%	vol%	g/cm3	µm2
Mixed Soil	1	1039	0.85	68.09	0.68	47.07	3.01	49.65	25.55	21.02	14.95	7283.25	13.74	2.65	86.33
Mixed Soil	2	571	0.89	64.34	0.64	44.34	5.98	51.62	24.11	20.00	14.75	8700.40	11.30	2.49	86.33
Mixed Soil	3	1087	0.87	68.36	0.68	42.67	18.13	52.17	30.04	25.69	19.61	9071.55	16.62	2.75	94.97
Mixed Soil	4	501	1.28	50.49	0.50	20.76	26.63	43.09	33.26	29.73	24.37	6698.86	23.03	2.58	90.65
Mixed Soil	5	140	1.09	62.32	0.62	41.68	12.88	46.17	23.64	20.64	14.37	5016.27	15.62	2.88	103.60
Mixed Soil	6	131	1.17	56.15	0.56	29.96	19.66	43.96	33.21	26.19	19.57	5794.66	20.40	2.66	60.43
Mixed Soil	7	961	0.93	64.06	0.64	44.68	2.67	43.01	24.76	19.38	13.13	5935.59	13.44	2.58	99.28
Mixed Soil	8	1327	0.98	65.79	0.66	37.19	23.61	47.52	32.46	28.60	22.49	5994.24	22.61	2.87	103.60
Mixed Soil	9	127	0.91	63.65	0.64	46.04	6.39	44.69	22.03	17.61	12.42	5085.27	12.52	2.52	107.92
Mixed Soil	10	658	1.19	55.65	0.56	33.50	3.12	42.34	27.82	22.15	14.22	5843.45	16.31	2.68	69.07
Mixed Soil	11	1164	1.17	52.83	0.53	32.90	11.69	38.85	25.50	19.93	13.96	6046.86	13.88	2.47	77.70
Mixed Soil	12	1410	0.97	63.68	0.64	39.09	16.64	51.63	29.20	24.59	17.58	6574.48	18.02	2.67	82.02
Mixed Soil	13	624	0.77	70.59	0.71	50.22	12.60	46.55	25.21	20.37	14.73	7551.03	3.88	2.74	77.70
Mixed Soil	14	747	1.07	59.11	0.59	36.88	3.78	28.52	27.56	22.23	16.75	8647.14	13.58	2.62	60.43
Mixed Soil	15	247	0.85	67.73	0.68	44.34	16.04	51.62	27.46	23.39	18.93	9158.83	14.23	2.65	107.92
Mixed Soil	16	208	0.98	62.28	0.62	37.82	14.08	50.05	31.48	24.46	17.15	7983.91	16.48	2.60	94.97
Mixed Soil	17	1517	1.32	48.44	0.48	23.61	20.66	41.40	31.35	24.83	19.27	6513.44	18.32	2.57	38.85
Mixed Soil	18	648	1.41	45.17	0.45	16.15	16.76	37.30	33.82	29.02	21.88	8493.36	20.53	2.57	51.80

Mixed Soil	19	871	1.08	59.48	0.59	37.19	14.42	43.67	29.20	22.29	16.92	4243.49	18.05	2.67	86.33
Mixed Soil	20	1205	1.04	61.37	0.61	41.03	15.39	49.54	25.49	20.34	16.25	6209.97	14.13	2.70	90.65
Mixed Soil	21	926	1.08	58.52	0.59	35.02	19.22	46.63	30.19	23.50	18.56	16519.10	6.98	2.60	60.43
Mixed Soil	22	880	0.89	64.72	0.65	41.03	14.91	47.83	29.54	23.69	19.17	11669.08	12.02	2.52	86.33
Mixed Soil	23	632	1.16	54.78	0.55	31.42	15.26	41.42	27.54	23.36	17.99	6649.21	16.71	2.55	82.02
Mixed Soil	24	1155	1.02	60.09	0.60	34.71	16.25	51.89	33.01	25.38	20.56	8952.46	16.43	2.55	51.80
Mixed Soil	25	347	0.83	71.29	0.71	49.87	9.31	52.28	26.37	21.42	16.95	7827.26	13.59	2.90	77.70
Mixed Soil	26	1391	1.19	54.38	0.54	31.42	18.51	42.50	28.00	22.96	18.62	4960.47	18.00	2.60	77.70
Mixed Soil	27	801	1.10	56.43	0.56	32.30	17.15	45.08	30.34	24.13	19.26	6058.13	18.07	2.53	69.07
Mixed Soil	28	6	1.00	62.19	0.62	39.41	19.49	43.59	29.46	22.78	18.10	5248.01	17.53	2.65	64.75
Mixed Soil	29	754	0.92	64.93	0.65	41.68	12.84	46.92	24.51	23.25	15.79	5922.66	17.33	2.62	86.33
Mixed Soil	30	358	0.98	62.66	0.63	36.56	15.78	47.79	31.56	26.10	20.65	9013.01	17.09	2.63	69.07
Mixed Soil	31	472	1.02	59.75	0.60	29.39	24.12	52.72	36.43	30.36	25.54	8794.96	21.57	2.54	64.75
Mixed Soil	32	1194	1.05	58.82	0.59	35.02	17.72	30.24	29.70	23.80	19.25	6423.64	17.38	2.56	60.43
Sandy Soil	1	1219	1.42	49.03	0.49	42.67	1.92	29.28	14.49	6.36	3.93	1395.38	4.96	2.78	73.38
Sandy Soil	2	400	1.61	41.61	0.42	37.19	1.01	33.51	11.84	4.42	2.85	1581.01	2.84	2.75	86.33
Sandy Soil	3	426	1.57	42.60	0.43	37.19	0.96	32.11	11.82	5.41	3.41	1531.63	4.92	2.74	69.07
Sandy Soil	4	824	1.53	44.13	0.44	37.82	0.99	34.00	11.61	6.31	3.24	1390.78	12.82	2.63	103.60

- Descriptive statistical results of the mixed and the sandy soil media properties in by Pf method

