University of Southern Queensland

Faculty of Engineering and Surveying

Investigating mechanisms for effluent pond sealing: the effect of suspended organic particulate on soil hydraulic conductivity

A dissertation submitted by

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Abstract

Feedlot regulating authorities have proposed a pond seepage infiltration rate guideline of 1.0x10^$^{-9}$ m/s (31.54 mm/year) in an effort to control environmental degradation. This project aims to investigate the effect of the organic particulates in feedlot effluent upon physical pore blockage and a reduction in soil hydraulic conductivity (HC). Two soils, a heavy clay and clay loam were treated with four solutions, calcium chloride, synthetic effluent, filtered effluent and raw effluent, and the hydraulic conductivity was calculated over an extended time period. The soils were compacted to 98% maximum dry density (MDD) to ensure the best chance at achieving the guideline infiltration rate. Hydraulic conductivity was calculated using a falling pressure head method. Calcium chloride application caused a slight increase in HC, likely due to an osmotic effect reducing the diffuse double layer. Synthetic effluent was compared against actual effluent, results showed actual effluent caused a much slower flow rate, from this observation it was concluded that accumulation of suspended solids was the major reason for a reduction in HC, not dispersion or swelling. The raw and filtered effluent samples were also compared and as expected the raw effluent produced a slower HC, due to the higher amount of total suspended solids (TSS) in the solution, although it was determined that particulate <3 μm was primarily responsible for pore blockage. A reduction in TSS from the percolating solution to leachate meant that solid organic matter has accumulating within the soil profile. It was concluded that the organic particulate in feedlot effluent does contribute to pore blockage and a reduction in HC. Regarding the guideline rate, the heavy clay achieved this target after approximately 500 hours of leaching with a final HC of 9.39x10^$^{-10}$ m/s. The clay loam was unable to reach this rate during the time period finishing with a HC of 1.52x10^$^{-9}$. However, HC trends indicate that given time the clay loam HC could be expected to achieve the guideline rate. This potential for a large cost saving, due to negation of the requirement for expensive plastic liners to limit HC, was identified. This project provides the groundwork for a more comprehensive study, involving a wider range of soils and effluent sources, which have the potential to ensure the sustainable operation of beef feedlot ponds by restricting pond seepage through organic particulate pore blockage.

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CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

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Chapter 1 INTRODUCTION

1.1 Project Overview

Intensive animal feedlots comprise a significant proportion of the meat and livestock industry within Australia. The effluent from beef feedlots is captured in drainage channels and stored in effluent-ponds for treatment, or left to settle and evaporate. Livestock effluent is high in bacteria, contains organic particulates, and is saline, sodic and alkaline (Bean *et al.* 1999). These properties have led to mounting concern from various Australian regulating authorities regarding seepage beneath the ponds and subsequent contribution to environmental degradation. Hence, national guidelines are being investigated to restrict the infiltration rate underneath feedlot effluent-ponds; $1.0x10^{\wedge-9}$ m/s has been suggested by authorities (Mohamed and Antia 1998). This is on the verge of being enforced in Queensland and New South Wales. Recent research conducted by the National Centre for Engineering in Agriculture, for FSA Consulting as a Meat and Livestock Australia initiative, has shown that the suggested hydraulic conductivity may be achievable for certain highly compacted soils (Bennett *et al.* 2011). However the research was unable to determine the contribution of accumulated suspended effluent particulates towards pore blockage. This factor has formed the basis for this research project.

This primary aim of this project is to show that suspended organic particulate in feedlot effluent ponds is capable of blocking soil pores and sealing ponds over time. There is a significant interest from the Beef Feedlot Industry and Meat and Livestock Australia in this research, due to these potential effluent pond guidelines. If instated, the infiltration beneath an effluent dam must not exceed 31.54 mm/year, which potentially has huge monetary ramifications for feedlot operators if the rate cannot be achieved. The specific focus of this project is to investigate and determine the effect of organic particulates and the solution chemistry of cattle effluent, on the hydraulic conductivity of a soil leached with raw effluent over an extended period of time. The results hold a significant outcome for the Australian Feedlot Industry as the research will provide an increased understanding of the effect of effluent organic particulates on soil permeability. Bennett *et al.* (2011) clearly showed that soils compacted to 98% of their maximum dry density (MDD) exhibited the greatest potential for achieving a hydraulic conductivity <1x10^{-9} m/s. Thus, effluent inherent organic particulate will presumably also have the greatest potential to reduce hydraulic conductivity when soil is compacted to 98% of the MDD. If a combination of soil compaction and pore blockage by organic particulate can achieve sufficient reduction in hydraulic conductivity, then the alternative method constructing plastic lined dams can be avoided and substantial savings made.

1.1 Project Objectives

The specific objectives of this project include;

1. Determine if effluent inherent organic particulate is capable of reducing soil hydraulic conductivity below the stated guideline, 1x10^$^{-9}$ m/s, for soils compacted to 98% of the MDD
2. Investigate the extent of soil hydraulic conductivity reduction attributable to effluent chemical properties.
3. Determine the effect of effluent inherent organic particulate particle size on soil pore blockage

To satisfy the project objectives an experimental procedure was developed. The hydraulic conductivity of two different soils, a heavy clay (fine textured) and clay loam (coarser textured), will be calculated using filtered and non-filtered feedlot effluent, synthetic effluent and calcium chloride. The soils will be compacted to 98% bulk density to ensure the infiltration rate is kept to a minimum, and therefore has the greatest chance of reaching the suggested infiltration rate guideline. The hydraulic conductivity will be calculated using Darcy's equation for a falling pressure head. The results collected will show the relationship between hydraulic conductivity and time for each sample. From these results an analysis of the physical and chemical effects each solution had upon soil hydraulic conductivity will be under-taken. To analyse the effect particle size has upon bore blockage the total suspended solids of the percolating and leachate solution will be analysed. It is expected that the leachate will contain less solids then the permeate which allows the assumption that a certain amount of solid particulate is being trapped inside the pore structure as the solution passes through the core. If the expected results are obtained the total suspended solids analysis will support the theory of organic particulates contributing to pore blockage.

1.2 Assessment of Consequential Effects

The outcomes of this research project will have various consequences for the feedlot industry, society and the public. Many of the project consequences will impact upon sustainability. The institution of Engineers Australia has an ongoing initiative with regard to sustainability and engineering practice. The assessment of consequential effects as a result of this project will be undertaken with regards to the Engineers Australia, 10 aspects of sustainability.

The project experimental procedure will make use of some finite resources such as poly pipe, plastic couplings and plastic drums. However the usage of this material is quite limited and most of the equipment such as the drums and poly-pipe can be re-used in future experiments. The natural resources being used include feedlot effluent and soil. The majority of the effluent is disposed of throughout the experiment running time; a small amount is kept in sample jars in case further analysis is required.

The major aim of this project is to reduce environmental degradation through reduction of seepage below effluent ponds. The experimental design has no effect on environmental condition as it is carried out in a controlled laboratory environment using. If a desired outcome is reached then the project will have a positive influence on environmental conditions, in particular surrounding feedlots. As this research only involves two different soils, a larger study would likely results from any promising results

The issue of involving all concerned citizens in environmental issues is not related to this project work. As the research being undertaken is preliminary in its nature, i.e. it is a scoping study and further research will be needed to make any industry based recommendations. If a solution is put forward in several years' time then the agricultural community, in particular any area involved with feedlot operations, will need to be notified and involved in the implementation process.

The pollution caused by implementing any potential solutions recommended by this project or future work includes are extremely minimal. The environmental impact associated with compacting the clay lined dams to the required level is the only real opportunity for environmental pollution. In this case, the heavy earthworks machinery required will have an impact on the environment due to fuel emissions.

The project and its outcomes don't involve the 'differences in living standards and the participation of woman, youth or indigenous people'. The project aims to solve an environmental problem using a naturally occurring phenomenon, thus there is no impact on jobs through the process of automation. The only employees required to implement the project outcome involve labourers or contractors who are hired to complete the earthworks. As mentioned this has no impact on poverty or the reduction in the differences of living standards.

If the project has meaningful and successful outcomes which are properly implemented in Australian Feedlots then there is potential for the same information to be incorporated in international countries, both developed and developing. The sustainability of the project would be the same in any countries as the implementation of compacted clay liners for effluent ponds is not heavily reliant on advanced technology, but will be contingent on soil type. Differences in the pricing and method of the solution would be dependent on the country. The equipment available to Feedlot operators would be the defining factor, not the actual research behind the solution to achieving low infiltration rates.

The final point raised by Engineers Australia regarding sustainable practices involves the contribution of engineering to international understanding and peace. This particular project will have no effect upon this area of sustainability. This is because the suggested guidelines that form the basis for this study are for Australia only. While it is possible that this research will be beneficial to feedlots in other countries there is no connection between implementing this research worldwide and supporting international understand; this project has no involvement with international politics.

It is also noted that the Engineers Australia Code of Ethics has been adhered to throughout this project. The researcher takes full responsibility for conducting this project in a manner that upholds the ethical nature in which professional engineers are required to operate. The outcomes of this project will be presented in a way which is equal and fair to all those involved and interested in this field of research.

Chapter 2 LITERATURE REVIEW

The potential for intensive livestock effluent inherent organic particulates to reduce soil permeability

2.1 Introduction

Throughout the past several decades the global population has increased significantly. With this trend expected to continue, the demand for agricultural produce in order to sustain the population will also increase. Given this escalation in agricultural demand, pressure is placed on current agricultural areas to produce more on the same land resource. In order to achieve this, farm management systems will need to change to allow for more intensive agriculture. In response, the occurrence of intensive livestock feedlots has increased (MLA 2009). Large scale beef feedlots have become much more common over the past two decades with cattle numbers increasing from two hundred thousand to over a million. Individually these feedlots contain anywhere from 5000 to 50,000 head of cattle (ALFA 2011). While the intensive nature of this industry addresses the demand for food and fibre, it also creates a significant and intensified waste source that requires management in order to limit any potential environmental impacts. Of particular concern is the localised concentration of nutrients and salts from cattle effluent contributing to the potential for toxic accumulations and soil permeability decline. To address this, liquid and organic particulate runoff caused during rainfall and washing practices is often diverted from feedlot pens to be captured in clay lined effluent ponds. Due to the chemical properties of the effluent, regulating environmental authorities have begun to enforce beneath pond seepage limits. High seepage rates create the possibility of contaminating ground water and soil in close proximity. Due to the risk of environmental contamination the Queensland guidelines for establishment and operation of beef cattle feedlots have proposed an allowable pond infiltration rate of 1.0×10^{-9} m/s (31.5 mm/year). Mohamed and Antia (1998) have suggested that this low infiltration rate can be achieved by clay lined effluent ponds. Other states have yet to enforce this particular infiltration guideline (WA Department of Agriculture 2002);

however it would be likely that this figure will be incorporated into more feedlot design guidelines in the future.

Importing suitable clay onto feedlot sites to create a clay liner is an expensive task, although less than the cost of rubber lining ponds. However, soils in the immediate location of pond construction sites could potentially achieve the infiltration rate limit proposed by Queensland regulatory authorities, through both chemical and physical manipulation of the soil structure. The sodicity of feedlot effluent will likely result in a solution with high sodium absorption ratio (SAR) which could cause a reduction in soil permeability through swelling and dispersion of soil aggregates (Quirk and Schofield 1955). However, feedlot effluent also has a high electrical conductivity (EC) which may cause the soil to maintain its structure even in the presence of sodic solutions, due to increased osmotic potential (Quirk and Schofield 1955; McNeal and Coleman 1966; Bennett and Raine 2012). Mechanical compaction of pond soil surfaces prior to commissioning will further reduce the hydraulic conductivity as soil porosity is a function of soil bulk density (Hillel 2004). Hence, as compactive effort increases, bulk density is increased, which decreases soil porosity and reduces soil hydraulic conductivity. Different levels of compaction have been used by feedlots in the past; however to achieve the 1.0×10^{-9} m/s guideline it is highly recommended that a 98% compaction level is used. In a report compiled by Bennett *et al*. (2011) it was found that the guideline infiltration rate was not achieved over the running length of the project for the majority of 17 Australian soils. This raises some doubt as to whether the proposed guideline is actually achievable. Another option for feedlot operators is to construct effluent holding ponds with rubber liners; however this is undesirable due to the high expense of the rubber liner and construction costs. Thus, if possible, compacted clay liners are the most suitable practice for the industry.

In the study of Bennett *et al.* (2011) soil compacted at 90, 95 and 98% of the maximum dry density (MDD) was observed to act as a filter for organic particulates contained in an intensive livestock cattle effluent solution. While reductions in permeability were measured, it was determined that these reductions were primarily due the compaction treatments, although entrainment of particulate within the soil pore matrix was likely to have contributed. Continued settling of solid components within effluents onto pond floors may therefore provide a means to completely seal ponds. Hence, this literature review aims to investigate the factors influencing hydraulic conductivity in soils and the potential for effluent contained organic particulates to induce pore blockage.

2.2 Soil Hydraulic Conductivity

Hydraulic conductivity (HC) is an important concept when analysing the infiltration rate of a solution into a permeable medium, such as a soil. To analyse whether the infiltration rate proposed by feedlot regulators is achievable; a basic knowledge of the various factors governing hydraulic conductivity need to be reviewed. Hydraulic conductivity is the parameter used to assess the ability of a soil to conduct water within its volume, usually in a downward direction (Sumner 1993). The presence of a hydraulic pressure head allows the HC of a soil to be determined using an empirical equation, such as Darcy's Law (Equation 1). The hydraulic head is created by the sum of hydrostatic pressure and atmospheric pressure under natural conditions, while the gradient of the hydraulic potential, or head, and is the force which governs solution movement (Dirksen 1999). The specific discharge rate is the volume of water flowing through a cross sectional area of the soil per unit time, this is known as the flux; which is proportional to the hydraulic gradient (Hillel 2004). The proportionality factor (K) is the hydraulic conductivity which can be calculated using Darcy's Law. In measuring the HC of a soil beneath an effluent pond, the soil should be considered as being in a saturated state (i.e. all pore space is filled with water and conducting). In this circumstance, the HC is described using Darcy's Law for one dimensional flow:

$$K = q\,\frac{L}{H} = \frac{VL}{At\Delta H} \qquad \text{Eq. 1}$$

Where q is the flux, measured as volume (V) per cross sectional area (A) of the soil core per unit time (t); L is the length of the soil core and ΔH is the total hydraulic head measured from the base of the soil core (**Error! Reference source not found.**).

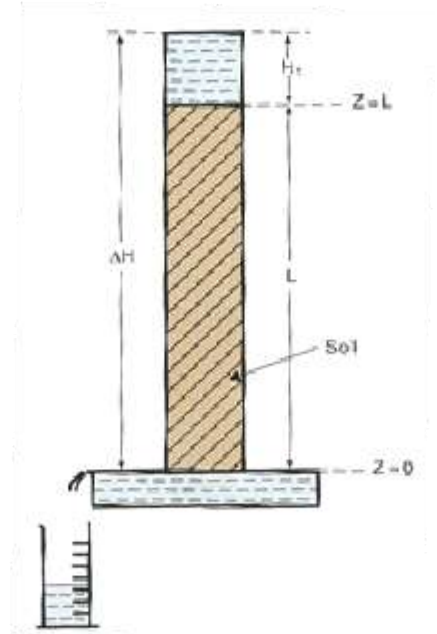

Figure 2.1: Gravitational Flow in a vertical soil column (source: Hillel 2004)

In a medium such as soil, solution flow is usually laminar, as it occurs at relatively low velocities and in narrow flow paths where laminar flow is known to be predominant. Under laminar flow, the average flow velocity is proportional to the hydraulic pressure drop. This occurs as the pressure required to transport the fluid is equal to the frictional resistance created by shear forces acting on the circumferential area of the flow path. Additionally, laminar flow is constant, as there is no acceleration caused by axial forces (Hillel 2004). These conditions allow for the application of Darcy's law to measure HC. As the velocity or cross sectional area increases flow approaches a turbulent state; in this state the mean velocity is no longer proportional to the pressure head and it becomes much harder to measure HC. Thus, in turbulent flow Darcy's law is inapplicable as the hydraulic gradient is no longer proportional to the flux (Hillel 2004). While the flow in soils is assumed to be laminar, due to the narrow pore spaces, turbulent flow can still occur under natural conditions, due to large cracks or crevices in the soil profile (e.g. dry, un-swollen Vertosols). However, given that soil beneath effluent ponds is in a saturated state and has undergone complete clay swelling, turbulent flow would be highly unlikely, especially where compactive effort has been applied. Thus, the use of Darcy's Law to describe the HC of effluent pond floors is warranted.

The HC of a soil greatly depends on the physical and chemical characteristics of a particular soil, and the flow properties of the fluid. Soil HC measurements help indicate the effects that other soil parameters have on infiltration rates, such as: the tortuosity of the flow path, pore size distribution of the soil, and viscosity and density of the liquid (Sumner 1993). Soil matrix structure can be altered by changes in the soil solution chemical composition and concentration, which may increase or decrease swelling and dispersive-potential. Thereby, it is important to realise that the HC value will also be affected. Other factors with potential to affect HC include organic matter accumulation (Vinten *et al*. 1983) and soil bulk density (Braunack & Peatey 1999; Paydar & Ringrose-Voase 2003); the impact of these two factors form the basis for analysing if clay lined dams can meet the infiltration rate guideline. Under normal circumstances the HC of a soil decreases over time due to various chemical, physical and biological effects (Vinten 1983; Rengasamy 1993; Magesan 1999; Abedi-Koupai 2006). The extent of the effect these factors have upon the HC of a soil will be explored throughout the remainder of the literature review.