Type of Soil	Properties	Units	Median	Max	Min	SD	IC 95%	
							-	+
Mixed soil	Soil Density	g/cm3	1.0	1.4	0.8	0.1	1.0	1.1
	Pore Volume	vol%	61	71	45	6	58	63
	Porosity (%)	%	0.6	0.7	0.5	0.1	0.6	0.6
	Air (100hPa)	vol%	37.0	50.2	16.2	7.9	34.3	39.8
	Saturation Volume [Water Content (1hPa)]	vol%	14.5	26.6	2.7	6.2	12.4	16.7
	Water Content (20hPa)	vol%	45.4	52.7	28.5	5.9	43.3	47.4
	Water Content (100hPa)	vol%	28.7	36.4	22.0	3.5	27.5	29.9
	Water Content (1000hPa)	vol%	23.5	30.4	17.6	3.1	22.5	24.6
	Water Content (15000hPa)	vol%	17.9	25.5	12.4	3.1	16.9	19.0
	Usable water	vol%	7340	16519	4243	2345	6527	8153
	Material density	g/cm3	15.9	23.0	3.9	4.0	14.5	17.3
	Air permeability	µm2	2.6	2.9	2.5	0.1	2.6	2.7
Sandy Soil	Soil Density	g/cm3	1.5	1.6	1.4	0.1	1.5	1.6
	Pore Volume	vol%	44	49	42	3	41	48
	Porosity	%	0.4	0.5	0.4	0.0	0.4	0.5
	Air (100hPa)	vol%	38.7	42.7	37.2	2.7	36.1	41.3
	Saturation Volume [Water Content (1hPa)]	vol%	1.2	1.9	1.0	0.5	0.8	1.7
	Water Content (20hPa)	vol%	32.2	34.0	29.3	2.1	30.1	34.3
	Water Content (100hPa)	vol%	12.4	14.5	11.6	1.4	11.1	13.8
	Water Content (1000hPa)	vol%	5.6	6.4	4.4	0.9	4.7	6.5
	Water Content (15000hPa)	vol%	3.4	3.9	2.9	0.4	2.9	3.8
	Usable water	vol%	1475	1581	1391	96	1380	1569
	Material density	g/cm3	6.4	12.8	2.8	4.4	2.1	10.7
	Air permeability	µm2	2.7	2.8	2.6	0.1	2.7	2.8

- Pf Curves by samples (rings)