2.3 Factors controlling hydraulic conductivity within the soil matrix

2.3.1 Clay content and relative soil pore size

As discussed in preceding sections, soil physical properties have a large effect on infiltration rates. Soil particles are classified into clay, silt and sand depending upon particle size (clay <2 μm, 2 μm <Silt<20 μm, 20 μm <sand<2000 μm). Soils with a high clay particle concentration are known as fine textured soil and have smaller pore spaces, due to each particles minimal surface area (Isbell 2002). The resultant situation in clay dominated soil is one where infiltration rates are low, as compared to sandier coarse textured soil, due to higher flow resistance. Clay soils also have a higher water holding capacity as the smaller pores create a higher tension force or suction within the soil matrix (Ward & Trimble 2004). Specifically, the suction force occurs at the boundary of the air and water contained in each pore, while the surface tension forces are caused by adhesion and cohesion. Adhesion refers to the attraction of the water to the sides of the pore while cohesion is the attraction of water to the existing water surface. The height (head) of water in a pore is inversely proportional to the radius of the pore, which means smaller pores attract more water. Thus, the smaller pores fill first as they exert larger tension forces (Ward & Trimble 2004). Due to these properties, soils with high clay content are chosen to line dams. As the clay content of many Australian subsoils is high (Northcote and Skene 1972), it stands that in-situ soil may well be suitable for reducing beneath pond permeability.

2.3.2 Clay swelling properties

Clay minerals have been found to contain a crystalline structure (Charman & Murphy 1991). Clay crystalline structures are either tetrahedral or octrahedral. Tetrahedral structure occurs where four oxygen atoms surround a central cation, often Si^{4+}; while octahedral structure has six oxygen atoms or hydroxyls surrounding a larger cation of lower valency like Al^{3+} or Mg^{2+} (Rengasamy 1993; Hillel 2004). Tetrahedra and octrahedra join together at the corners of a shared oxygen atom to form silica or alumina sheets, as can be seen in Figure 2.2.

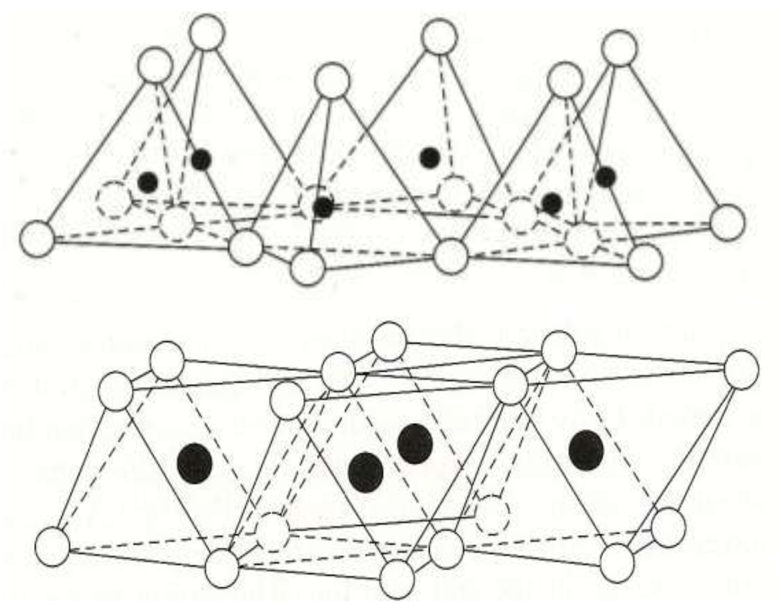

Figure 2.2: Clay crystalline structure; a) Tetrahedral forming a silica sheet; and b) Octahedra forming an alumina sheet (Hillel 2004)

There are two main types of clay aluminosilicate layers which depend on the ratio of tetrahedral to octahedral sheets, either 1:1 or 2:1. The most common 1:1 clay mineral is kaolinite. The structure of this clay type is a pair of silica-alumina sheets that are stacked together in alternating fashion. Holding the sheets together is hydrogen bonding in a strong, multilayered lattice (Charman & Murphy 1991; Hillel 2004). Water and ions cannot enter between these layers and only the outer edges of the structure are exposed, this means Kaolinite has a low specific surface area. These characteristics result in Kaolinite exhibiting less swelling and cracking than other clays. Montmorillonite is the most present 2:1 clay type. The lamellae (composite layers) are stacked in loose layers known as tactoids (Hillel 2004). The cleavage planes in-between the lamellae draw in water and ions which results in expansion of the layers. As the lamellae expand a greater percentage of the crystals surface becomes exposed, thus dramatically increasing the effective specific surface area (Hillel 2004). Montmorrillonite clay is often classed as plastic in its nature and will often undergo greater swelling when upon wetting, due to this plasticity (Charman & Murphy 1991). During drying, the soil cracks and forms hard peds reducing the ability for water to infiltrate effectively within these peds, but also produces large fissures that encourage rapid infiltration until the point that swelling once again closes the fissures (Karathanasis & Hajek 1985).

2.3.3 Clay dispersive potential

The dispersive potential of a clay soil depends on several governing factors including; the quantity of exchangeable sodium ions within the soil cation exchange capacity (CEC), the electrolyte concentration of the soil solution, and the degree of mechanical disturbance the soil has undergone. However, the primary reason for dispersion in soil is due to chemical instability. This generally occurs when there is an abundance of sodium present within the soil solution – termed sodicity. Northcote and Skene (1972) defined that an Australian sodic soil has an exchangeable sodium percentage (ESP) of >6.These phenomena are discussed in further detail below.

2.3.4 Diffuse double layer theory

Dispersion of soil aggregates into clay silt and sand is chemically governed by the electrostatic or diffuse double layer. When a colloidal particle is dry, the neutralizing counter-ions are attached to its surface creating an equilibrium state. When the particles become wet some of the ions dissociate from the surface and enter into solution. The negatively charged colloidal surface and the positively charged cations in solution form the diffuse double layer (Sposito 1989; Sparks 2003); this is demonstrated in Figure 2.3 below.

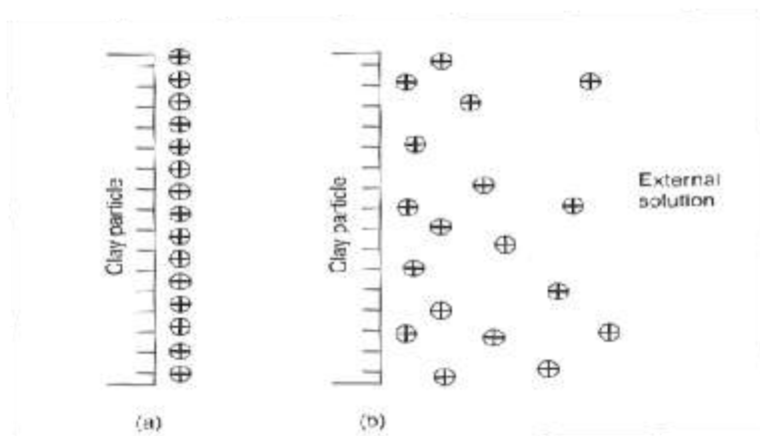

Figure 2.2: Diffuse double layer: (a) Colloidal surface when dry; (b) Colloidal surface when wet (Hillel 2004)

This condition occurs due to the equilibrium between two opposite attractions; the bond between positive and negative ions, which pull the cations closer to the colloidal surface; and the kinetic motion of the fluid molecules, which causes the outward diffusion of the cations to maintain equilibrium throughout the soil solution (Sposito 1989; Sparks 2003; Hillel 2004). The valencies of the ions in solution also play an important role in relation to the size of the diffuse double layer. Divalent cations such as calcium (Ca^{2+}) are attached closer to the colloidal surface due to a stronger attraction to the clay anions (Sumner 1993). However if a greater concentration of monovalent cations like sodium (Na^+) are present in the solution, the distance of the diffuse double layer from the colloidal surface will be greater due to the weaker attraction force (Hillel 2004).

Soil cation exchange reactions have the ability to affect clay dispersion due to the valency of ions and concentration of the soil solution. Cation exchange reactions occur rapidly as a result of changes in the concentration of the soil solution; this is usually caused by applying saline water. Therefor the composition of the CEC adapts in order to reach equilibrium, the change in CEC properties affect swelling and dispersion tendencies (Hillel 2004; Shainberg & Levy 2005). Mechanical dispersion can also occur within sodic soils, either due to solution mixing or energy applied through raindrops on the surface. This occurs when hydrated clay particles in equilibrium with a low SAR solution are further separated by applying mechanical pressure (Shainberg & Levy 2005). Clay particles close to the soil surface are more susceptible to dispersion through mechanical disturbance.

The hydrated radius of different cations also has an effect upon the dispersive potential of soil. Ions with a larger hydrated radius are held less strongly than ions with a small radius (Hillel 2004). This explains why sodium ions have such a dispersive effect; in combination with its monovalency, Na^+ also has a large hydrated radius, which creates an extremely weak attraction force. Hence, Na^+ provides conditions that allow a significant increase in the size of the diffuse double layer. Both calcium and magnesium are divalent cations; however, due to the smaller hydrated radius of calcium, calcium has greater stabilising properties when compared to magnesium (Sposito 1989).

2.3.5 Threshold electrolyte concentration

While sodicity and dispersion are primarily known to occur due to an adverse ESP, it is possible that a soil will not undergo dispersion even in the presence of adverse sodium levels. Due to an osmotic effect, soil stability can be maintained in the presence of sodium. Such an effect is a function of soil salinity. If a percolating solution of greater electrolyte concentration than the soil solution is applied to a soil; the soil solution (lower EC) is contained close to the colloidal surface, where it is effectively pulled through the diffuse double layer due to kinetic energy (Sparling *et al.* 1989). This osmotic effect is generated due to the soil solution solute load. This osmotic effect allows the positive attraction forces to prevail, which maintains a degree of soil stability, even in the presence of excess sodium ions (Northcote and Skene 1972).

Bodman and Fireman (1950) first demonstrated that soil permeability is a function of both ESP and EC. It was found that a high ESP (SAR) and low EC resulted in a reduction of HC. Quirk and Schofield (1955) later proposed the 'threshold concentration' concept (termed threshold electrolyte concentration; TEC), which refers to the electrolyte concentration required to maintain soil permeability at an acceptable level in the presence of a given ESP or SAR value. TEC is the concentration of salt which causes a 10 to 15 % decrease in soil permeability (Quirk & Schofield 1955). Experimental results for a soil leached with various solutions showed that NaCl had the lowest molar threshold concentration of 2.5×10^{-1} M. The decrease in permeability was greatest for sodium saturated soils and least for the calcium saturated soils. Further investigation by Quirk and Schofield (1955) showed that montmorillonite pads became visibly swollen and impermeable when leached with 0.25 M of NaCl, while maintaining reasonable flow rate when leached with 0.1 M of $CaCl_2$. . The TEC varies depending on other factors such as clay content, organic matter content, and bulk density which all strongly influence the permeability of a soil (Frenkel *et al*. 1978; Shainberg *et al*. 1991).

During dispersion the clay particles separate from the silt and clay causing pores to become blocked, dependent on pore size and the extent of dispersion. This phenomenon has caused many researchers to propose that swelling and dispersion are the major mechanisms contributing to the reduction in HC as EC is reduced (Quirk and Schofield 1955; Shainberg *et al.* 1991; Sumner 1993). Soils begin to swell as the EC of the solution is lowered; this is more noticeable for SAR values greater than 10 as is shown in Figure 2.4 below, although the effect is highly soil specific (Bennett and Raine 2012). Figure 2.4 shows that soil stability, measured as a 25% reduction in HC, can be maintained at a given SAR provide a sufficiently high concentration of salt is present in solution (Sumner 1993). The threshold curve on the graph shows the relationship between SAR, salt concentration and the level at which soil becomes unstable. The values below the curve indicate soil in a stable condition, while values above the TEC curve result in soil dispersion.

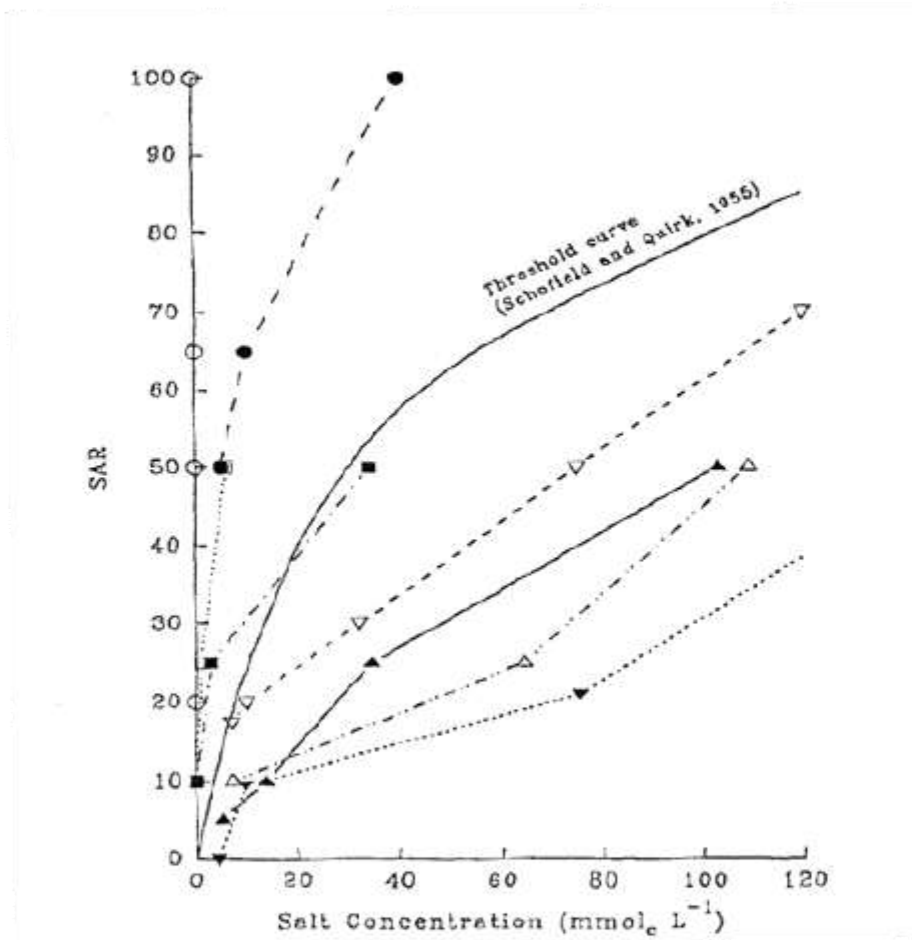

Figure 2.3: Threshold Concentration Curve with respect to salt concentration (mmol/L) and SAR (Sumner 1993)

2.3.6 Effect of dispersion on pore networks

The images below re-iterate the theory of increased SAR causing reduction in HC. This occurs through blockage of pores by dispersed clay, which results in a reduction of the pore network. A study by Awedat *et al.* (2012) showed the effect of SAR on soil pore distribution. Figure 2.5, illustrates pore network reduction due to increasing SAR of the permeating solution, where the green and yellow represent dyed resin filled pores and the brown and red portions are soil particles. As the SAR increases there is a noticeable decrease in pore spaces due to soil dispersion, once again this results in a significant decrease in HC.

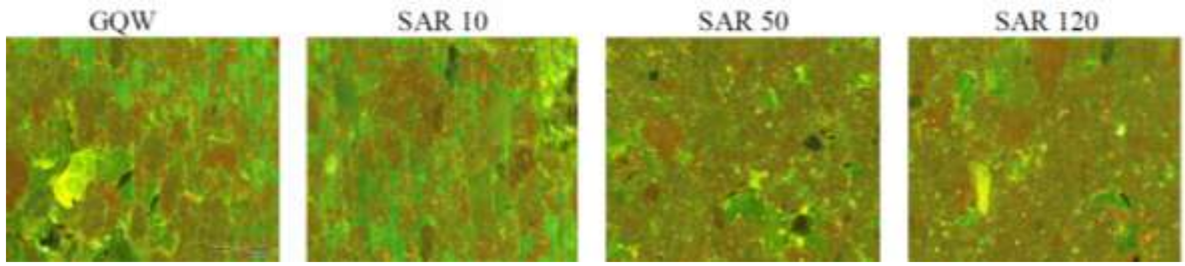

Figure 2.4: Influence of SAR on pore distribution and dispersion (Awedat et al. 2012)

2.4 Bulk density

The term 'bulk density' expresses the ratio of the mass of solids to the total soil volume (Hillel 2004). Dry bulk density and total porosity are often used to characterise the state of soil compactness (Lipiec & Hatano 2003). When a soil is heavily compacted there is an increase in bulk density which causes several changes regarding the physical characteristics of a particular soil. These include soil strength, aeration, hydraulic, thermal and structural properties (Lipiec& Hatano 2003). This literature review will focus on the hydraulic properties of a compacted soil as this is highly relevant when analysing compacted clay liners used in feedlot-effluent ponds.

Sassouline *et al.* (1997) showed that soil compaction decreases volumetric water content at high matric potentials, while slightly increasing at low potentials. This results from a decrease in the proportion of large pores and an increase in small pores. A drastic reduction of hydraulic conductivity under increasing compaction has been reported by several researchers such as Hakansson & Medvedev (1995) and Lipiec and Hatano (2003). Saturated hydraulic conductivity is likely to occur beneath effluent ponds, due to the ponded hydraulic head that is the pond. Saturated water flow in a soil occurs mainly through the larger pores, this is known as preferential flow. As discussed these pores are greatly diminished under compaction and as a result water movement is greatly restricted. Research has also indicated that compaction reduces not only the volume of macropores but also their continuity, which effectively increases the tortuous nature of the pore spaces within the structure (Lipiec & Hatano 2003). The active macropores are known to significantly contribute to water flow; it was found that 10% of macropores (>0.5 mm) and mesopores (0.06 – 0.5 mm) contribute to approximately 90% of the total water flux (Lin *et al*. 1996). Hence, a reduction of pore diameter in this soil to <0.06 mm would likely result in approximately a 90% decrease in soil HC. Another study by Hayashi *et al*. (2006) showed the relationship between pore sizes and hydraulic conductivity, micropores classified by a diameter of less than 60 μm had a slower HC than larger pores. Hayashi *et al*. (2006) concluded this was due to micropores requiring more energy to absorb water. Furthermore, a study by Horn *et al*. (1995) showed that soil porosity and hydraulic conductivity of a soil 40 cm below the surface decreased from 4.5×10^{-1} cm/s to 3.5×10^{-1} cm/s after compaction occurred. In this case compaction has been caused by excessive traffic from heavy machinery and farm vehicles; approximately 100 kPa of stress was placed upon the A horizon of the soil profile. Figure 2.6 shows that after compaction there is a significant decrease in pore volume, which results in a significant increase in bulk density from 0.87 Mg m^{-3} to 1.46 Mg m^{-3}.

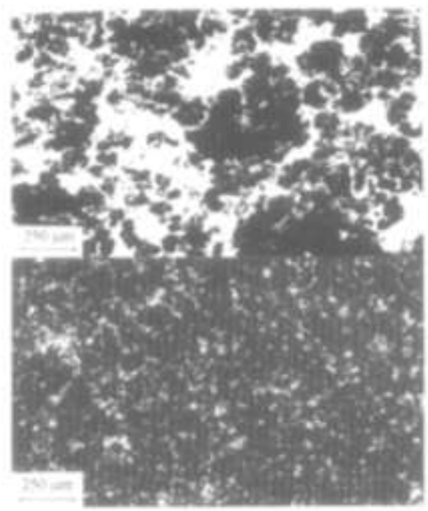

Figure 2.5: Photograph showing void space ratio before and after compaction (Semmel 1993)

Semmel (1993) further showed that the reduction in saturated hydraulic conductivity as a cropping soil is slowly compacted over several years (Figure 2.7). This graph shows that at high compaction levels, such as used in clay lined dams, HC is drastically reduced.

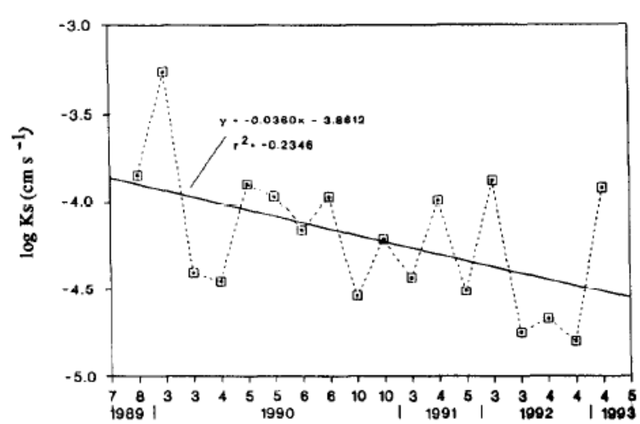

Figure 2.6: Reduction in saturated HC due to long term compaction (Semmel 1993)

This research regarding compaction and reduced hydraulic conductivity has formed the basis for implementing compacted clay liners to reduce infiltration rates from below feedlot-effluent ponds. Higher levels of compaction will result in a higher bulk density which will produce the best result when attempting to restrict permeability to below the guideline rate (McCurdy & McSweeney 1993).

2.5 Percolating solution considerations

Irrigating with saline-sodic water has various chemical and physical affects upon a soil. Salinity is a measure of soluble salts and influences soil properties and plant growth (Vance *et al.* 2008). Salinity problems in Australia are in majority caused by excessive sodium; any process that accumulates NaCl salt in the soil profile leads to soil sodification unless a sufficient source of soluble calcium or magnesium minerals is present (Rengasamy 1993). This further causes swelling of the diffuse double layer and potentially dispersion of clay particles (Sumner 1993), thus resulting in a blockage of pore spaces and a reduction in permeability (So and Aylmore 1993).

Research has shown that irrigation with saline-sodic waters cause soils to experience, low plant available water capacity, low hydraulic conductivity, increased swelling and high bulk density (Rengasamy and Olsson 1993; Vance *et al*. 2008; Ezlit 2010). If the salinity of the percolating solution is high and the sodicity low, then the solution is likely to have a positive chemical effect on soil hydraulic conductivity through osmosis.

A study involving land application of coal seam gas water (highly saline and sodic) by Vance *et al*. (2008) analysed the chemical and physical soil properties. Results showed that clay soils were at risk of increased bulk density from swelling of clay on wetting and from potential clay particle dispersion. Dispersed clay particles accumulated in subsurface pores as leaching continued. Surface water infiltration rates were also significantly decreased in depths up to 120 cm. The reduction in infiltration was likely caused by surface seal formation, clay dispersion, plugging of soil pores, and swelling from increased SAR in soil solutions (Ben-Hur *et al*. 1985). This is further evidence that saline-sodic solutions, such as feedlot effluent, may influence various soil parameters to cause a reduction in HC.

2.6 Potential for effluent solutions to seal clay lined ponds

2.6.1 Bio-physical Properties

The physical characteristics of wastewater and soil play a major role regarding soil hydro-physical properties. Several studies over the past three decades have shown that treated wastewater used to irrigate agricultural land reduced the HC of a soil at a greater rate than fresh water. This reduction in hydraulic conductivity has been associated with the clogging of soil pores in the upper soil horizon with suspended solids (Vinten *et al*. 1983), as Wastewater contains a higher load of suspended solids and organic matter than fresh water obtained from a bore or dam. The extent of soil sealing due to organic particulates depends heavily on the pore size distribution of the soil. Organic matter will block micropores within the soil structure quicker than macropores; in the case of compacted clay the majority of the remaining pore spaces are micropores due to the results of compaction (Feigin *et al.* 1991).

The growth of microorganisms and extracellular carbohydrate production due to high nutrient content in the wastewater was also shown to contribute to pore blockage (Magesan *et al.* 1999). This study conducted by Magesan *et al.* (1999) suggested that the mechanism for the decrease in HC after wastewater was applied to land, was due to increased microbial growth and extracellular carbohydrate production. Microorganisms in the soil accumulate in the soil due to growth accelerated by an abundance of nutrients; this causes pore blockage and a further reduction of hydraulic conductivity (Magesan *et al.* 1999). These can be assumed to be a change in the biological soil properties. Magesan *et al.* (1999) also noted the reduction in HC due to wastewater application on the environment varies with soil type, wastewater characteristics, and the vegetation of the irrigated soil.

Results for wastewater treated to different levels produced inconsistent results. For example Levy *et al.* (1999) found that treated wastewater that has received primary treatment, usually involving screening, settling, flocculation and filtering; produced almost identical results to fresh water. On the other hand, Tarchitzky *et al*. (1999) reported a decrease in hydraulic conductivity.

2.6.2 Specific Past Research

Bennett *et al.* (2011) conducted a research project to evaluate the effect of feedlot effluent water on the permeability of soil used for constructing effluent dams. The project aimed to determine if the infiltration guideline of $1x10\text{^}^{-9}$ (m/s) could be achieved with compacted feedlot soils. Results showed that while there was a substantial reduction in hydraulic conductivity post leaching with effluent, the guideline was only satisfied by one soil. The reduction in HC was suggested to be caused primarily due to soil compaction in conjunction with dispersed clay. However, organic particulate accumulation was also suggested as a means of HC reduction. While this study shows the potential of organic matter as a contributor to soil sealing the magnitude of its effect was not considered in the original experimental design. In this study, the soils were leached for two and a half months; a longer time period may have further reduced HC due to extended accumulation of organic matter.

Furthermore, Bean *et al.* (1999) showed that the effect on HC of leaching compacted soil with feedlot effluent was drastically different to leaching with water from the local council supply. When leaching with either filtered effluent or raw effluent, there was a significant decrease in soil permeability compared with water. Results showed a HC of $1x10\text{^}^{-6}$ (m/s) for water and $5x10\text{^}^{-8}$ (m/) for feedlot effluent. Furthermore, when the clay soil samples were removed from their mould and bisected a manure stain could be seen within selected voids, indicating that effluent contained organic matter was becoming trapped within the soil pores, thus contributing to the decrease in permeability over time (Bean *et al.* 1999).

There has been very little research on the potential of agricultural effluent as a means of reducing the hydraulic conductivity of clay lined ponds, although the impact of irrigating agricultural land with treated wastewater has been relatively well researched throughout the past few decades (Vinten *et al.* 1983, Halliwell *et al*. 2001; Magesan *et al*. 1999). Land application of treated wastewater in agricultural areas is a method of effluent disposal and a means to sustain agricultural production, especially in regions where there is a shortage of freshwater (Mandal *et al.* 2008). There are various similarities between treated wastewater and feedlot effluent, often including high sodicity, high EC, high organic matter content (OMC), and the presence of suspended solids. However, treated wastewater usually has fewer suspended solids and a lower amount of organic matter present, due to removal during settling and filtration processes. It has been shown that soils subjected to treated wastewater with high sodium concentrations were generally found to have a substantial reduction of 20 to 30% HC compared to soils leached with calcium dominated water, (Hansen 2010).

Soil hydraulic conductivity may also be decreased through physical blocking of soil pores, as a result of high amounts of suspended solids in the applied wastewater. It was found that continued application of wastewater with high loads of suspended solids [total suspended solids (TSS) ranged from 57-304 mg/L], may cause the formation of restricted layers that can severely decrease the infiltration rate if not controlled (Halliwell *et al.* 2001; Viviani *et al*. 2004). The effect of wastewater upon infiltration rate when applied to soils was also observed by Vinten *et al.* (1983). When analysing the influence of the suspended particles within the wastewater on the hydraulic conductivity, they found that soil with majority smaller particle size, such as a clay loam, decreased in HC more severely than in a sandy soil. This is a function of pore size, as influenced by clay percentage. Wastewater irrigation was also found to increase ESP and a reduce soil porosity (Abedi-Koupai *et al.* 2006). These findings indicate that reduction in soil HC after application of wastewater is due to both the retention of organic matter during infiltration and the change in pore size distribution resulting from expansion and dispersion of clay particles (Vinten *et al*. 1983; Abedi-Koupai *et al.* 2006).

A recent study by Awedat *et al*. (2012) highlighted the effect that pore size has upon pore blockage and therefor HC Solutions containing various suspended clay concentrations; 0, 5, 10 and 20 g/L; were leached through soils at two bulk densities, 1.0 g cm^{-3} and 1.2 g cm^{-3}. After percolating 10 pore volumes the water retention of each core was measured. Results showed that soils with lower bulk density retained less water even at high clay concentrations. This shows that soils with greater porosity will allow a greater percentage TSS to pass through the core. Both bulk densities showed a significant increase in water retention at the surface compared to the subsurface, indicating that the water soil interface acts as the throttle to HC. Due to the high concentrations of suspended solids contained in effluent it could also be expected that a pore blockage would similarly occur at the surface.

From the literature presented above it is evident that potential exists for effluent to act as a sealant for compacted, clay lined ponds, through both chemical and physical blockage mechanisms. However, there is a dearth of information examining the effects of untreated and unfiltered effluent, in particular the extent by which it may reduce the hydraulic conductivity of a soil. From previous studies, most dealing with treated wastewater application to agricultural land, it can be deduced that the hydraulic conductivity of a soil will be reduced due to three processes: 1) biological - the growth of microcellular bacteria and extracellular carbohydrates; 2) physical - the soil pores becoming blocked by suspended solids and organic matter; and 3) chemical - dispersion and swelling of clay particles caused by the high SAR of the wastewater. There were no studies related to the application of treated wastewater to highly compacted clay soils. Past studies have also neglected to investigate the impacts of applying and/or leaching effluent to/through soil for a prolonged period.

2.7 Conclusion

This literature review has examined the ways in which feedlot pond effluent and its chemical, biological and physical characteristics can affect soil physical and chemical properties that are responsible for governing HC. In the circumstance of effluent ponds, a reduction in HC for the pond floor is a positive outcome, and in this regard previous studies have shown promise for saline-sodic water, treated wastewater and effluent in reducing the HC of various soils (fine and coarse textured). Literature shows potential exists for effluent to reduce the hydraulic conductivity in compacted soils to below the guideline limit of $1x10^{\wedge-9}$ (m/s). It was also highlighted that there is a requirement for further understanding of the role of suspended organic particulate in decreasing soil HC.

Chapter 3 METHODOLOGY

3.1 Overview

To achieve the project aims outlined in the introductory chapter the following experimental process was developed. Two soils, heavy clay from Undabri Feedlot in Queensland, and clay loam from Rangers Valley Feedlot in New South Wales were selected for analysis. These two soils were chosen due to their contrasting clay content, which allowed for comparisons in hydraulic conductivity between fine and coarser textured soils. Soil was compacted into soil cores at 98% compaction of the maximum dry density (MDD). Each soil and solution contained five replicates to limit uncontrolled variation. Four treatment solutions were then prepared:

1. Calcium Chloride $CaCl_2$
2. Synthetic Effluent Solution
3. Filtered Feedlot Effluent
4. Raw Feedlot Effluent

The soil cores were then leached with the appropriate treatment solution for approximately three months, with measurements for the hydraulic conductivity (HC) being taken daily for the first ten days and then weekly for the remainder of the experiment. Total suspended solids (TSS) of the filtered and raw effluent treatments was determined and periodically compared to TSS of leachates obtained throughout the experimental duration in order to assess the soils ability to entrain effluent inherent organic particulates.

3.2 Initial Preparation

The first stage of the experimental procedure was the initial preparation period. This involved being inducted into the laboratory and shown where all the equipment was stored and where the personal protective equipment was located. A large proportion of this stage was spent organizing funding for the experimental equipment not available from the laboratory. Before parts were purchased quotes were collected which allowed for a cost analysis of the entire experiment, more detail on the project budget will be given in the resource requirements contained in Appendix B. The final task in this stage was to thoroughly clean the secondary IBC tank. This was completed using a gurney capable of applying hot water which effectively removed the existing grime from inside the tank.

3.3 Solution Preparation

As mentioned in the overview the project was designed around the hydraulic conductivity testing of four unique solutions. Preparing each solution was a significant and vital part of the total experimental preparation stage. The four treatment solutions were prepared as follows. Justification for each solution is also provided in the respective sections below.

3.3.1 Calcium Chloride $CaCl_2$

A calcium chloride ($CaCl_2$) solution prepared at the same EC as the effluent (5.6 dS/m) was used as a control because this removed the osmotic effect on soil structure as a variable and ensured that soil structural integrity was maintained. In doing this, a baseline hydraulic conductivity relative to the soil specific structure and osmotic effect of permeating solutions was obtained.

The chemical properties of the effluent had previously been examined by Bennett *et al*. (2011) (Table 3.1). Hence the $CaCl_2$ solution was formulated to match the electrical conductivity (EC) of the raw effluent which was 5.6 dS/m. To create ten liters of solution 41.216 g of Calcium chloride dehydrate ($CaCl_2$ $2H_2O$) powder was mixed with 10L of de-ionized water.

Table 3.1: Raw Effluent Chemical Properties

Analysis	*Unit*	*Effluent Value*
pH		7.6
Conductivity	uS/cm	5,600
Total Hardness	Mg/L $CaCO_3$	426
Total Alkalinity	Mg/L $CaCO_3$	390
Calcium	mg/L	78.6
Sodium	mg/L	270
Magnesium	mg/L	55.8
Sodium Absorption Ratio		5.7

3.3.2 Synthetic Effluent

A synthetic effluent solution was then prepared to determine the extent to which the chemistry of effluent solutions provide a deleterious effect on soil HC, as opposed to the effect of effluent contained organic particulates. Thus, the chemical and physical effects of the effluent solutions can be examined as separate mechanisms.

As with the $CaCl_2$ solution the synthetic effluent was formulated to match the chemical properties of the effluent (Table 1) which included; electrical conductivity (EC) of 5.6 dS/m, desired bicarbonate (HCO_3) of 390 mg/L and a sodium absorption ratio (SAR) of 5.7. To create ten liters of synthetic effluent solution 5.369 g of sodium bicarbonate $NaHCO_3$, 9.773 g of sodium chloride NaCl and 24.204 g of $CaCl_2$ were added to 10 L of deionised water. After mixing the solution the EC was tested using an EC probe.

3.3.3 Filtered Effluent

Raw effluent was filtered to <3 μm in order to assess the importance of particle size of effluent suspended solids. Where soils are compacted to 98% of the MDD, macropores are significantly reduced. In this capacity, it is important to understand if larger organic particulates are responsible for creating a surface seal, or if organic particulates similar in particle size to dispersed clay (<2 μm) are more effective in blocking fine pore networks.

The suspended solids and organic particulate contained in the raw effluent was filtered using a two tier filtration process. The initial filtration implemented the use of a geo-textile fabric which was folded inside a large funnel (150 mm diameter). Gravitational pressure head was used to transport the effluent from an IBC tank situated at an elevated level, through the porous geo-textile material into a second IBC tank at ground level. The geo-textile material allowed the effluent to flow through at a fast rate while still retaining larger suspended solids. Removing the larger particles in the initial filtration prevents the fine filter paper used in the secondary tier process from prematurely clogging and blocking effluent flow.

The secondary stage involved filtering the effluent from the second IBC tank into ten separate 10 L drums. Ten smaller funnels (100 mm diameter) were lined with 240mm diameter Whatman qualitative filter paper with a Grade 6 rating. The Grade 6 Cellulose filter paper has 3 μm pores which allows for extremely fine particle retention. The flow rate through the fine filters was incredibly slow; ten days of filtration produced approximately 8 L of filtered effluent solution. The filter papers were replaced every second day to prevent the flow from ceasing. The secondary tier, fine filtration process is demonstrated in Figure 3..