  - Mixed-soil samples

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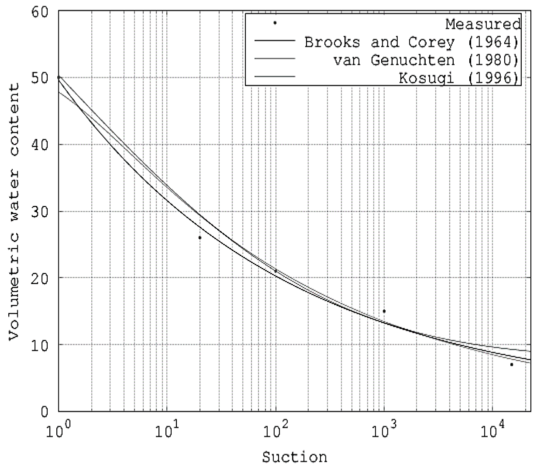	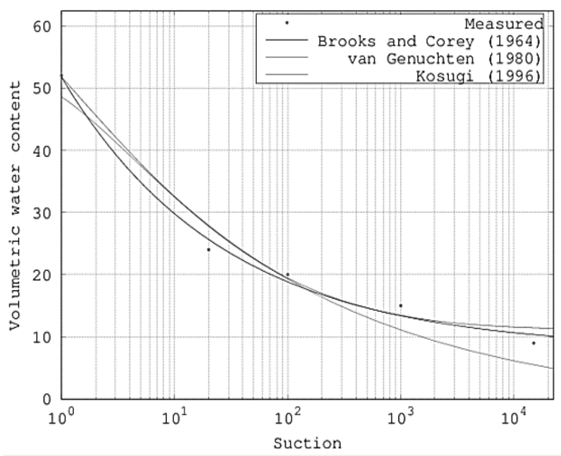
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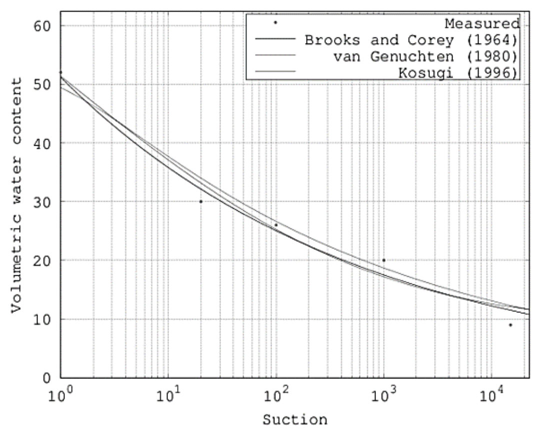	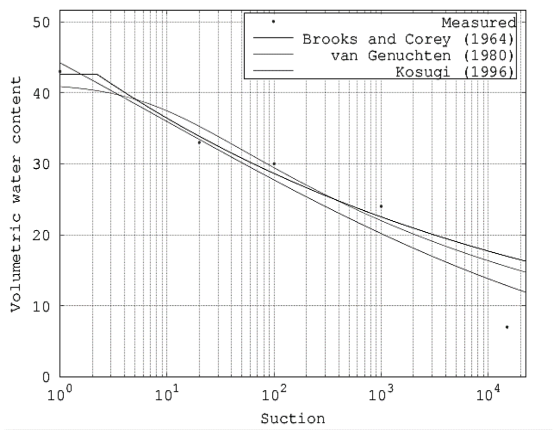
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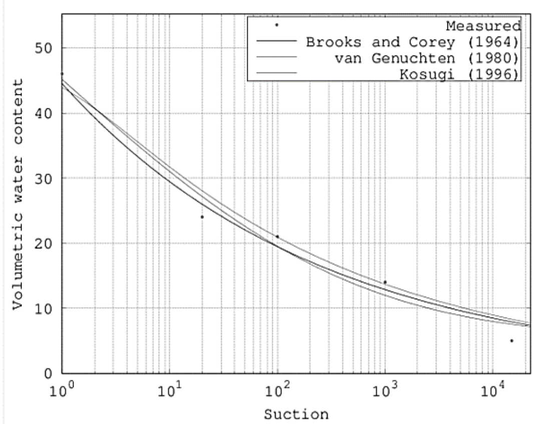	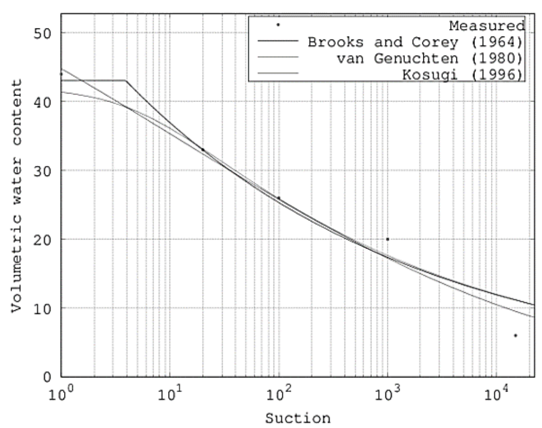
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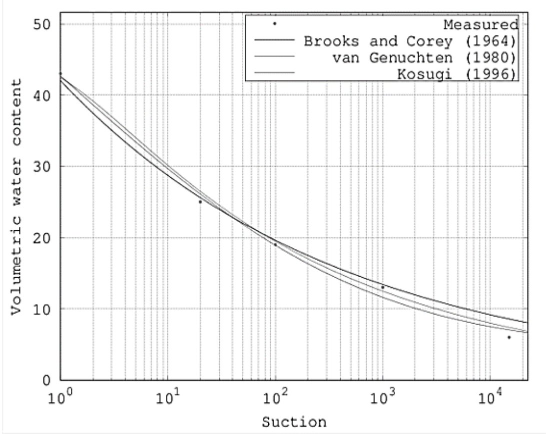	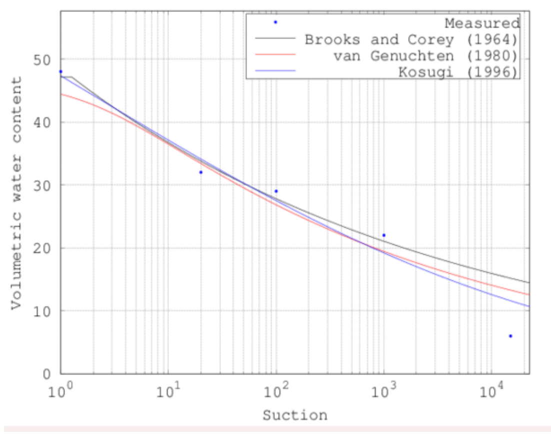
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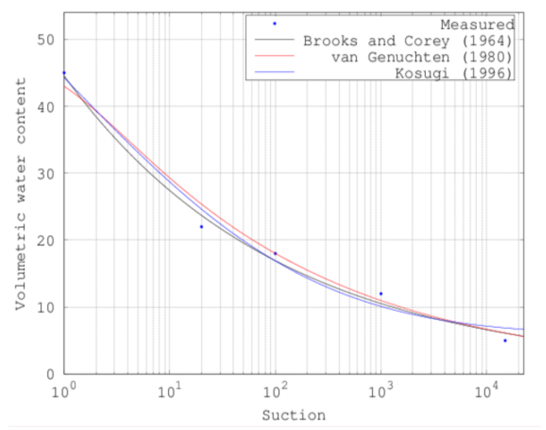	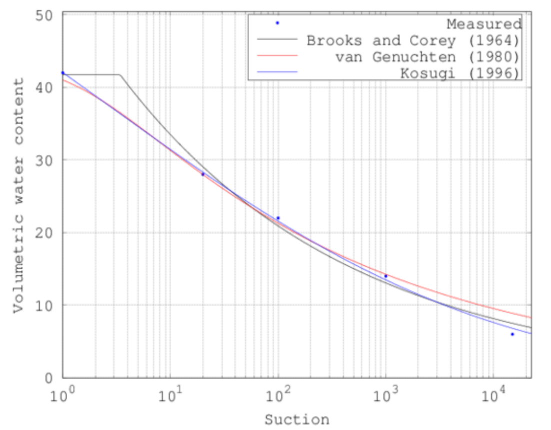
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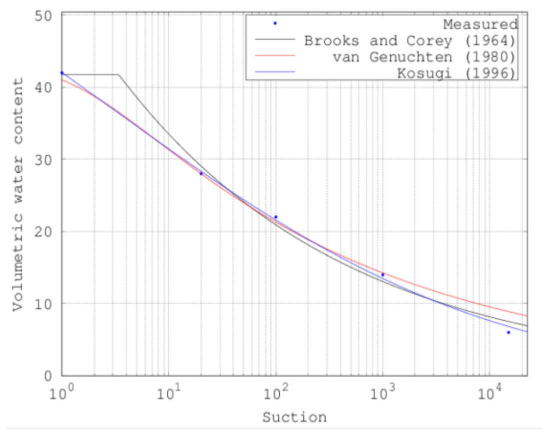	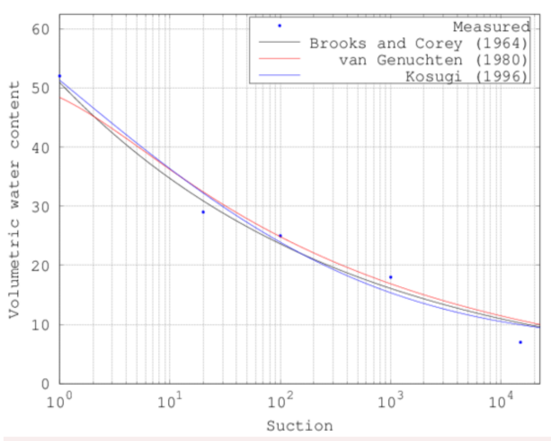
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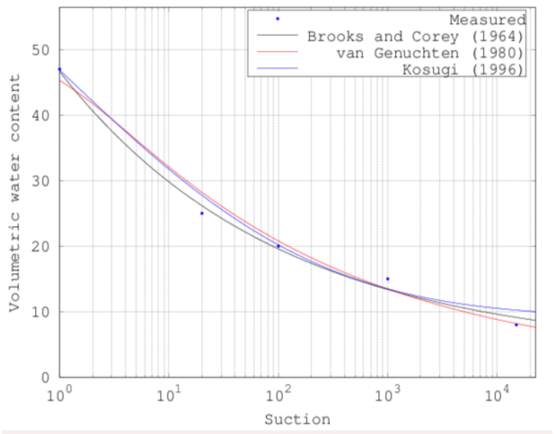

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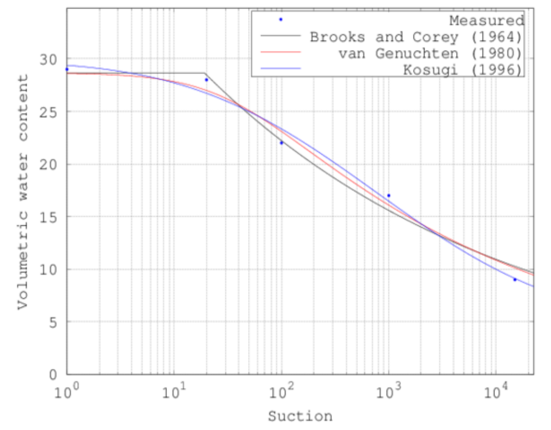

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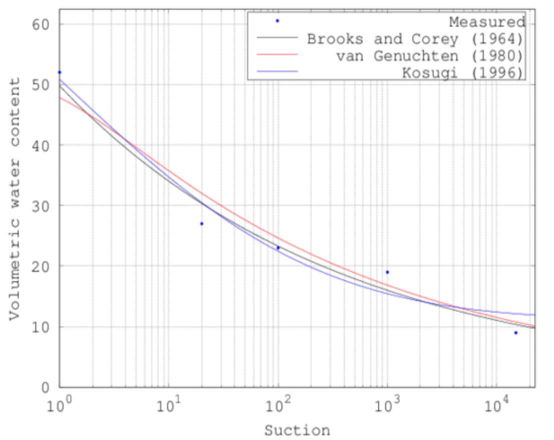

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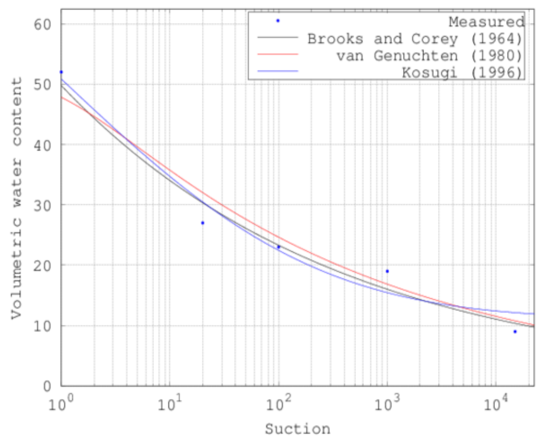

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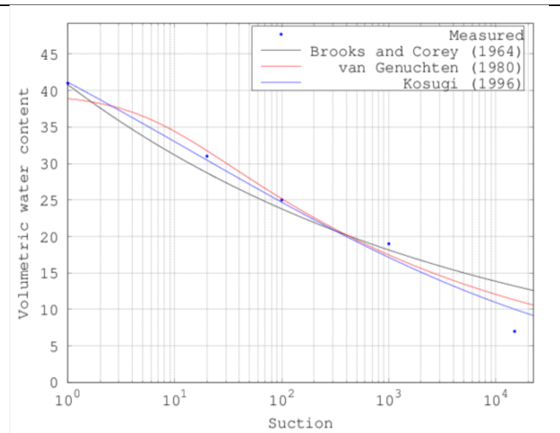

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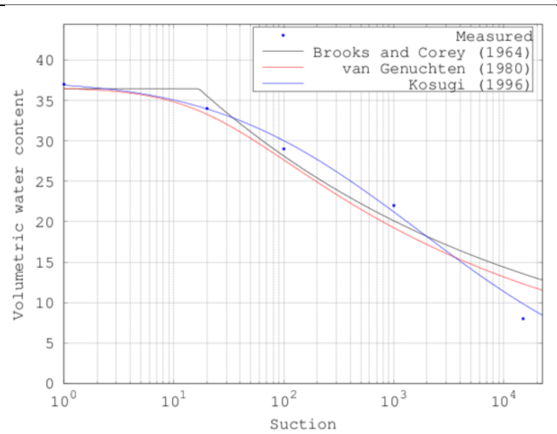

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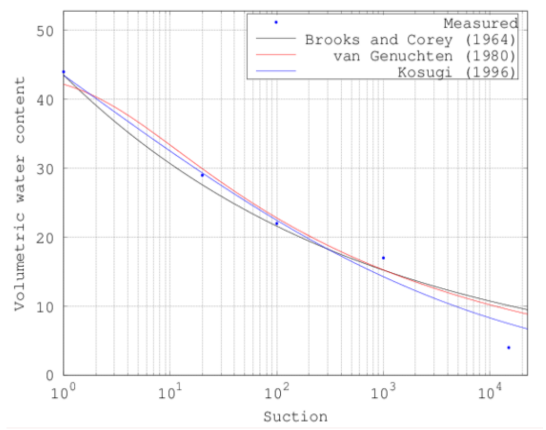

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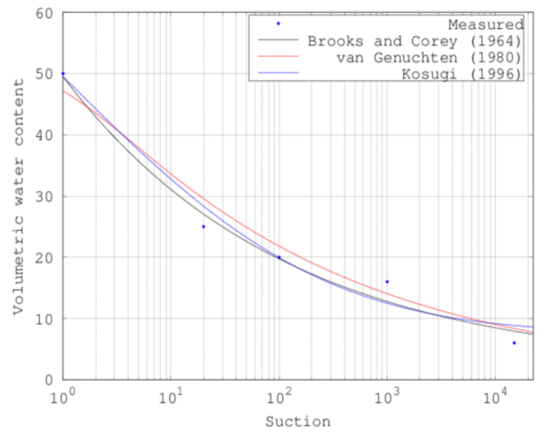

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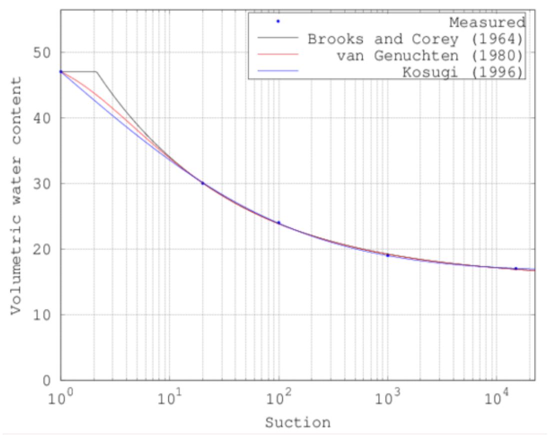