Figure 3.1: Secondary filtration process using 3 um pore size, Whatman filter paper for fine particle retention

3.3.4 Raw Effluent

Raw effluent was used to emulate the settling processes expected under a functioning feedlot effluent pond. Raw effluent was obtained from a functioning feedlot and was the same source and time sample used in Bennett *et al.* (2011). The effluent was thoroughly stirred using a large mixing rod to ensure all the suspended solids were uniformly distributed throughout the solution. The effluent was then decanted into ten, 10 L drums.

3.4 Soil Preparation

Initially, soil was crushed using a mortar and pestle to pass a 2 mm sieve. This ensured the soil had a largely homogenous aggregate structure and decreased soil core HC edge effects know to occur with larger aggregate sizes. Samples were weighed to specific weights (Table 3.2) to achieve 98% compaction inside an 87.5 mm diameter and 50 mm length section of poly-pipe. The soil was separated into two equal lots of half the total weight to ensure that when wet, the optimum moisture content (OMC) would be evenly distributed throughout the soil sample which results in even compaction levels throughout the soil core. This is important as by compacting the soil as a single weight would result in over-compaction at the top of the core and under-compaction at the base of the core with bulk density correct when averaged across the compaction gradient. This un-even compaction would then likely alter HC measurements at the infiltration interface. The required soil weight and amount of deionised water to achieve OMC is shown in Table 3.2 below. The core size is 8.75 x 5 cm which gives a volume of 300.66 cm^3.

Table 3.2: Physical Soil Properties

Soil	*MDD (t/m³)*	*OMC (%)*	*98% MDD (t/m³)*	*Soil weight for 98% (g)*	*Moisture to achieve OMC at 98% (mL)*	*50% soil weight for 98% (g)*	*50% OMC at 98% compaction (mL)*
Undabri	1.492	8.1	1.46216	440	76	220	38
Rangers	1.689	5.36	1.65522	498	37	249	18

After the soil samples had been prepared to correct OMC soils were compacted to 98% of the MDD inside storm water-pipe soil rings. The poly-pipe was measured and marked to ensure that the compaction level was accurate. This is demonstrated in Figure 3.2 below. A compaction cylinder, hammer and ring were used to compact the soil to the appropriate level inside the poly-pipe. This usually involved approximately four or five drops of the hammer; an example of the compaction equipment used is displayed in Figure 3.2. The soil chemical attributes for the soils in their initial state are presented in Table 3.3.

Table 3.3: Soil Initial Chemical Properties

Soil ID/ Type	*pH*	*OM (%)*	*EC (dS/m)*	*ESP (%)*	*ECEC (cmol/kg)*	*Ca:Mg*
D (heavy clay)	7.8	1.6	0.13	6.7	41.76	1.7
E (clay loam)	6.8	0.5	0.06	1.7	13.29	2.4

Figure 3.2: Soil Core Compaction depth measurement for 98% MDD

Figure 3.3: Quick release compaction cylinder and standard hammer used in soil compaction process

Once the soil was compacted the plastic core was placed into a mesh cylinder with two standard Grade 1 90 mm Whatman filter papers. This formed the bottom of the core. A 90 mm plastic coupling was then placed on the top half of the core with two more identical filter papers placed on the top of the soil. The mesh bottom and coupling top were firmly fitted together to ensure there was no gap. Electric tape was wrapped around the connection between the mesh and coupling to secure the core. The thread of the coupling was wrapped in plumber's tape to reduce the chance of leakage from the lid. Finally, a neoprene gasket was placed inside the lid and the lid was connected to the coupling and tightened so as to be water tight. The apparatus used to construct the core as explained above is shown in Figure 3.4.

Figure 3.4: Soil Core Construction: A) soil core, B) 90 mm mesh filter socket, C) 90mm coupling, D) 3 mm thick neoprene gasket, E) screw-on end cap, F) 19mm nozzle, G) o-ring, H) brass nut

3.5 Experiment Assembly

After preparation of the solutions and soils was complete, construction of the piping and valve system was undertaken. The drums containing the various treatment solutions were placed on elevated pallet racks approximately 1.32 m above the base of the core. The soils cores, in Buchner funnels and supported by leaching racks, were placed on a stainless-steel bench below the treatment solutions (Figure 3.5). To allow solutions to permeate the soil, and for the hydraulic conductivity to be measured using a falling pressure head a pipe system was designed.

A 35 cm section of clear 13 mm diameter polyvinyl tubing was connected to the tap on each drum using a steel clamp. This was then merged to 19 mm irrigation pipe with a 13 mm to 19 mm pipe adapter. All pipe joins were heated using a heat gun to ensure water tight connections were made between barbed adaptors/joiners and the pipe. This section of 19 mm irrigation pipe was cut to 65 cm lengths. A 19 mm plastic barbed valve, which allowed for easy control of the flow from ground level, was then attached. Finally another section of 19 mm pipe, of appropriate length, was run from the valve to the soil core intake where it was firmly connected (Figure 3.5).

Figure 3.5: Fully constructed apparatus for measuring HC via falling pressure head

Before the experiment was commenced the top of each soil core was filled with Calcium Chloride with an EC of 5.6 dS/m. This allowed for the soil to become saturated and to remove any air from the system, while having little or no effect on the soils aggregate structure. When the taps were turned on it was observed that some air was still trapped within the pipes. The pipes were bled to remove the air and a connection with the solution in the drums was restored. The lid of the drums were loosened to allow for atmospheric pressure to act upon the system, but still left on to prevent any evaporation losses and subsequent potential for solution concentration.

The soil cores and the plastic containers used to catch any discharge were suitably labelled to ensure the correct results were obtained. The layout of the drums upon the pallets was randomized to ensure the data collected was completely unbiased regarding location. Finally the system was checked for leaks; if any leaks were found silicone sealant gel was applied and the source of the leak taped.

3.6 Hydraulic Conductivity Measurements

3.6.1 Falling head technique using 1.32 m of hydraulic head

The system was turned on at the beginning of each day and turned off in the late afternoon for the first ten days of operation, with time in operation meticulously recorded. After this ten day period the Calcium Chloride permeate was switched off as ample solution volume had passed through the soil (up to 10 L). From this point the remaining treatment solution measurements were taken weekly with the apparatus constantly flowing, due to the extremely slow infiltration rate. The discharge collected in the plastic containers below the soil core was measured and recorded at the end of each measurement period. The initial height of the solution in the drums and the height at the end of each measurement period were also recorded in order to calculate the hydraulic conductivity using Darcy's Law adapted for a falling pressure head (Equation 1). The time the system operated between each measurement cycle was also recorded.

$$K = \frac{2.3aL}{At} \log \frac{h1}{h2} \tag{1}$$

Where *a* is the internal cross sectional surface area of the pipette, *L* is the core length, *A* is the cross sectional area of the soil core, *t* is the time over which the change in head was measured, and *h1/h2* is the height differential between the initial head (*h1*) and the final head height (*h2*).

3.6.2 Falling head technique using pipettes

After approximately three months of treatment solution percolation through the soil cores, the final HC rate was measured using in a highly precise manner. The pipe and drum system was disconnected and replaced with pipettes secured in place by watertight rubber grommets. The temperature of the room was controlled at 20˚C as to control changes in water temperature that would affect solution viscosity and density. Pipettes were then filled to the maximum mark with the respective treatment solution and placed into the soil core reservoir that was filled with the same respective treatment solution (Figure 3.6). This formed the falling pressure head. HC was then calculated using Equation 1.

Figure 3.6: Pipette analysis to obtain the final HC reading

3.8 Total Suspended Solids

Up to 100 mL of both the filtered and raw effluent permeate solution were collected in a container of known weight and analysed for total suspended solid concentration. Prior to sampling, the bulk solutions were thoroughly shaken to ensure an even suspension of solution particulate. Sampling occurred immediately after shaking to avoid rapid settling of heavier particles. Five replicates of each solution were placed into individual aluminum trays of known weight (accurate to 5 decimal places) that were suitable for oven drying at 105˚C. The weight of the solution and tray was then recorded. The trays were placed into the laboratory oven and left for 24 hours at 105˚C to ensure complete evaporation. Remaining after evaporation was the suspended solids contained within the solution. By reweighing the trays, the exact weight of the suspended solids were obtained by weight difference calculation and converted to grams per liter.

This process was repeated several times throughout the experiment with treatment solution leachates that had been collected and stored in the laboratory refrigerator. This data was used to determine the extent to which soils were acting as filters for the suspended particulates contained in the effluent.

3.9 Statistical Analysis

To thoroughly analyse the accuracy of hydraulic conductivity and total suspended solids data collected in the experiment a statistical analysis was performed. The Minitab 14 Student Version software package was used to conduct one-way analysis of variance (ANOVA). Where significant differences were found, Tukey's multiple comparison tests (honest significant difference, HSD) were used to investigate differences between mean pairs. The HSD value was then applied as an error bar for each graph. A 95% confidence interval was used in the case of both ANOVA and Tukey analysis.

Chapter 4 RESULTS

4.1 Hydraulic Conductivity

4.1.1 Calcium Chloride

As explained in the introductory chapter the main objective of this research project is to discover if organic particulate contained in feedlot effluent contributes to pore blockage and a reduction of hydraulic conductivity below $1x10^{-9}$ m/s. To achieve this, the HC of two soils leached with four solutions over an extended period of time was examined. Figure 1 shows the hydraulic conductivity of the two soils when leached with calcium chloride solution of EC 5.6 dS/m. As expected the clay loam 'E' soil had a faster infiltration rate; the clay loam has a lower amount of clay particles (<0.002 mm) and a higher amount of silt (0.002-0.02 mm) and sand (>0.02 mm), which results in a coarser aggregate structure.

Figure 4.1 shows a gradual increase in the HC of the clay loam soil during the 50 hour leaching period, while the heavy clay reaches a maximum around 50 hours before decreasing back towards the initial HC. The HSD bars show there is a significant increase between the initial and final HC of the clay loam. The change in heavy clay HC reached a significant stage from about 35 to 60 hours, however considering the reduction in HC after the 60 hour mark, the difference between the initial and final HC at 75 hours is stable and not significant.

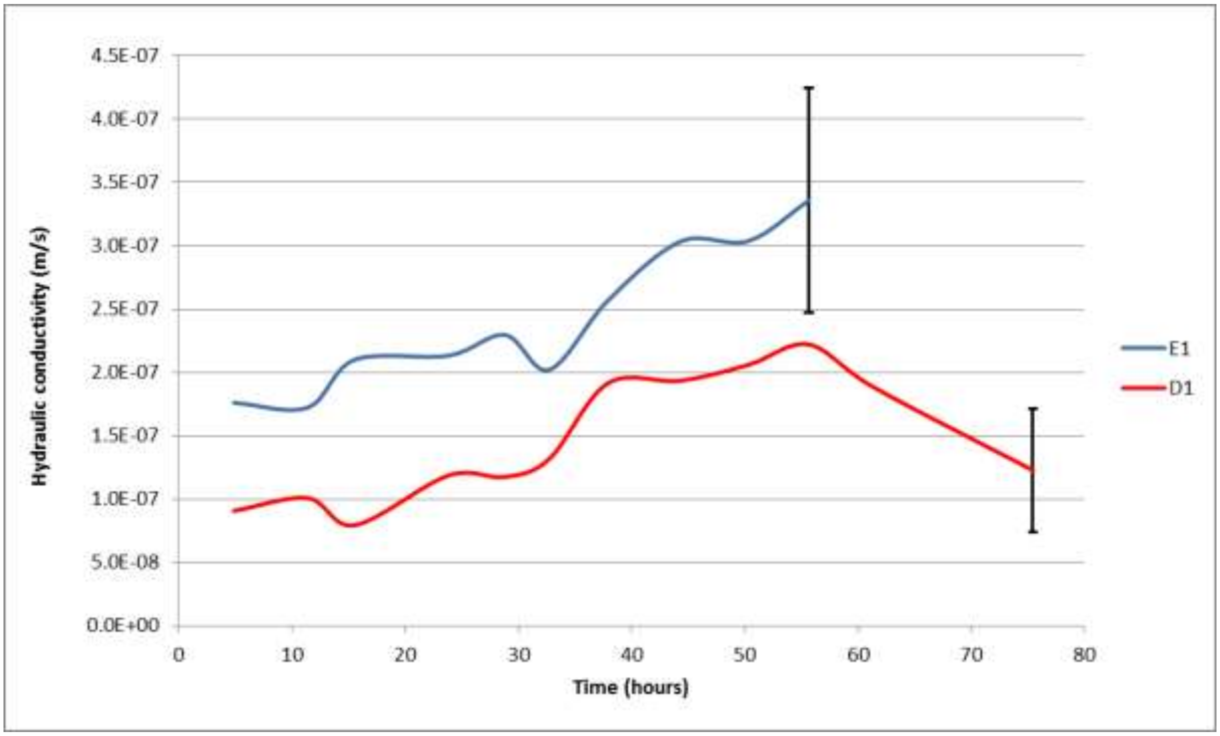

Figure 4.1: HC Curve for soils treated with calcium chloride solution, error bars show least significant difference

4.1.2 Raw and Filtered Effluent

Figure 4.2 shows the HC of both soils leached with filtered and raw effluent over an extended period, approximately 1300 hours or 55 days. Once again the heavy clay soil has a slower infiltration rate than the clay loam. This is the case both initially and consequently. A noticeable difference in HC between the filtered effluent and raw effluent for both soils was obtained. Statistical analysis showed that the HC of both filtered and raw treatments in the heavy clay was not significantly different. However, in the clay loam there is a significant difference between filtered and raw treatments after 650 hours, after which the difference decreases approaching the final HC rate, which was not significantly different between filtered and raw treatments. A significant decrease in HC from time 100 h to time 1300 h was observed for both soils and both filtered and raw effluent treatments. The potential guideline HC of 1x10^¯9 m/s is shown by the horizontal black line in Figure 4.2. After approximately 500 and 750 hours of leaching the HC of the heavy clay soil (soil D) treated with raw and filtered effluent, respectively, was below this rate. The clay loam soil (soil E) has not met the guideline hydraulic conductivity on average for the raw and filtered treatments. However, final variation for the filtered treatment suggests that the guideline has been statistically met and the trend of both raw and filtered treatment HCs to be steadily declining suggests the target HC will likely be achieved.

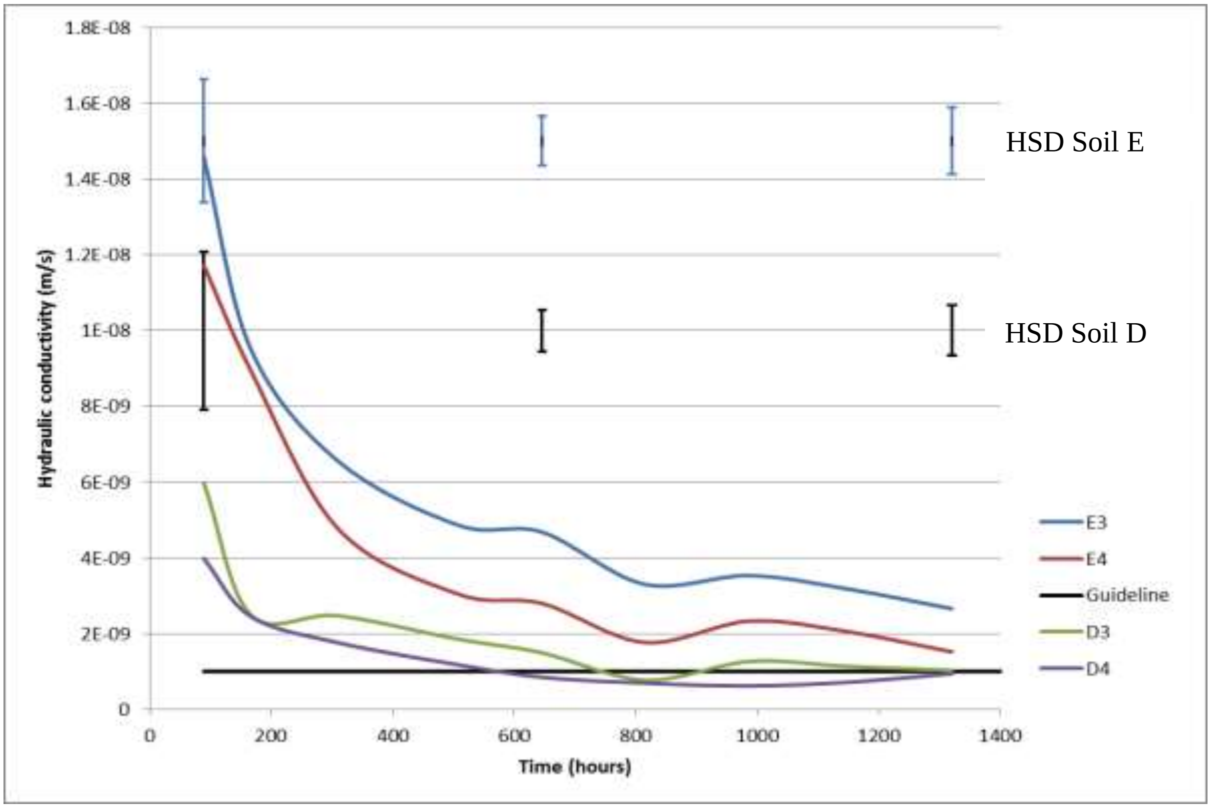

Figure 4.2: HC Curve for soils treated with filtered (3) and raw (4) feedlot effluent, error bars show least significant difference statistical results, the black line represents proposed infiltration rate

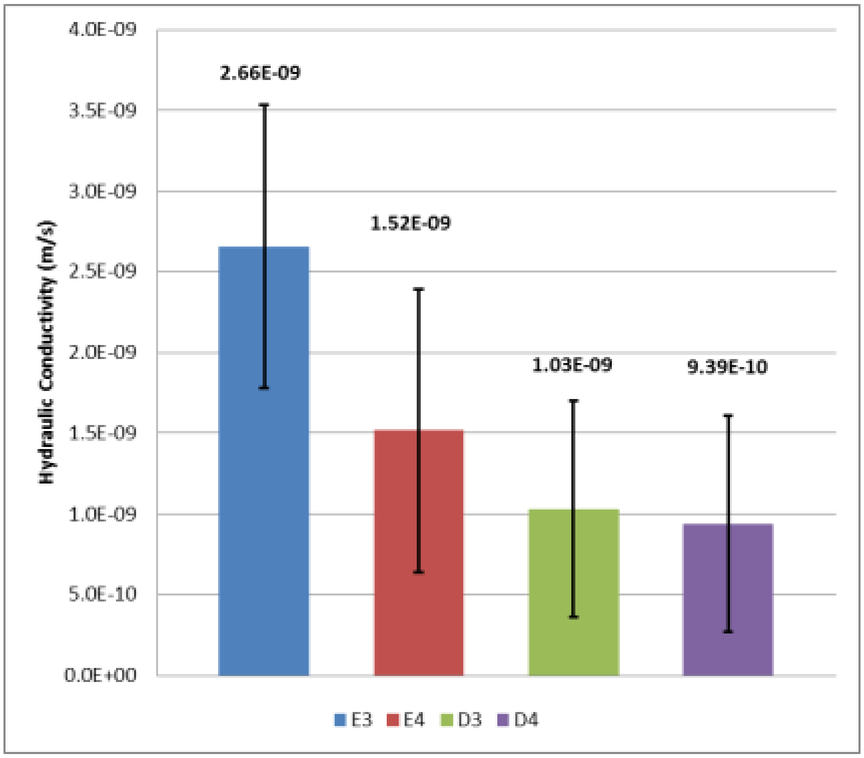

Figure 4.3: Final HC of soils leached with filtered and raw effluent solutions, error bars show least significant difference between treatments for each soil, clay loam (soil E) and heavy clay (soil D)

Figure 4.3 shows the final HC of both soils after approximately 1300 hours or 55 days of leaching with filtered effluent and raw effluent. As expected the infiltration rate of the heavy clay soil (soil D) is significantly lower than the clay loam (soil E). For both soils, the difference in final HC between soils treated with filtered and raw effluents is not significant.

4.1.3 Synthetic Effluent Comparison

Figure 4.4 and 4.5 compares soil HC when treated with synthetic effluent, filtered effluent and raw effluent solutions for the first 50 h. The HC of the treatments applied to the clay loam are shown in Figure 4.4 while the heavy clay results are displayed in Figure 4.5. The synthetic effluent treatments were applied for 50 hours so it was only possible to compare throughout this time-period. In the clay loam (Soil E), Figure 4.4, the synthetic effluent HC has increased from 1.7×10^{-7} to 3.4×10^{-7} m/s. After 45 h, soils leached with synthetic effluent have a significantly higher HC than those leached with filtered or raw effluent. For the heavy clay soil (D), Figure 4.5, similarities in HC between the synthetic, filtered, and raw effluent can be observed after 50 h. In the heavy clay the difference between the solutions HC was analysed statistically analysed at 50 hours. The raw and filtered effluent is similar to the synthetic effluent at 25hours; however at 50 hours the HSD bars shows these same treatments to have significantly lower HC as compared to the synthetic solution.

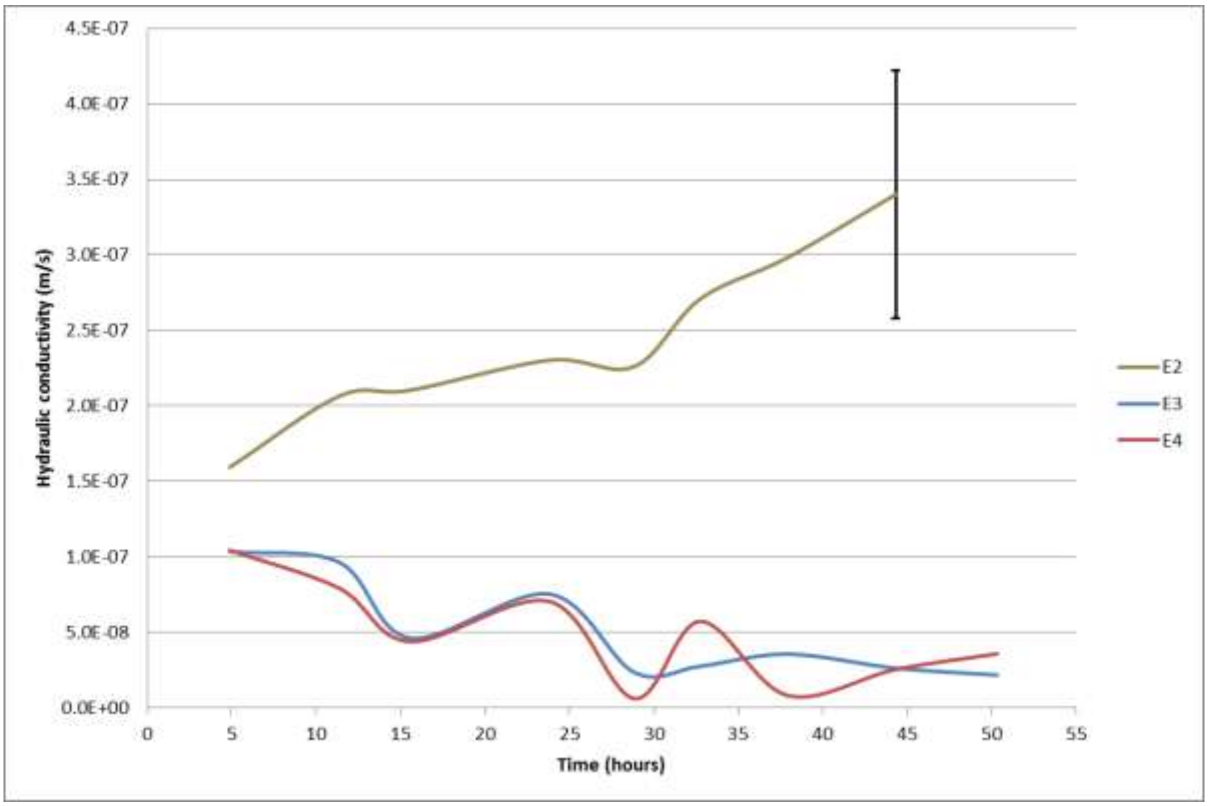

Figure 4.4: HC Curve for Clay Loam (E) treated with synthetic (2), filtered (3) and raw (4) effluent solutions over initial 50 hours, error bars show least significant difference with respect to the synthetic treatment

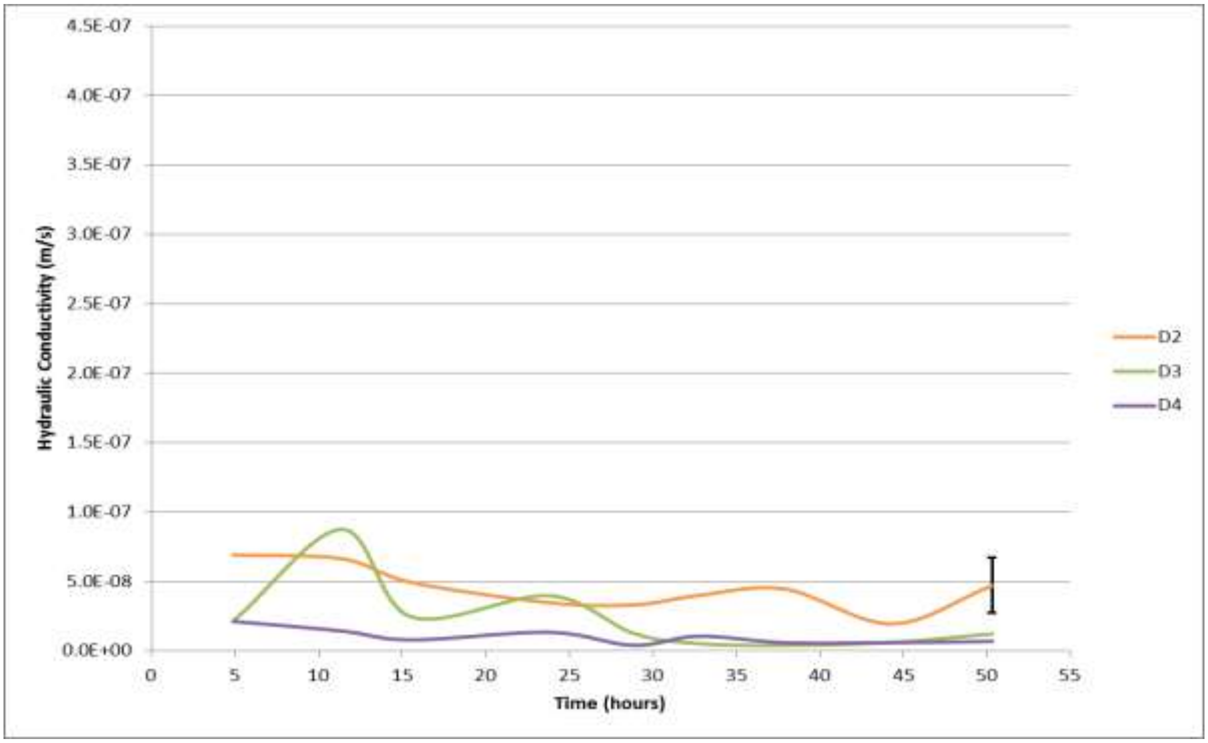

Figure 4.5: HC Curve for Heavy Clay (D) treated with synthetic (2), filtered (3) and raw (4) effluent solutions over initial 50 hours, error bars show least significant difference with respect to the synthetic treatment

4.1.4 Pore Volumes

Table 4.1: Hydraulic conductivity and pore volumes of solution leachate after 50 hours and 1300 hours of application

	50 Hours Application		*1300 Hours Application*	
Sample	*HC (m/s)*	*PV*	*HC (m/s)*	*PV*
E2	3.53E-07	75	-	-
E3	2.17E-08	12	2.66E-09	36
E4	3.58E-08	10	1.52E-09	28
D2	4.72E-08	11	-	-
D3	1.24E-08	2	1.03E-09	9
D4	6.99E-09	2	9.39E-10	7

Table 4.1 shows that after 50 hours of treatment application, there is a significant difference for both soils with respect to synthetic effluent compared to either filtered or raw effluent. In both soils at least five times the pore volume (PV) of synthetic solution, passed through the core compared to the actual effluent solutions. This result highlights that synthetic effluent is not an accurate representation of a soil's HC behaviour under real effluent application. After 1300 hours of treatment a greater difference between the HC and PV of filtered and actual effluent has prevailed, this is especially the case for the clay loam, where there is eight PV's difference, this equates to approximately 1 L of discharge. The pore volume achieved after 50 hours compared to 1300 hours also demonstrates how the infiltration rate has reduced over time. Pore volumes leached at a faster rate during the initial stages compared to the later stages, for example in the raw treatment for heavy clay pore volumes passed through at 1 per 25 hours initially compared to 1 per 185 hours towards the end. Furthermore, by 1300 h of experimental run-time the raw/filtered effluent treatments have leached less PVs than the synthetic treatment leached in 50 h, for both soils. The HC after 1300h was also 1–2 orders of magnitude less than that of the synthetic treatment post 50 h for raw/filtered effluent treatments.

4.1.5 Final Hydraulic Conductivity

As displayed in Figure 4.6, the final experimental HC of the heavy clay soil was significantly slower than the clay loam, which was expected given the difference in clay content. It is apparent that the final HC rate of the synthetic effluent is significantly slower than the calcium chloride for the heavy clay (soil D). In the clay loam (soil E) the final HC of after leaching with synthetic effluent was slightly higher than the calcium chloride, but not statistically significant.

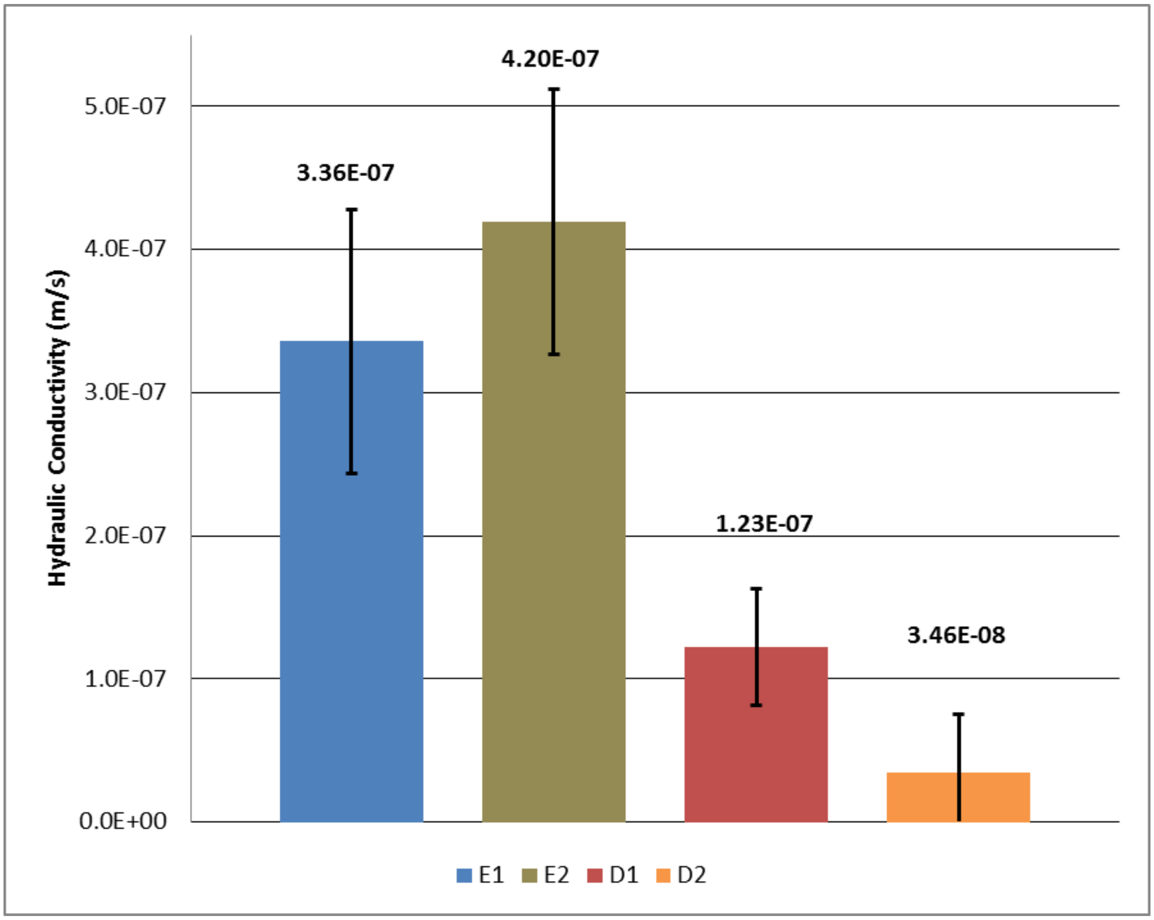

Figure 4.6: Final HC for soils leached with Calcium Chloride (1) and Synthetic effluent (2) solutions, HSD error bars included

Table 4.2: Initial and final hydraulic conductivity (m/s) and infiltration rate (mm/year) for all samples

	Hydraulic Conductivity (m/s)		*Infiltration Rate (mm/year)*	
Sample	*Initial*	*Final*	*Initial*	*Final*
D1	9.07E-08	1.23E-07	2859.2	3867.6
D2	6.92E-08	3.46E-08	2181.4	1090.9
D3	2.15E-08	1.03E-09	678.9	32.4
D4	2.14E-08	9.39E-10	674.7	29.6
E1	1.76E-07	3.36E-07	5552.0	10590.0
E2	1.59E-07	4.20E-07	5026.1	13232.3
E3	1.04E-07	2.66E-09	3268.0	83.8
E4	1.04E-07	1.52E-09	3293.7	47.8

Table 4.2 shows the initial and final hydraulic conductivity and infiltration rate (IR) for all samples. As the results show the soils leached with effluent experience a large reduction in HC and IR over 1350 hours. Both soils leached with $CaCl_2$ experienced a small increase in HC over the time period. The synthetic solution caused an increase of HC by approximately 2.5 times in the clay loam while a reduction of about 50% was measured in the heavy clay. This was after approximately 55 hours of experiment run-time.

4.2 Total Suspended Solids

The total suspended solids (TSS) results are shown in Figure 4.7. Time zero represents the permeating solution while the following time steps represent the reduction in TSS of the leachate at that particular time. Significantly higher TSS concentration was contained in the percolating solutions (t=0) compared to the leachate solutions, ranging from 0.4 to 1.0 g/L. Regarding the percolating solutions, the filtered effluent contains approximately 0.25 g/L less suspended solids than the raw effluent. Analysing the leachate solutions it can be seen that in both soil types the filtered leachate samples contain less TSS. The leachate or discharge from the heavy clay soil on average contains less TSS compared to the clay loam.

There is no distinguishable relationship or trend regarding the concentration of TSS contained in the leachate as the experiment progresses. Figure 4.7 shows that the filtered effluent leachate contains less TSS than raw effluent. Soil D, the heavy clay, traps a higher amount of TSS within its structure which results in a lower amount of TSS compared to the clay loam. The error bars on the column graph show the least significant difference of each sample's results compared to the initial permeate results. There is a significant difference between the percolate and leachate for the filtered treatment of both the clay loam and heavy clay.