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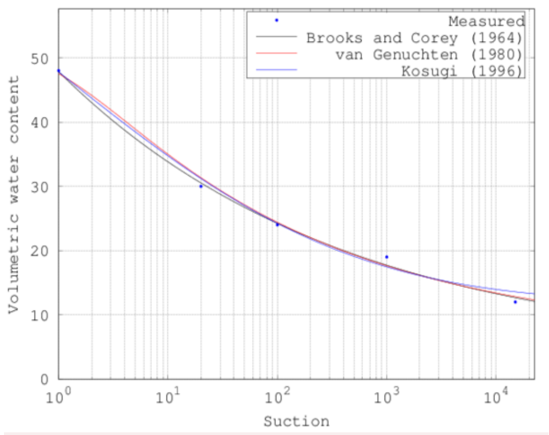

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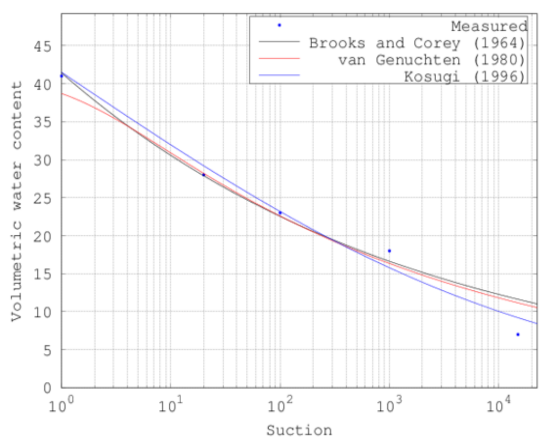

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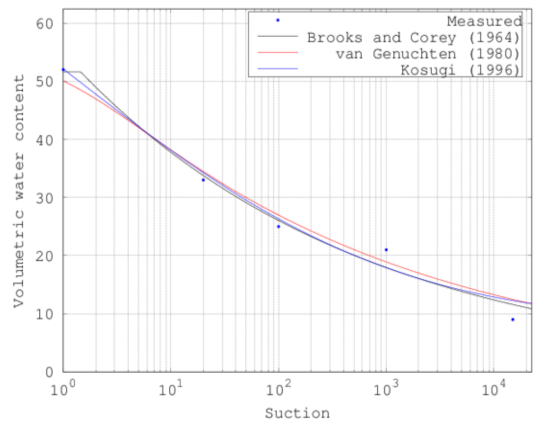

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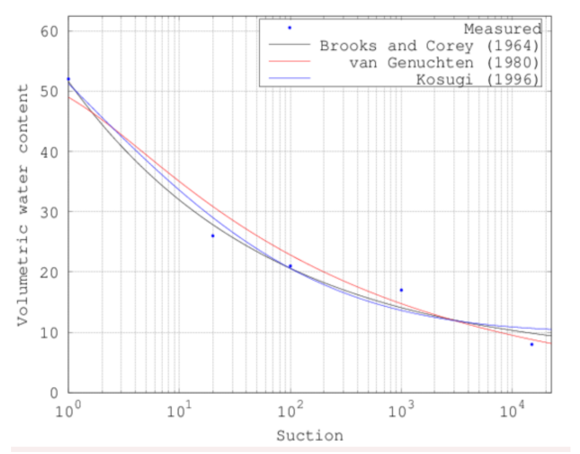

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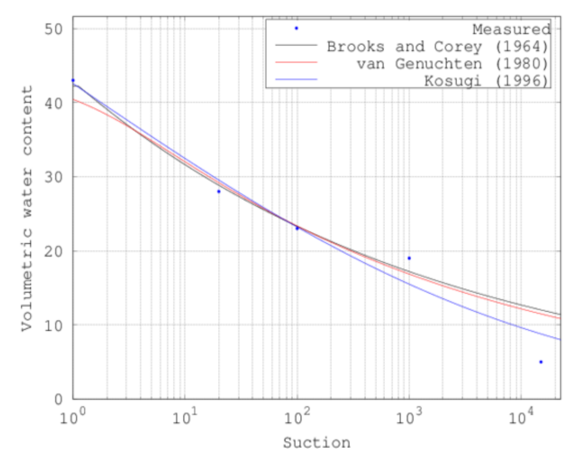

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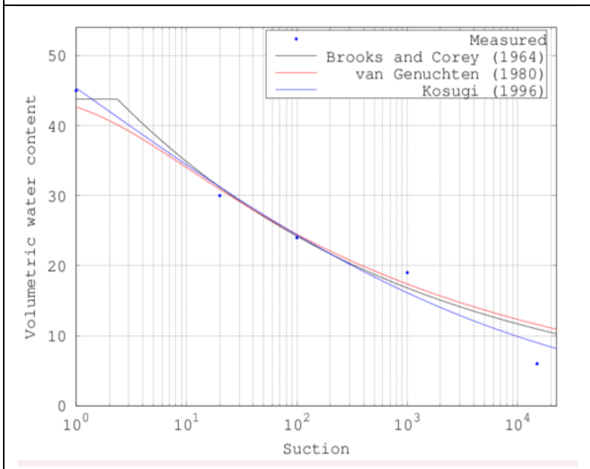

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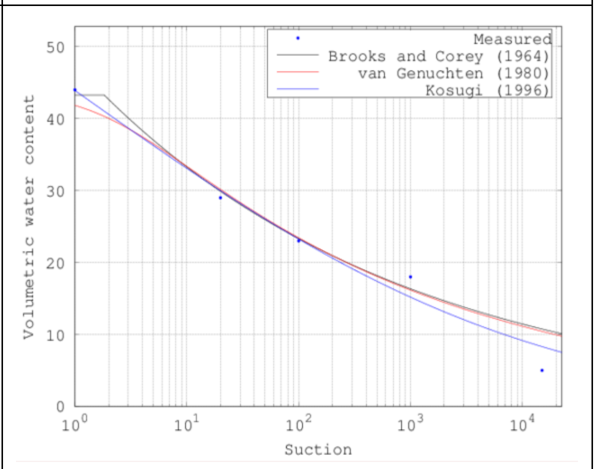

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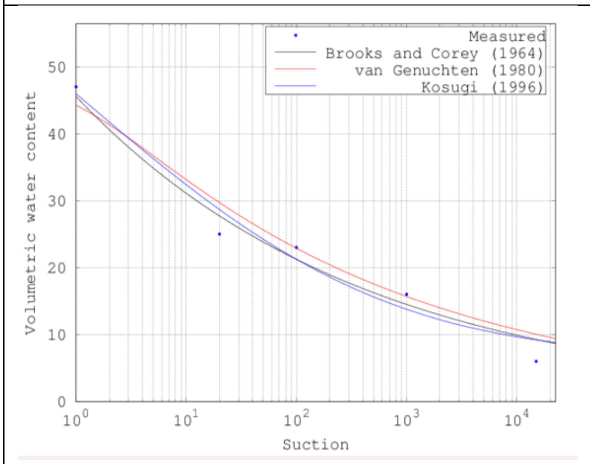

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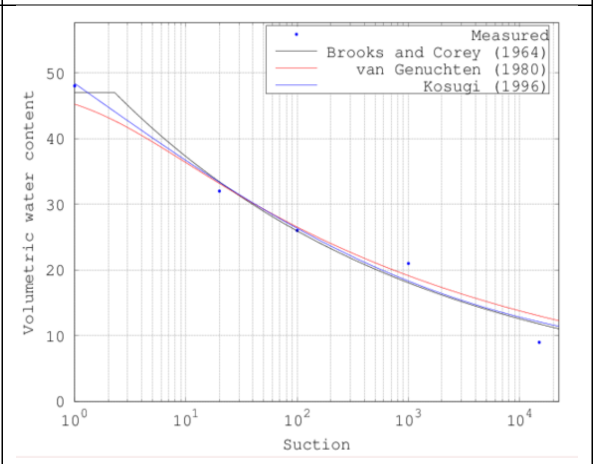

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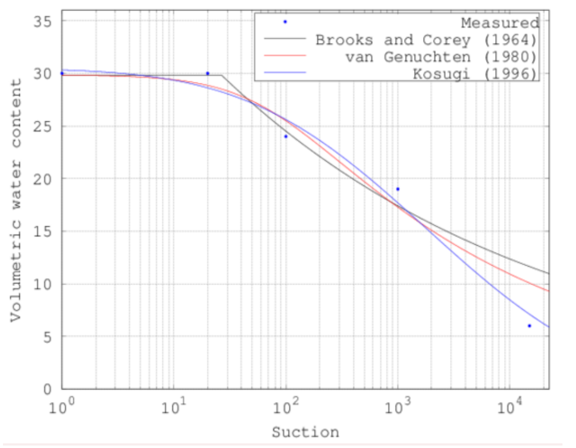
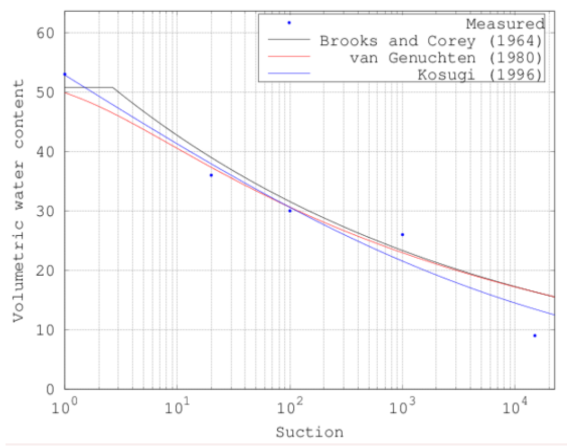
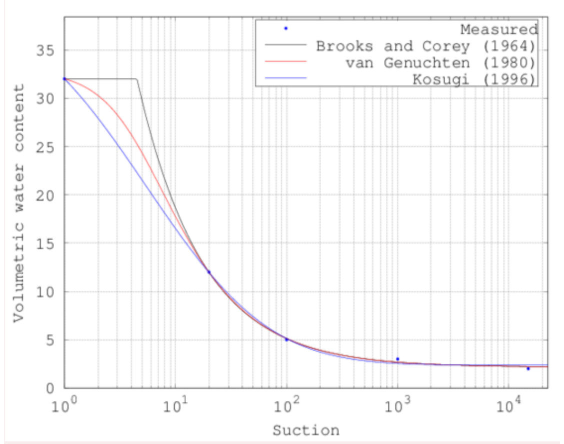
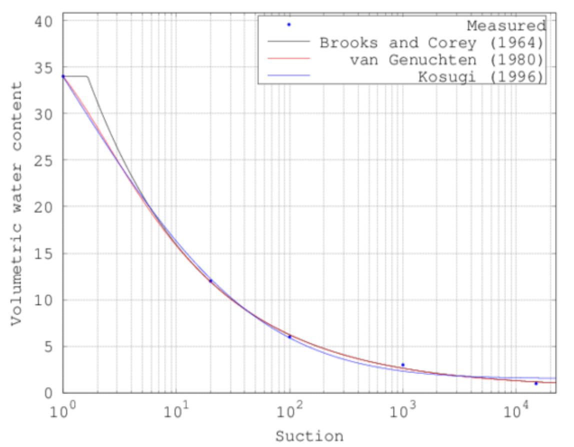
	

- Sandy-soil samples

1	2
	
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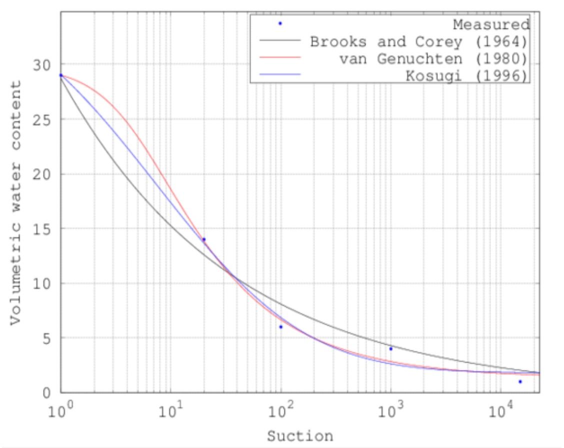	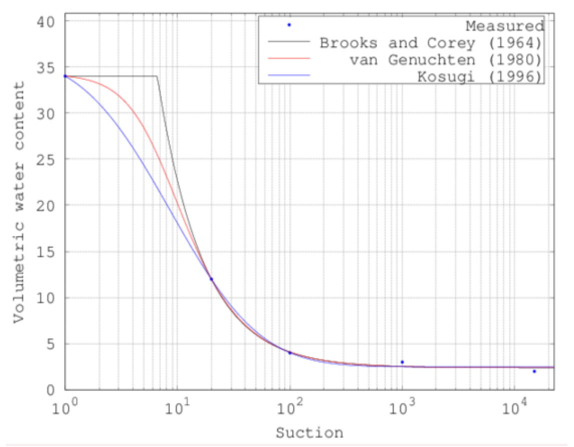