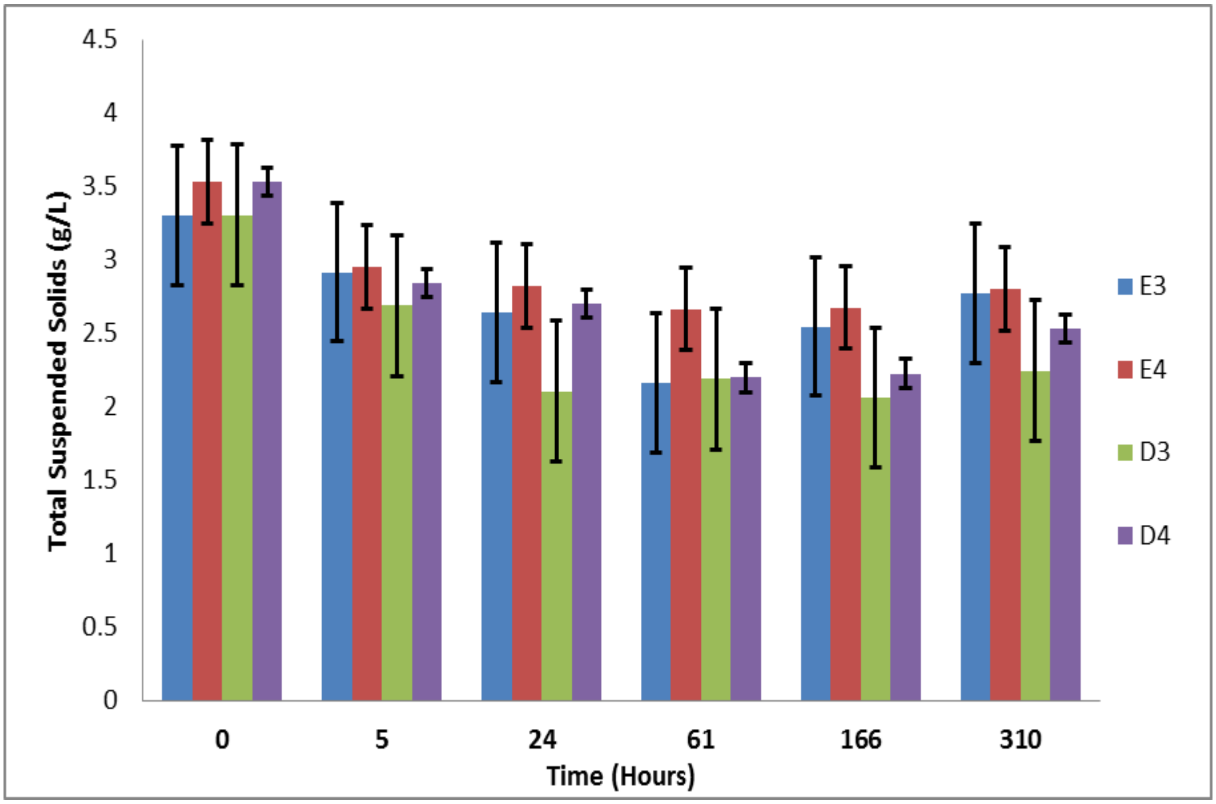

Figure 4.7: Total Suspended Solids TSS (g/L) measured at different time periods throughout the experiment, time zero shows permeate TSS while time 5-310 shows leachate TSS, HSD bars represent difference of each treatment compared to time zero

Figure 4.8: Colour difference between permeate (darker) and leachate solutions (lighter)

Figure 4.8 shows the permeate and leachate solutions side-by-side. The leachate solutions shown here are taken after 61 hours of application. The difference in colour between the permeate and leachate solutions is quite obvious indicating filtration of suspended solids (Table 4.3). The TSS values in Table 4.3 are taken from an overall average of each of the five time-step results.

Table 4.3: Average TSS (g/L) contained in each sample (E) clay loam and (D) heavy clay, values in parenthesis are standard errors

Sample	*Average TSS (g/L)*
Filtered	3.304 (0.432)
Raw	3.532 (0.432)
E3	2.607 (0.472)
E4	2.783 (0.284)
D3	2.257 (0.479)
D4	2.498 (0.096)

Chapter 5 DISCUSSION

The two soils, a heavy clay and clay loam, were selected for analysis as their differing structural and chemical properties allowed for a comparison with respect to particle size and hydraulic conductivity. The soils were compacted to 98% MDD, which due to a high bulk density reduces pore volume and the soils infiltration potential, thus allowing the lowest physically manipulated HC rate to be achieved (Lipiec & Hatano 2003). The initial chemical properties of the soils are shown in Table 3.3.

Physical differences between the soils are due to variances in particle size distribution. The heavy clay contains a higher percentage of clay particles which reduce porosity throughout the structure, as they have a small surface area. The clay loam contains more silt and sand particles and has a less dense structure which results in a higher porosity. This meant that a greater weight of clay loam was needed to reach the same compaction level as the heavy clay; however less water was required to achieve optimum moisture (OM), the clay loam also has a lower OM %. Analysing the chemical differences it is apparent the heavy clay has a greater EC, exchangeable sodium percentage, and a greater cation exchange capacity. Due to these higher values, in particular the ECEC, the heavy clay is less susceptible to sodic solutions, as compared to the clay loam. Considering both chemical and physical soil properties; there are significant differences between the two soils which comparison good comparative analysis of solutions effects.

5.1 Soil Hydraulic Conductivity after $CaCl_2$ application

Calcium Chloride Solution with an Electrical Conductivity of 5.6 dS/m was applied to heavy clay and clay loam soils compacted to 98% maximum dry density. The results displayed in Figure 4.1 showed a gradual increase in HC throughout the application period for the clay loam while the HC of heavy clay increased before decreasing towards the initial rate after 50 hours. There was a significant increase in HC for the clay loam from the initial to final stage. The heavy clay was significantly different at points where fluctuations were high, however when the difference in initial and final infiltration was analysed the change was not statistically significant. Due to the high concentration of Ca^{2+} ions present in this solution the diffuse double layer could have been reduced in size through an osmotic effect for the clay loam. Due to soils desire to maintain equilibrium between the colloidal surface and soil solution the excess calcium ions in solution may have permeated through the diffuse double layer; this is known as the osmotic effect. Osmosis ensures the positive attraction forces prevail and the diffuse double layer remains compressed preserving structural stability (Sparks 2003). This would result in an increase in soil porosity which explains the slight increase in HC. The soil Ca:Mg ratio would also have been increased; this is due to the smaller hydrated radius of calcium ions compared to magnesium, as a result the diffused double layer is further reduced (Sposito 1989). The $CaCl_2$ discharge also maintained a clear appearance, devoid of any soil sediments, which is also reflection of the soil aggregates remaining stable.

The chemical effects of $CaCl_2$ application explained above provide theoretical reasoning to the gradual increase in HC. The results also show several fluctuations in the HC curve which reflect certain errors within the experiment. The statistical analysis showed the $CaCl_2$ treatments had the highest standard errors over each day of measurements. As this solution generally had the fastest infiltration rate of all treatments, a greater range of results from each replicate was expected. It is plausible that fast, or increased, flow was responsible for gradual erosion of pores through turbulent flow (Hillel 2004), although the absence of suspended solids in the leachate suggests this to be unlikely. Hence, the increase in hydraulic conductivity is most likely to be a ramification of chemistry alteration. The large cross sectional area of the drums and the fact laboratory temperature wasn't controlled could have potentially contributed to measurement errors. In summary, there is theoretical basis for the gradual increase in HC experienced in the project results; however it was expected the HC would remain at a more stable level. When leached with calcium chloride the HC of both soils is theoretically expected to maintain a stable rate. This is due to the Ca^{2+} ions decreasing the size of the diffuse double layer, which restricts swelling and/or dispersion. Upon further analysis the high standard deviation of the results raise concern that data errors may have influenced this particular result. While the $CaCl_2$ is considered appropriate for determining stable soil hydraulic conductivity, it can be concluded it is not representative of effluent treatment effects and should not be used as a substitute permeate in laboratories that cannot receive raw effluent solutions.

5.2 Chemical effects of Synthetic Effluent

Synthetic Effluent containing identical chemical properties to the actual effluent was applied to both soils. In doing this, the difference between the synthetic and raw/filtered effluent samples is that the raw/filtered effluent contains suspended solids. This allows the chemical effect of the effluent solutions to be analysed for its role in HC reduction.

Synthetic effluent was also assessed for its applicability in estimating the soil HC that would be achieved through application of actual effluent solution. The importance of this is that many laboratories are not certified to receive and handle effluent in its raw state. If the chemical properties were entirely responsible for reducing HC, then theoretically the HC of the synthetic and raw/filtered effluent would be statistically similar. However, results showed this was not necessarily the case. Comparing the two soils, there is a major variation in the behaviour of the synthetic treatment HC curves. This is likely caused by the soils initial chemical properties detailed in Table 3.3, which results in different mechanisms controlling hydraulic properties when the treatment is applied. Due to the different reactions of each soil the effects will be discussed separately. It should also be noted that the synthetic treatment was abandoned after 50 h of infiltration, as adequate pore volumes of synthetic solution had passed through in this time to obtain a satisfactory appreciation of the hydraulic conductivity.

The clay loam experienced a significant increase in the HC over the leaching period compared to actual effluent solutions as Figure 4.4 shows. A far greater number of pore volumes of this treatment also passed through compared to other treatments as displayed in Table 4.1 This result was not surprising given past research that has showed sodic solutions, such as the effluent solution; reduce soil permeability (Rengasamy and Olsson 1993; Shainberg & Levy 2005; Vance et al. 2008; Ezlit 2010). The increase in HC experienced is likely a result of the initial soil chemical properties. The clay loam has a low initial ESP (1.7%) and the SAR (5.7) of the synthetic treatment is considered to be suitable for irrigation in Australia (ANZECC 2000). Although there would be a slight contribution to the soils sodicity levels, the EC of the permeate was likely sufficient to provide an osmotic effect that improved soil structure, given the low ESP. In this case, the EC is the driving mechanism for the synthetic solutions effect on the clay loam's HC. Sparling *et al*. (1983) found that if a percolating solution of greater EC than the soil solution is applied the ions within the existing soil solution are pulled through the colloidal surface to maintain structural equilibrium. This reduces swelling of the diffuse double layer and therefore maintains or improves soil permeability. That is to say, it is likely that the soil TEC is satisfied. While this theory provides a possible explanation to the increase in HC, the actual effluent with the same chemical properties caused a substantial reduction in HC over the same period. This suggests the physical effect of pore blockage due to suspended solids was the dominant factor causing a reduction in HC for the clay loam.

Regarding the heavy clay, soil HC over the initial 30 hours is not significantly different to the filtered effluent it should still be noted that the HC of synthetic effluent dropped significantly throughout the leaching period as displayed in Figure 4.5. This is likely due to various chemical effects; firstly the Na^+ ions have contained in the synthetic treatment have contributed to the soils already sodic ESP and increased the size of the diffuse double layer due to weaker attraction forces (Shainberg & Levy 2005). Secondly, the heavy clay has a high ESP of 6.7%, meaning that when even small increases in soil exchangeable sodium are likely going to exacerbate the sodicity effect. Given the relative similarity of the synthetic and effluent treatments HC, it is likely that the threshold electrolyte concentration (TEC) is not satisfied by the solution EC (Sumner 1993); this causes clay particle dispersion that contributes to pore blockages.

However, when both soils are considered in terms of the treatment PVs to have leached through the soil cores, it can be seen in Table 4.1 that the synthetic treatment has infiltrated greater than 7 times that of the effluent solutions. Additionally, after 1300 h, the effluent solutions still have not infiltrated an equivalent number of PVs to the synthetic treatment and have reduced in HC by 1–2 orders of magnitude. Hence, synthetically produced solutions to match raw effluent chemical properties are not a suitable replacement for actual effluent, when measuring soil HC changes.

5.3 Effluent Particle Size

Suspended solids in the effluent of greater than 3 µm particle size were removed by filtration in the filtered effluent treatment.

The raw effluent contained 3.53 g/L of suspended solids while the filtered effluent contained 3.30 g/L. While this was a noticeable difference, initial expectations were for a larger difference in TSS between the solutions. Hence, the overwhelming majority (93%) of TSS within raw effluent were less than 3 µm diameter.

Ultra filtration of solutions is an expensive proposition and given the time and budget constraints of this project more technologically advanced filtration devices were not accessible or practical. Recommendations for future work involving the filtration of effluent include using pipettes sealed with meniscus liners to ensure even minuscule particles are captured. This method was quickly explored but ultimately was decided against due to cost and time issues. Using sand and soil filters is another method often used in water treatment facilities; once again the time it would take to produce the required 100 Litres of solution while maintaining a reasonable budget wasn't practicable. However, it would be advantageous to understand the particle size proportions of effluent and their subsequent effects on pore blockage.

5.4 Total Suspended Solids Analysis

A total suspended analysis was also carried out on the leachate solution so a comparison between the discharge and percolating solution was possible. There is a difference ranging from 0.4–1.0 g/L TSS between the permeate and leachate depending on the treatment and soil. It is likely that some soil sediments are contributing to the TSS in the leachate due to the soil having undergone dispersion, which means the difference in permeate and leachate TSS is likely greater than the results demonstrate. In reducing the TSS content in the leachate the soil column has acted as a filtration device by removing sediments from the solution. It was observed that the colour of the leachate was significantly lighter (clearer) than the permeate, which further supports that the soil has filtered out solids. It is highly likely the solid matter has been trapped within the soil pores forming a physical barrier.

The results also showed the TSS in the leachate differed between each soil. The heavy clay was a more effective filter, presumably due to a finer texture and initial pore structure and the ESP of the soil. The clay loam on the other hand has a coarse texture and therefore a coarser initial pore structure, meaning that more suspended solids are required to block preferential flow paths. This soil was also initially non-sodic and thus had a higher initial conductivity than the heavy clay, again meaning that preferential flows paths were less likely to be blocked.

The TSS results also showed the concentrations of solids in the leachate compared to the permeate, measured over five separate time-steps throughout the period. There was no trend of either increasing or decrease TSS over the experiment run-time, except for the reduction in TSS between permeate and leachate. It was hypothesised that continued accumulation of suspended solids in the pore network would occur and that leachate TSS would continue reduce over time. It is possible that this effect may have been negated by continued dispersion and break-down of the soils structure due to the sodic nature of the solution; which infers soil sediments may have broken away from the bottom of the core and thus contributed to TSS content in the discharge. Even still, TSS analysis shows there is a significant decrease of TSS between the permeate and leachate which indicates solid matter is accumulating within the soil. This result provides confirmation to the observations noted by Bennett *et al.* (2011), who also saw a significant colour difference between the effluent leachate and permeate and assumed this was due to organic matter accumulation.

5.5 Contribution of Organic Particulate to a reduction in HC

To achieve the main project objective of discovering if organic particulate in feedlot effluent contributes to pore blockage in soils compacted to 98% MDD, the HC results of raw and filtered effluent were analysed. The raw effluent, containing the full amount of organic particulate, caused greater pore blockage than the filtered effluent, although these differences were not significant after 1300 h for the heavy clay. The TSS test showed that a portion of the solids are accumulating in the soil and the HC results further support this notion. The hypothesis that feedlot effluent inherent organic particulate contributes to a reduction in HC in compacted clay liners due to pore blockage, has been confirmed by both TSS and HC results. Furthermore, the synthetic effluent results clearly suggest that in the long term pore blockage occurs physically due to TSS rather than chemically due to solution chemistry. Hence, pore blockage is the major mechanism by which soil HC is lowered.

The final HC for both soils is lower when the raw effluent treatment was applied, significantly so in the clay loam. In the heavy clay, the difference in HC after 1300 hours of leaching with raw and filtered effluent is less at 8.97×10^{-11} m/s compared to the clay loam at 1.14×10^{-9} m/s. Analysing in terms of infiltration rate of mm/year the raw effluent of the heavy clay reached 29.6 mm/year while the filtered effluent reached 32.9 mm/year. In the clay loam the raw effluent reached 47.8 mm/year while the filtered samples reached 83.8 mm/year. However the HC curve still shows a noticeable difference between the two rates for both soils throughout the leaching time. The smaller variance is likely due to the fine sediments present in the filtered solution still accumulating in the tight pore network of the heavy clay. This would still have occurred in the clay loam but the mineralogy of the soil makes the results less noticeable over this time period of leaching. These assumptions are in line with Awedat *et al*. (2012) who found that even low amounts of suspended clay concentrations still contributed to pore blockage especially if the soil had a high bulk density.

The results achieved in this project support the findings by various past researchers who applied treated waste-water, similar properties to effluent, to agricultural soils. Vinten *et al.* (1983) found suspended solids contained in wastewater were blocking soil pores in the upper soil horizon and reducing infiltration characteristics. Viviani et al. (2004) and Abedi-Koupai *et al*. (2006) also saw a reduction in HC after applying sodic wastewater to soils, and contributed this to retention of organic matter and changes in pore size distribution from clay particle dispersion. Halliwell *et al.* (2001) found that continuous application of suspended solids to soil caused the formations of restrictive layers near the soil surface. It is likely that the majority of the suspended solids are trapped at, or near the surface of the core which results in surface sealing. This was observed when the cores when taken apart at the end of the leaching period. Cores where effluent had been applied had a thick coating of organic matter which formed a crust on the soil surface; there was no obvious change in appearance at the base of the core. It was observed in cores leached with synthetic effluent or $CaCl_2$ that there were no signs of surface sealing, thus it can be assumed this was caused by the organic particulate contained in the effluent. From these observations it's likely the organic matter has been trapped in the upper layer of the core; this hypothesis will be tested in the future using a total carbon analysing machine; due to operating difficulties and time constraints it was unable to be completed at this time.

The project has quantified the effect of organic matter build-up upon soil HC, which is a significant finding for the beef feedlot industry. The results show that physical pore blockage and, potentially, surface sealing due to organic matter accumulation significantly restricts the infiltration potential of soils. Further project work will involve the analysis of soil organic carbon content, which will enable the location of organic matter accumulation within the soil to be investigated.