- VG Model Parameters

Type of Samples	Ring No.	VG parameters					
		Ss	Sr	Alpha (α)	n	m	r2
Mixed-Soil	1	53.666	0.013	1.000	1.200	0.167	0.982
Mixed-Soil	2	55.119	1.47690	0.99983	1.218	0.179	0.962
Mixed-Soil	3	54.186	0.00001	0.99988	1.154	0.134	0.964
Mixed-Soil	4	41.327	0.00062	0.13201	1.129	0.114	0.878
Mixed-Soil	5	48.916	0.00090	0.99979	1.184	0.156	0.966
Mixed-Soil	6	42.098	0.00104	0.17295	1.169	0.144	0.951
Mixed-Soil	7	47.501	0.00008	0.99997	1.194	0.162	0.994
Mixed-Soil	8	46.478	0.00064	0.49344	1.141	0.123	0.915
Mixed-Soil	9	48.602	0.00013	1.00000	1.215	0.177	0.981
Mixed-Soil	10	43.899	0.00003	0.63227	1.175	0.149	0.987
Mixed-Soil	11	39.609	0.01000	0.48064	1.176	0.150	0.988
Mixed-Soil	12	53.055	0.00176	0.91395	1.168	0.144	0.964
Mixed-Soil	13	50.663	0.75872	0.99997	1.198	0.165	0.981
Mixed-Soil	14	28.677	0.00004	0.02820	1.172	0.147	0.984
Mixed-Soil	15	52.746	0.00057	0.99984	1.165	0.142	0.948
Mixed-Soil	16	53.880	0.00025	0.98689	1.173	0.147	0.992
Mixed-Soil	17	39.494	0.00144	0.15923	1.161	0.139	0.960
Mixed-Soil	18	36.617	0.00000	0.04832	1.166	0.142	0.946
Mixed-Soil	19	44.260	0.00018	0.43663	1.175	0.149	0.956
Mixed-Soil	20	52.728	0.00031	0.99980	1.192	0.161	0.961
Mixed-Soil	21	50.486	15.44400	0.59770	1.349	0.259	1.000
Mixed-Soil	22	52.666	6.37550	0.99987	1.205	0.170	0.994
Mixed-Soil	23	41.287	0.00032	0.71998	1.141	0.123	0.959
Mixed-Soil	24	54.822	0.00012	0.98290	1.155	0.134	0.974
Mixed-Soil	25	54.684	0.09579	0.99984	1.189	0.159	0.961
Mixed-Soil	26	43.384	0.00097	0.79359	1.142	0.124	0.928
Mixed-Soil	27	45.211	0.00055	0.60850	1.149	0.130	0.951
Mixed-Soil	28	43.991	0.00101	0.48617	1.162	0.139	0.953
Mixed-Soil	29	48.725	0.00008	0.98512	1.164	0.141	0.949
Mixed-Soil	30	47.922	0.00058	0.63250	1.142	0.125	0.965
Mixed-Soil	31	29.857	0.00012	0.01450	1.202	0.168	0.942
Mixed-Soil	32	53.225	0.00112	0.81354	1.126	0.112	0.926
Sandy-soil	1	32.829	2.1634	0.21283	1.7642	0.433	0.99972
Sandy-soil	2	41.262	0.52864	0.94112	1.4322	0.302	0.99969
Sandy-soil	3	29.851	1.3387	0.20901	1.5515	0.355	0.99552
Sandy-soil	4	34.261	2.3926	0.13985	2.1116	0.526	0.99946

Appendix G. Retention Time calculations

			Well_5T - Well_3T	Well_5T - Well_3B
Travelled distance (m)			5.01	5.04
Design 1	Scenario 1	1/2 Max Conc. (g/m3)	1.34E-03	6.41E-06
		T50 (s)	18000	18000
	Scenario 2	1/2 Max Conc. (g/m3)	2.70E-05	8.98E-09
		T50 (s)	43200	43200
Design 2	Scenario 1	1/2 Max Conc. (g/m3)	1.66E-04	5.48E-08
		T50 (s)	18000	18000
	Scenario 2	1/2 Max Conc. (g/m3)	4.45E-06	1.67E-09
		T50 (s)	43200	43200
Design 3	Scenario 1	1/2 Max Conc. (g/m3)	1.35E-04	5.36E-07
		T50 (s)	18000	18000
	Scenario 2	1/2 Max Conc. (g/m3)	1.95E-05	5.27E-09
		T50 (s)	43200	43200