5.6 Implications for Beef Feedlot Industry

The suggested infiltration rate guideline of $1.0x10^{\wedge -9}$ m/s or 31.5 mm/year was achieved in the 98% MDD compacted heavy clay after approximately 500 hours of raw effluent application as displayed. The filtered effluent treated heavy clay reached this level after 750 hours and remained close to this level for the remainder of the experiment. These results firstly show that the proposed guideline is possible to be met in heavily compacted clay liners. This is a positive result for the feedlot industry as the current alternative is construction of rubber lined ponds, which are very expensive. Secondly, the ability for the guideline to be achieved is also dependent upon the soil type; the clay loam, containing a higher infiltration potential, did not meet the guideline after 1300 h. However, the HC results curve show that the clay loam's HC was still decreasing after 1300 hours of leaching which suggests that this soil may still reach the stipulated guideline. Further testing on a wider range of soils with differing chemical and physical properties is recommended to obtain a wider understanding of the impacts feedlot-effluent TSS has upon soil HC. It should also be noted that feedlot effluent chemical and physical properties will differ between feedlots which means that feedlot effluent TSS sand chemical properties should be survey and investigated for their potential to reduce HC.

Importantly, the potential to save the Australian Feedlot Industry large sums of money and reduce environmental degradation has been identified.

Chapter 6 CONCLUSIONS

6.1 Conclusions of Results

This research project was conducted to investigate the effect of organic particulate contained in beef feedlot effluent upon soil hydraulic conductivity. The major project aim was to investigate if effluent inherent organic particulate is capable of reducing soil hydraulic conductivity to the proposed rate of 1.0X10^$^{-9}$ m/s or 31.5 mm/year. This infiltration rate guideline has been proposed by feedlot regulating authorities to restrict the contamination of surrounding land and the water table caused by seepage of effluent. It was shown that the raw effluent treatment produced the slowest HC in both soils when compared to filtered effluent that only contained suspended solids greater than 3 µm. It was concluded from these results that the organic particulate contained in feedlot effluent accumulates within the soils structure and contributes to pore blockage. The stated guideline was achieved in the heavy clay soil but not in the clay loam, and both soils treated with raw/filtered achieved HC 1–2 orders of magnitude lower than a synthetic solution with matched chemical properties to raw effluent with less PV of effluent required to realise this effect. From this result it can be concluded that the infiltration rate guideline of 1.0X10^$^{-9}$ m/s is achievable primarily due to the physical mechanism of pore blockage. It is recommended that further studies test the HC of a wider range of soil types with effluent and a wider range of effluent sources

Synthetic effluent, with identical chemical properties to feedlot effluent, was shown to be unsuitable as a substitute for raw/filtered effluent in terms of HC reduction potential. The heavy clay experienced a gradual reduction in HC which was expected given the sodic nature of the solution causing clay particle dispersion. The HC was still faster than the filtered effluent solution but this may be due to remnant suspended solids remaining after the filtration process. When the pore volumes were analysed it was found that several times the amount of synthetic effluent had infiltrated the soil compared to actual effluent within 50 h and that after 1300 h raw/filtered effluent still had not leached equivalent PV as compared to synthetic effluent. From this result it could be concluded that the major reason causing a reduction in soil HC was the organic matter accumulation. In the clay loam the HC increased when treated with synthetic effluent, this result highlights the importance of initial soil chemical properties. As the clay loam had a much lower ESP and EC values than the heavy clay the osmotic effect reduced the soil diffuse double layer when a solution with much higher EC was applied.

The final project objective was to analyse the effect of effluent inherent particulate particle size on soil pore blockage. A comprehensive total suspended solid analyse of both percolating and leachate solutions was conducted. It was found that the filtered permeate contained 0.25 g/L less TSS than the raw permeate. The majority of effluent contained particulate matter was identified as less than 3 µm. The filtered effluent caused less of a reduction in soil HC in both soils, and this was much more apparent in the clay loam. However, it is concluded that particulate matter less than 3 µm is primarily responsible for pore blockage. The mineralogy and bulk density of the soil is also a factor with the more porous clay loam trapping fewer amounts of the small suspended solids. The TSS analysis did show that the soil core acts as a filter by reducing the number of suspended solids in solution by between 0.4 and 1.0 g/L. This result provides proof that suspended solids are becoming entrained within the soil pores and causing a significant reduction in soil HC.

This project has successfully investigated the chemical and physical effects that feedlot effluent has upon the permeability of compacted clay soils. The guideline rate proposed by authorities has been achieved, or has been projected to be achieved based on HC trends, which likely negates the need for expensive plastic lined effluent ponds. It is recommended that the soils selected for pond construction contain properties similar to the heavy clay, fine textured soil used in this project. There is great potential for future work regarding sustainable feedlot operations such as effluent capture and control; in particular further testing on soil HC, for example organic carbon analysis, design of new filtration methods and testing soil TEC. The ability for the chemical and physical properties of effluent to seal compacted clay results in significant environmental benefits for Australian agriculture, in particular the beef cattle feedlot sector. As many feedlot corporations also manage a farming irrigation system, often to grow grain-feed for their cattle, ensuring the water table and soil conditions are kept healthy is of great importance. Sustainable farming operation and management is at the forefront of the Australian agricultural industry, this research project has provided insight into a specific area of environmental control, conveying beneficial results to the feedlot sector.

6.2 Future Work

As mentioned in the discussion section this report has provided the potential for compacted clay liners to be effectively used as effluent pond liners even with regards to the proposed infiltration rate. It is recommended that the effect of multiple feedlot effluents, with differing chemical and physical properties be tested upon the same two soils to identify the significance that slight changes in solution will have upon HC. Experimentation using a wider range of soil types will provide a more comprehensive picture of soil behaviour under effluent application. Finally it is also highly recommended that the zones of organic matter accumulation within the soil profile be identified. This will be achieved in the near future by testing layered samples for total organic carbon.

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Appendix A: Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

FOR: BRADLEY WARREN

TOPIC: Investigation mechanisms for effluent-pond sealing: the effect of suspended organic particulates and solution chemistry in feedlot-effluent on soil hydraulic conductivity.

SUPERVISORS: Dr John Bennett, Mr Rod Davis (FSA Consulting)

ENROLMENT: ENG 4111 – S1, 2012 ENG 4112 – S2, 2012

PROJECT AIM: This project seeks to investigate and determine the effect of organic particulates and effluent chemistry on the hydraulic conductivity of a soil leached with cattle-feedlot-effluent over an extended period of time.

SPONSORSHIP: Feedlot Services Australia Pty Ltd (as a Meat and Livestock Australia initiative)

PROGRAMME: Issue A, 21st March 2012

1. Research previous studies on the effect of organic matter contributing to soil pore sealing. Research the design of Feedlot Effluent ponds, specifically the type of clay used and the compaction level.
2. Design an experimental procedure that will enable the hydraulic conductivity of two soils to be measured using feedlot-effluent (filtered and non-filtered), synthetic effluent and $CaCl_2$ (each test will have five samples to ensure accurate results).
3. Set up experimental apparatus and leach solutions through compacted soils. Perform initial test such as temperature, colour and turbidity. Measure the falling hydraulic pressure head on a daily basis or as required over a three month period.
4. Use Darcy's falling pressure head equation to calculate the hydraulic conductivity of the soils. Graph the change in hydraulic conductivity over time.
5. Analyse the results and make conclusions on the change in hydraulic conductivity, colour and turbidity of the solutions.
6. Link results back to the potential of organic particulates to reduce the permeability of clay lined dams; specifically the implications of the results for effluent ponds and the feedlot industry.

AGREED:

BWarren (Student) ______, ______ (Supervisors)

20/3/12 20/03/12 20/3/12

DR. J. MCL. BENNETT FSA CONSULTING

Appendix B: Experimental Design and Planning

B.1 Initial Design

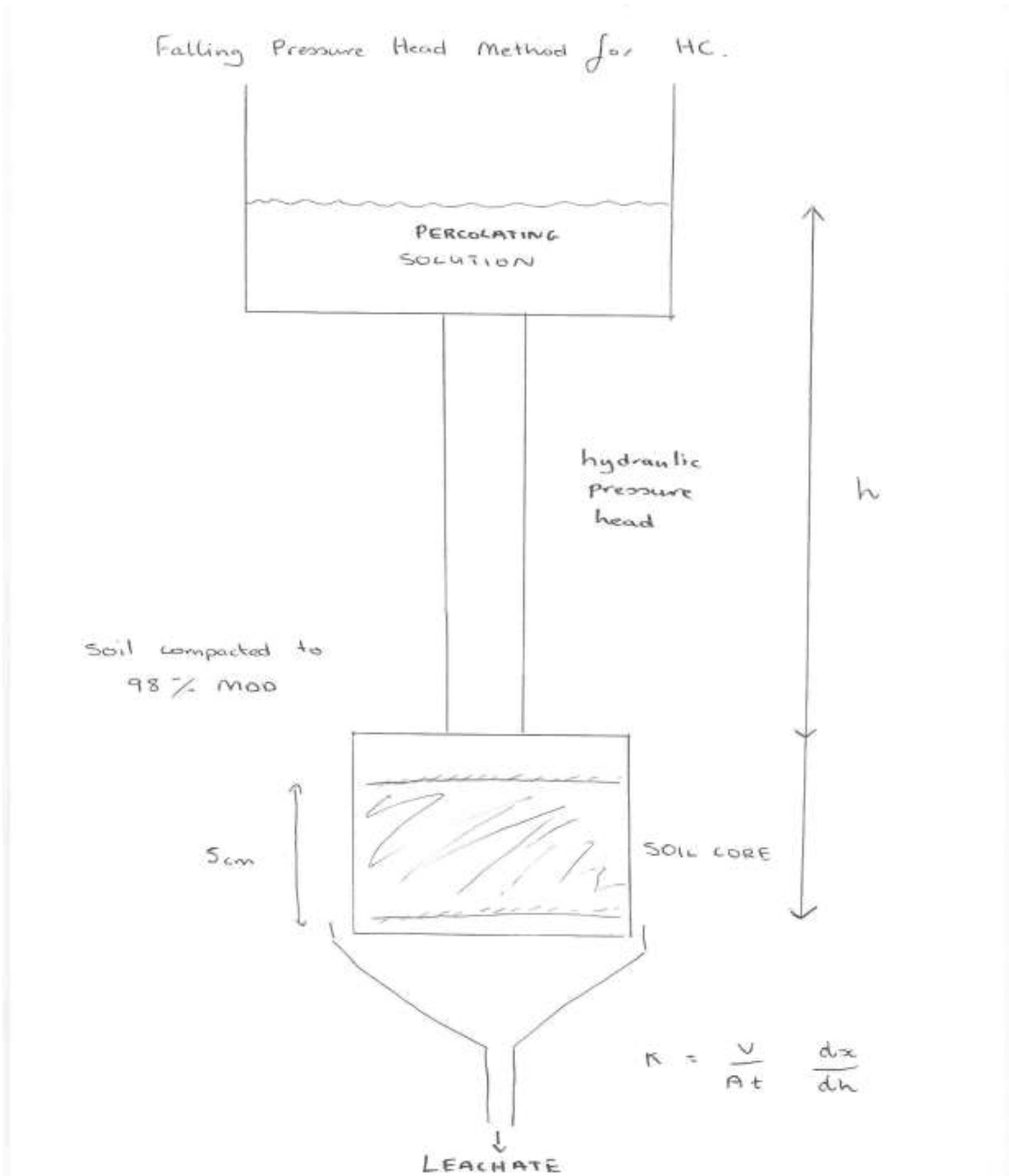

Figure B1: Preliminary Falling Pressure Head Design

B.2 Risk Assessment

Effluent

The first risk identified when specifying this research project was the involvement of raw cattle feedlot effluent. As the effluent is a core part of the experiment the researcher will be working in close proximity with this substance on a daily basis. The hazard proposed by the effluent is the chance of biological infection resulting from the handling of the product. As a waste product the effluent contains large amount of potentially dangerous bacteria which have the potential to cause serious illness when someone is heavily exposed. To reduce the chance of contracting any disease plastic gloves can be worn when handling the effluent. Other means of managing this risk include wearing a lab coat or face mask. This reduces the chance of coming in contact with the solution or inhaling any fumes produced from the effluent. Carefully handling the effluent during the filtration and measurement process as well as wearing the appropriate protective equipment will significantly reduce the chance of this particular hazard.

Chemical Exposure

Mixing the solutions requires measuring out portions of chemical powders which have various health dangers. It is recommended to avoid contact with skin or eyes when handling these chemical as a severe irritation can occur. To prevent this from occurring safety gloves and glasses can be worn. If any contact with the skin occurs then it should be washed off immediately to reduce the severity of any irritation. The relevant MSDS forms for handling chemicals were adhered while handling any chemicals to ensure correct procedures were followed and safety hazards were recognized.

Heat Gun

When assembling the pipe system the ends of the 19mm pipe had to be heated so they could be connected to the adapter. This required the use of a heat gun which introduces a health and safety risk. The heat gun is powered using an electrical cord which is plugged into a power output. Safe handling and connection of this power cable is required to ensure there is no danger of an electrical shock. The heat gun itself has the potential to cause severe burns if it comes in contact with bare skin. To negate the chance of this occurring, large oven gloves were worn when operating this tool.

Pipe Cutter

To cut the pipe into the required lengths a cutting blade was used. Due to the sharp edge of this tool a risk was introduced. The hazard caused by this risk is cutting a finger or hand while handling the pipe. To control this risk safety gloves were used to reduce the chance of an accident occurring. This control method does not negate the chance of the hazard as the blade could still cut through the glove. This meant that extreme care was also taken while using the blade.

Taking measurements

The final risk involved in this project is introduced when taking the daily pressure head height measurements. As the pallets with the drums on them are located approximately 2.5 meters above ground level a ladder is required. The ladder is bolted to ensure it is stable. When crouching on the pallets to take the measurements there is a danger of losing balance and falling. The pallets do provide solid support as they are rated to hold well over a ton. There is no real way to control this risk apart from taking extreme care when on the pallets, the measurements are vital to achieve the hydraulic conductivity results.

B.3 Resource Requirements

Due to the extensive nature of the experimental work required in this project there is a large demand for resources. Many of the required materials are already present in the laboratory, either left unused from previous experiments or just generally available. However many resources were still required from outside sources for example, Tradelink, Total Eden Water and Bunnings warehouse. Approximately one month of the experiment preparation was spent acquiring the costs and availability of the required materials. As some of the resources had to be specially ordered, such as the drums and filter paper, it had to be organized early so they would arrive on time.

There were direct cash payments involved from the researcher to cover small costs such as funnels and the geotextile fabric. After all the parts required were purchased the project budget reached $1150, refer to budget spreadsheet below. The budget is acceptable given the scale and size of the experimental set-up.

Item	Supplier	Quantity	Individual Cost	Total Cost
90mm socket couplings	Tradelink Plumbing	40		$92
19mm polypipe tap (2 pack)	Bunnings	20	$10.81	$216.20
10L clear plastic drums	Bunnings	40	$10.95	$438.00
IBC couplings	Total Eden Water	2	$44.25	$88.50
			Price	**Dimensions**
Geotextile	BMS Mitre 10		$3.65/m	12mm depth
Geofabric	CJR Industries		$1.14/m	600mm width
Geofabric	CJR Industries		$3.80/m	2000mm width
Geotextile matting	Tradelink Plumbing		$94/roll	1m x 50m
				Estimated Total
Other				$1,149.90
IBC connections	$70			
Clamps/Pipes	$70			
Funnels	$20			
Drum Taps	$60			
Filter Paper	$80			

The funding for the project was provided by the NCEA and FSA Consulting. FSA footed the cost for the 10L drums which was $440 in total. FSA are overseeing the project and will report the results to the Australian Meat and Livestock Industry as part of their contract. NCEA covered the cost for the other parts as most of the equipment would be useful for further research experiments conducted by this organization. The purchasing arrangements were agreed on by the NCEA and FSA consulting in the initial stages of the project. Since then all payments have been completed successfully.

If any of the parts failed to be obtained the make-up of the project experiment would need to be altered to make more use of parts already present in the lab. This would likely mean reusing soil couplings and drums, this would create extra work as cleaning these parts to the required standard would involve significant time and effort. The other solution if parts were not available would be to use another supplier. While possible in most cases the suppliers chosen for the materials offered the lowest prices and best value. Using other suppliers would increase the budget of the project which given the already high cost, is not acceptable.

B.4 Timeline

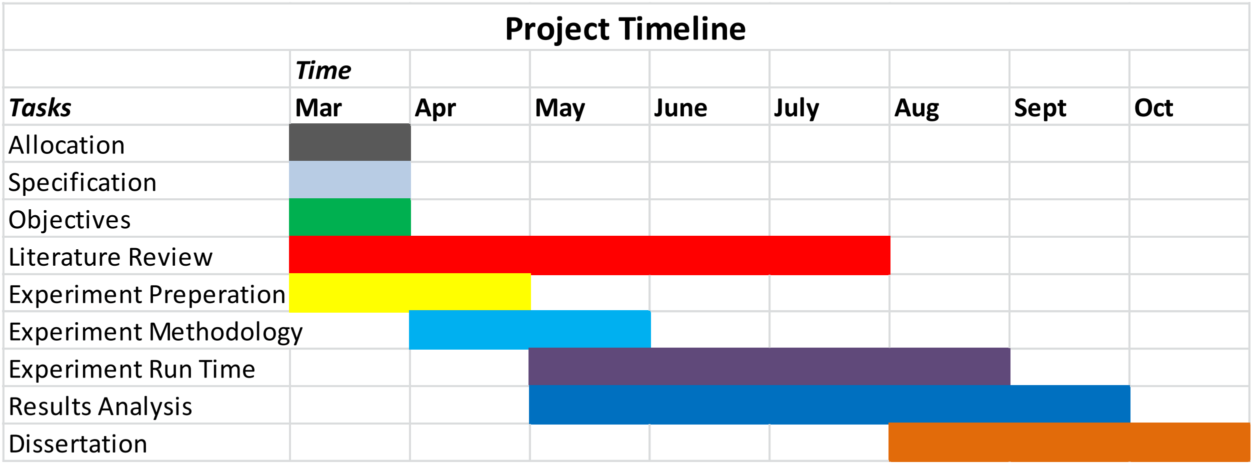

Figure B2: Timeline Graphical Chart

The chart above shows a simplistic view of the tasks involved with the project and the timeline for completion. Each task represents a milestone for the project, achieving each milestone by the set date is an important part of ensuring that the project runs smoothly. The most critical areas of the timeline are insuring the experiment preparation and methodology (design/ construction) are completed on time. This is vital as a major aim of the project is to test the hydraulic conductivity of the soils over a significant time period. This means that starting the experiment on time is essential. When the experiment is finished sufficient time has been allowed to analyse the results and produce the final dissertation.