Appendix H. Fluid mass budget

- Flow scenario no. 1

Time Step	Scenario 1								
	Design 1			Design 2			Design 3		
	Sum of increases (+)	Sum of decreases (-)	Net Change	Sum of increases (+)	Sum of decreases (-)	Net Change	Sum of increases (+)	Sum of decreases (-)	Net Change
1	4.7E-06	6.5E-02	-6.5E-02	4.7E-06	8.3E-02	-8.3E-02	4.7E-06	8.6E-02	-8.6E-02
2	2.7E-08	9.3E-08	-6.6E-08	1.6E-07	4.1E-08	1.2E-07	5.6E-08	9.2E-08	-3.7E-08
3	3.4E-09	3.6E-09	-1.7E-10	6.6E-09	1.1E-08	-4.5E-09	6.6E-09	4.6E-09	2.0E-09
4	9.2E-08	0.0E+00	9.2E-08	1.5E-07	0.0E+00	1.5E-07	3.1E-07	0.0E+00	3.1E-07
5	0.0E+00	9.2E-08	-9.2E-08	0.0E+00	1.5E-07	-1.5E-07	0.0E+00	3.1E-07	-3.1E-07
6	1.5E+00	7.9E-02	1.4E+00	4.0E-01	4.7E-02	3.5E-01	1.6E+00	1.6E-01	1.4E+00
7	4.0E-01	3.5E-01	4.7E-02	5.9E-02	2.8E-01	-2.2E-01	5.4E-01	3.8E-01	1.6E-01
8	2.0E-02	1.7E+00	-1.7E+00	3.3E-03	1.6E-01	-1.6E-01	4.9E-02	2.0E+00	-1.9E+00
9	1.6E-05	4.8E-04	-4.6E-04	6.0E-08	2.6E-06	-2.5E-06	1.7E-05	5.7E-04	-5.5E-04
10	2.0E-08	3.5E-09	1.6E-08	6.1E-10	2.2E-09	-1.6E-09	2.7E-08	4.4E-08	-1.7E-08
11	7.9E-12	3.8E-12	4.2E-12	4.0E-13	2.1E-11	-2.1E-11	5.3E-12	1.2E-10	-1.1E-10
12	1.9E-12	4.4E-14	1.9E-12	8.2E-14	7.0E-12	-6.9E-12	9.1E-13	5.2E-11	-5.1E-11
13	7.7E-13	1.3E-14	7.5E-13	3.0E-14	2.5E-12	-2.5E-12	5.7E-13	2.7E-11	-2.6E-11
14	3.2E-13	5.4E-15	3.1E-13	1.0E-14	9.0E-13	-8.9E-13	3.1E-13	1.3E-11	-1.3E-11
15	1.3E-13	2.8E-15	1.3E-13	4.6E-15	3.3E-13	-3.2E-13	1.6E-13	6.7E-12	-6.6E-12
16	5.2E-14	1.1E-15	5.1E-14	1.3E-15	1.2E-13	-1.2E-13	8.1E-14	3.3E-12	-3.3E-12
17	2.1E-14	7.6E-16	2.0E-14	6.3E-16	4.5E-14	-4.4E-14	4.1E-14	1.7E-12	-1.6E-12
18	8.5E-15	1.5E-16	8.3E-15	1.1E-16	1.7E-14	-1.7E-14	2.2E-14	8.2E-13	-8.0E-13
19	3.4E-15	4.4E-16	2.9E-15	2.8E-16	6.2E-15	-6.0E-15	8.5E-15	4.0E-13	-4.0E-13
20	1.4E-15	2.0E-16	1.2E-15	3.1E-20	2.6E-15	-2.6E-15	5.9E-15	2.0E-13	-1.9E-13
21	5.4E-16	1.4E-16	4.0E-16	0.0E+00	1.1E-15	-1.1E-15	2.4E-15	9.8E-14	-9.5E-14
22	2.2E-16	8.3E-17	1.3E-16	4.9E-17	3.3E-16	-2.8E-16	2.8E-15	4.8E-14	-4.5E-14
23	9.6E-17	3.5E-17	6.0E-17	2.0E-21	2.0E-16	-2.0E-16	2.3E-15	2.4E-14	-2.1E-14
24	3.6E-17	4.7E-18	3.1E-17	1.8E-19	8.0E-17	-8.0E-17	2.1E-15	1.2E-14	-9.4E-15
Total	**1.9E+00**	**2.2E+00**	**-2.8E-01**	**4.6E-01**	**5.7E-01**	**-1.1E-01**	**2.2E+00**	**2.6E+00**	**-4.2E-01**

- Flow scenario no. 2

Time Step	Scenario 2								
	Design 1			Design 2			Design 3		
	Sum of increases (+)	Sum of decreases (-)	Net Change	Sum of increases (+)	Sum of decreases (-)	Net Change	Sum of increases (+)	Sum of decreases (-)	Net Change
1	1.97078E-07	0.002698725	-0.002698527	1.97077E-07	0.003242923	-0.003242726	1.97E-07	3.59E-03	-0.003591488
2	1.1101E-09	3.86117E-09	-2.75107E-09	3.40848E-09	1.97275E-09	1.43573E-09	2.32E-09	3.84E-09	-1.52186E-09
3	1.41398E-10	1.48274E-10	-6.87585E-12	2.48496E-10	2.05893E-10	4.26031E-11	2.75E-10	1.91E-10	8.41202E-11
4	3.51047E-11	0	3.51047E-11	4.8394E-11	0	4.8394E-11	1.20E-10	0.00E+00	1.19919E-10
5	1.58786E-15	1.02066E-16	1.48579E-15	4.00022E-15	2.33892E-17	3.97683E-15	2.59E-15	9.28E-17	2.49241E-15
6	1.40E-03	1.96E-05	0.001383472	0.000187772	5.52897E-06	0.000182243	1.81E-03	4.58E-05	0.001762132
7	1.61067E-05	0.000151038	-0.000134931	3.26826E-06	1.06582E-06	2.20244E-06	3.85E-05	1.59E-04	-0.000120039
8	1.69717E-05	0.001266163	-0.001249191	5.35204E-06	0.000189714	-0.000184362	3.88E-05	1.68E-03	-0.001644765
9	3.61881E-09	1.53813E-07	-1.50195E-07	1.29014E-08	2.08153E-07	-1.95251E-07	6.12E-09	1.83E-07	-1.766E-07
10	7.77169E-12	1.70102E-12	6.07067E-12	1.96565E-12	6.76759E-12	-4.80195E-12	1.52E-11	7.34E-12	7.81613E-12
11	1.0644E-15	6.3054E-15	-5.241E-15	1.74351E-16	9.91893E-14	-9.90149E-14	7.61E-16	1.54E-14	-1.4597E-14
12	5.25646E-17	1.80299E-16	-1.27735E-16	4.39841E-19	1.60229E-15	-1.60185E-15	1.57E-16	5.47E-16	-3.89539E-16
13	3.32663E-21	2.4645E-17	-2.46417E-17	0	8.42706E-17	-8.42706E-17	1.36E-16	1.93E-17	1.16589E-16
14	6.32938E-20	2.57803E-18	-2.51473E-18	2.42084E-17	1.10245E-18	2.31059E-17	2.91E-20	5.11E-18	-5.08525E-18
Total	**1.436E-03**	**4.136E-03**	**-2.699E-03**	**1.966E-04**	**3.439E-03**	**-3.243E-03**	**1.886E-03**	**5.480E-03**	**-3.594E-03**

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