Appendix C: Raw Data

C.1 Raw HC Data Sample

	Day 1 17/5								
Soil	On 24h	Off 24h	RT (min	Cum RT (	Start Height	End Height	Discharge	Adj Q (mL)	Cum Discharge
E15	1032	1525	293	293	289	276	548.16	530.217	530.217
D31	1032	1525	293	293	260	258	85.43	67.487	67.487
D21	1032	1525	293	293	291	285	298.62	280.677	280.677
D41	1032	1525	293	293	259	256	85.91	67.967	67.967
E31	1032	1525	293	293	240	234	235.4	217.457	217.457
D11	1032	1525	293	293	287	278	330.17	312.227	312.227
D24	1032	1525	293	293	290	282	316.07	298.127	298.127
D33	1032	1525	293	293	240	239	50.83	32.887	32.887
D42	1032	1525	293	293	254	251	98.6	80.657	80.657
D25	1032	1525	293	293	292	284	258.84	240.897	240.897
D43	1032	1525	293	293	239	237	52.43	34.487	34.487
E21	1032	1525	293	293	289	275	603.59	585.647	585.647
E11	1103	1525	262	262	285	273	401.32	383.377	383.377
E34	1032	1525	293	293	229	220	283.96	266.017	266.017
D45	1032	1525	293	293	286	285	54.65	36.707	36.707
E12	1032	1525	293	293	287	264	982.79	946.904	946.904
E24	1032	1525	293	293	278	237	1453.29	1399.461	1399.461
D34	1032	1525	293	293	253	251	76.72	58.777	58.777
D44	1032	1525	293	293	265	265	110.23	92.287	92.287
E23	1032	1525	293	293	287	273	708.47	672.584	672.584
D32	1032	1525	293	293	250	247	165.22	147.277	147.277
D22	1032	1525	293	293	287	285	91.56	73.617	73.617
D13	1032	1525	293	293	285	278	339.96	322.017	322.017
E41	1032	1525	293	293	274	265	430.07	412.127	412.127
D35	1032	1525	293	293	227	225	120.4	102.457	102.457
E44	1032	1525	293	293	264	260	429.22	411.277	411.277
D23	1032	1525	293	293	295	286	290	272.057	272.057
D12	1032	1525	293	293	285	279	313.1	295.157	295.157
E42	1032	1525	293	293	250	237	317.38	299.437	299.437
E22	1032	1525	293	293	247	234	641.97	624.027	624.027
E13	1032	1525	293	293	295	288	226.82	208.877	208.877
D15	1032	1525	293	293	242	239	204.18	186.237	186.237
E35	1032	1525	293	293	231	218	496.9	478.957	478.957
E43	1032	1525	293	293	275	257	434.97	417.027	417.027
E25	1032	1525	293	293	272	253	604.83	586.887	586.887
D14	1032	1525	293	293	290	272	715.8	679.914	679.914
E14	1032	1525	293	293	285	258	979.02	943.134	943.134
E33	1032	1525	293	293	248	237	421.85	403.907	403.907
E45	1032	1525	293	293	261	246	530.15	512.207	512.207
E32	1032	1525	293	293	290	281	413.4	395.457	395.457

Figure C1: Day 1 Raw Data

	Day 9 31/5								
Soil	On 24h	Off 24h	RT (min)	Cum RT (n	Start Heig	End Heigh	Discharge	Adj Q (mL	Cum Disch
E15	930	1530	360	3019	143	121	733.78	697.894	5414.368
D31	930	1530	360	3019	212	212	31.87	13.927	222.203
D21	930	1530	360	3019	252	246	149.51	131.567	1564.803
D41	930	1530	360	3019	252	250	29.98	12.037	199.083
E31	930	1530	360	3019	196	193	90.41	72.467	1346.853
D11	930	1530	360	3019	214	198	508.89	490.947	2967.993
D24	930	1530	360	3019	230	225	303.57	285.627	2335.933
D33	930	1530	360	3019	231	231	27	9.057	117.603
D42	930	1530	360	3019	245	244	30.27	12.327	225.513
D25	930	1530	360	3019	259	252	110.75	92.807	1214.893
D43	930	1530	360	3019	231	231	27.35	9.407	117.913
E21	930	1214	164	2823	82	62	646.03	628.087	7478.782
E11	930	1530	360	2988	164	147	519.3	501.357	4078.78
E34	930	1530	360	3019	183	181	69.54	51.597	1055.003
D45	930	1530	360	3019	278	278	30.82	12.877	198.103
E12	930	1207	157	2816	101	76	979.95	944.064	10577.9
E24	930	1207	157	2816	94	58	1333.03	1297.144	14051.35
D34	930	1530	360	3019	233	230	34.67	16.727	252.343
D44	930	1530	360	3019	255	254	36.2	18.257	291.053
E23	930	1207	157	2816	95	80	637.33	619.387	6896.282
D32	930	1530	360	3019	236	234	40.28	22.337	422.193
D22	930	1530	360	3019	274	271	70.26	52.317	492.813
D13	930	1530	360	3019	157	132	951.85	915.964	5172.784
E41	930	1530	360	3019	239	237	72.35	54.407	1272.993
D35	930	1530	360	3019	216	214	40.22	22.277	351.683
E44	930	1530	360	3019	237	236	67.15	49.207	1195.503
D23	930	1530	360	3019	249	243	208.92	190.977	1704.963
D12	930	1530	360	3019	198	174	740.41	704.524	3735.187
E42	930	1530	360	3019	216	209	61.79	43.847	1030.283
E22	930	1530	360	3019	138	92	1593.68	1539.851	8532.429
E13	930	1530	360	3019	238	232	217.5	199.557	1977.293
D15	930	1530	360	3019	187	176	363.21	345.267	2048.153
E35	930	1530	360	3019	183	180	83.9	65.957	1511.093
E43	930	1530	360	3019	204	195	57.67	39.727	1057.373
E25	930	1530	360	3019	109	88	685.57	649.684	5296.438
D14	930	1207	157	2816	105	90	521.86	503.917	6499.535
E14	930	1207	157	2816	86	62	926.69	890.804	9877.366
E33	930	1530	360	3019	204	201	73.32	55.377	1346.253
E45	930	1530	360	3019	219	218	67.81	49.867	1340.423
E32	930	1530	360	3019	253	252	70.15	52.207	1298.923

Figure C2: Day 9 Raw Data

C.2 Hydraulic Conductivity Averages

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
E1	1.76E-07	1.72E-07	2.1E-07	2.13E-07	2.3E-07	2.02E-07	2.57E-07	3.03E-07	3.04E-07	1.69E-07
E2	1.59E-07	2.07E-07	2.1E-07	2.3E-07	2.26E-07	2.71E-07	2.98E-07	3.4E-07	3.53E-07	
E3	1.04E-07	9.63E-08	4.62E-08	7.54E-08	2.35E-08	2.76E-08	3.56E-08	2.63E-08	2.17E-08	1.81E-08
E4	1.04E-07	7.91E-08	4.39E-08	7.05E-08	6.16E-09	5.73E-08	8.19E-09	2.55E-08	3.58E-08	3.64E-08
D1	9.07E-08	1.01E-07	7.94E-08	1.19E-07	1.17E-07	1.32E-07	1.91E-07	1.93E-07	2.06E-07	2.22E-07
D2	6.92E-08	6.65E-08	4.95E-08	3.48E-08	3.32E-08	4.01E-08	4.47E-08	1.96E-08	4.72E-08	4.77E-08
D3	2.15E-08	8.76E-08	2.46E-08	3.99E-08	1.28E-08	5.41E-09	4.12E-09	6.24E-09	1.24E-08	0
D4	2.14E-08	1.45E-08	8.05E-09	1.36E-08	4.14E-09	1.07E-08	6.08E-09	6.13E-09	6.99E-09	3.91E-09
CT (efflue	293	683	1072	1430	1730	1965	2275	2659	3019	3340

	Day 11	Day 12-13	Day 14-17	Day 18-23	Day 24-31	Day 32-37	Day 38-44	Day 45-51	Day 52-58	Day 59-65
E1	1.95E-07	1.37E-07	1.43E-07	1.35E-07	1.86E-07	2.06E-07	2.23E-07			
E2										
E3	1.72E-08	1.46E-08	9.51E-09	6.56E-09	4.86E-09	4.68E-09	3.3E-09	3.53E-09	3.18E-09	2.66E-09
E4	4.35E-08	1.17E-08	8.95E-09	4.77E-09	3.04E-09	2.8E-09	1.77E-09	2.33E-09	2.05E-09	1.52E-09
D1	1.88E-07	2.15E-07	2.03E-07	1.34E-07	1.12E-07	1.28E-07				
D2	5.59E-08	6.36E-08	8.33E-08	8.17E-08	7.48E-08	9.06E-08	9.73E-08	7.96E-08		
D3	4.28E-09	5.97E-09	2.49E-09	2.47E-09	1.85E-09	1.49E-09	7.69E-10	1.26E-09	1.13E-09	1.03E-09
D4	3.68E-09	3.98E-09	2.45E-09	1.76E-09	1.18E-09	8.47E-10	6.93E-10	6.19E-10	7.15E-10	9.39E-10
CT (efflue	3683	5344	9977	18585	30468	38744	48879	59190	68944	79205

Figure C3: Average Hydraulic Conductivity Data

Table C1: Raw Final HC Data

Sample	Final HC (m/s)	Sample	Final HC (m/s)
D11	8.905E-08	D31	9.702E-10
D12	1.756E-07	D41	3.133E-10
D13	2.305E-07	D33	6.334E-10
D14	2.842E-07	D42	6.289E-10
D15	1.562E-07	D43	3.172E-10
D21	3.735E-08	D45	3.066E-10
D22	1.723E-08	D34	1.278E-09
D23	8.319E-08	D44	3.128E-09
D24	7.061E-08	D32	6.380E-10
D25	3.184E-08	D35	1.623E-09

E11	2.191E-07	E31	1.713E-09
E12	4.525E-07	E34	3.462E-09
E13	2.243E-07	E41	1.641E-09
E14	5.503E-07	E44	1.299E-09
E15	4.525E-07	E42	1.996E-09
E21	3.859E-07	E35	2.784E-09
E22	5.218E-07	E43	1.657E-09
E23	4.515E-07	E33	2.387E-09
E25	3.192E-07	E45	9.880E-10
		E32	2.940E-09

C.3 Discharge Volume

Table C2: Discharge Volume Raw Data

Day 9 Discharge Volume (mL)					
D2	D3	D4	E2	E3	E4
1564.803	222.203	199.083	7478.782	1346.853	1272.993
2335.933	117.603	225.513	14051.35	1055.003	1195.503
1214.893	252.343	117.913	6896.282	1511.093	1030.283
492.813	422.193	198.103	8532.429	1346.253	1057.373
1704.963	351.683	291.053	5296.438	1298.923	1340.423
1462.681	273.205	206.333	8451.055	1311.625	1179.315

Day 65 Discharge Volume (mL)			
D3	D4	E3	E4
1104.053	851.233	3888.257	3633.66
646.233	1014.333	3714.94	3118.683
1444.4	669.943	4738.167	2952.523
1383.133	822.153	4179.527	2726.523
1347.913	1100.703	3742.62	3252.713
1185.146	891.673	4052.702	3136.82

C.4 Total Suspended Solids

Table C3: Total Suspended Solids Raw Data

	Leachate TSS (g/L)				
Hours	5	24	61	166	310
E31	3.504	2.516	2.136	2.6	2.744
E32	2.66	2.732	2.152	2.508	2.812
E33	2.584	2.676	2.188	2.524	2.764
E41	3.632	2.616	2.684	2.472	2.8
E42	2.276	3.024	2.68	2.804	2.812
E43			2.632	2.752	2.784
D31	3.228	2.088	2.188	2.036	2.236
D32	2.688	2.12		2.068	2.228
D33				2.08	2.264
D41	2.792	2.644	2.196	2.272	2.584
D42	2.884	2.756		2.228	2.548
D43				2.176	2.456

Permeate TSS	
Sample	TSS (g/L
3A	3.584
3B	2.78
3C	3.548
4A	3.608
4B	3.536
4C	3.452

Appendix D: Statistical Error Minitab Output

This appendix has been included to provide a sample of the Minitab Statistical Analysis Output from which the HSD error was calculated.

HC Comparison for final raw and filtered effluent data (Heavy Clay)

One-way ANOVA: C2 versus C1

```
Source  DF         SS         MS     F      P
C1       1  0.0000003  0.0000003  0.02  0.881
Error    8  0.0000881  0.0000110
Total    9  0.0000883

S = 0.003318   R-Sq = 0.30%   R-Sq(adj) = 0.00%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level  N      Mean     StDev    +---------+---------+---------+---------
1      5  0.003703  0.001536     (-----------------*----------------)
2      5  0.003380  0.004434    (----------------*----------------)
                                +---------+---------+---------+---------
                              0.0000    0.0020    0.0040    0.0060

Pooled StDev = 0.003318


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of C1

Individual confidence level = 95.00%


C1 = 1 subtracted from:

C1       Lower     Center     Upper  -------+---------+---------+---------+--
2   -0.005162  -0.000323  0.004516  (---------------*---------------)
                                     -------+---------+---------+---------+--
                                         -0.0030    0.0000    0.0030    0.0060
```

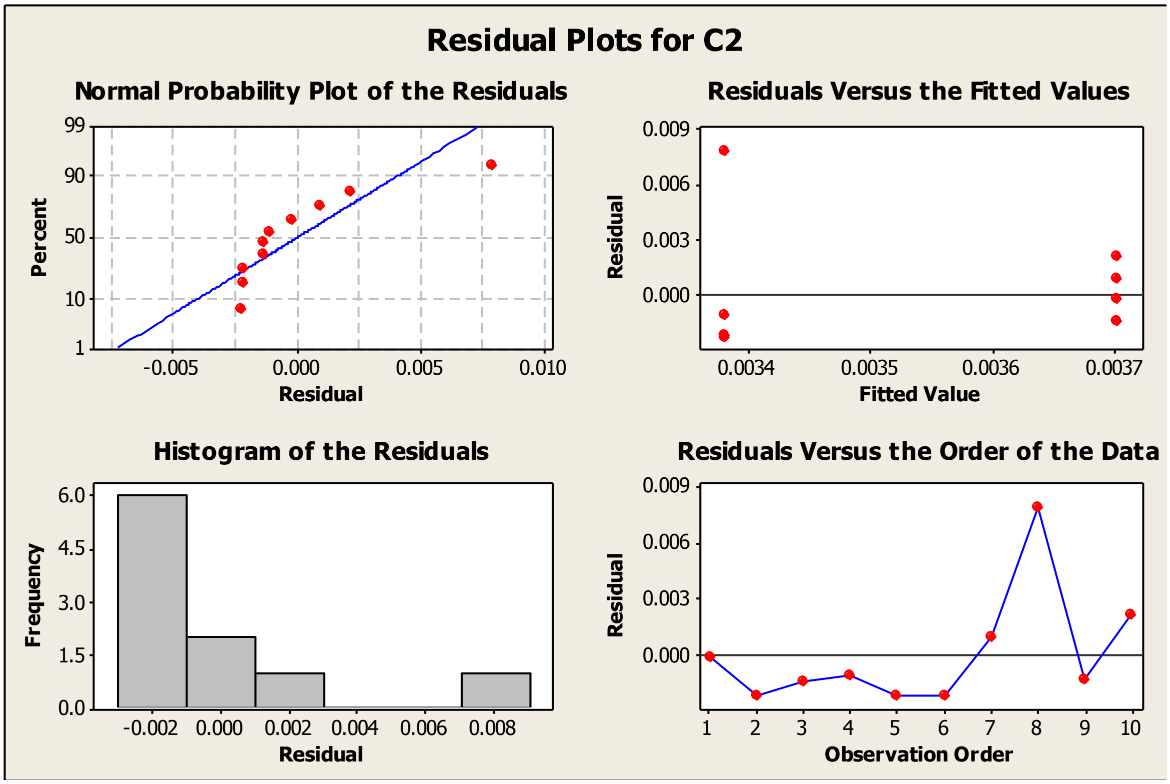

Figure D1: HC Stats Analysis Example Plots

TSS Comparison for Leachate Filtered v Permeate Filtered Effluent (Clay Loam)

One-way ANOVA: C2 versus C1

```
Source  DF     SS     MS     F      P
C1       1  0.422  0.422  4.07  0.114
Error    4  0.415  0.104
Total    5  0.837

S = 0.3221   R-Sq = 50.45%   R-Sq(adj) = 38.06%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
1      3  2.7733  0.0349  (------------*------------)
2      3  3.3040  0.4542                (------------*------------)
                          ----+---------+---------+---------+-----
                            2.40      2.80      3.20      3.60

Pooled StDev = 0.3221


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of C1

Individual confidence level = 95.00%
```

```
C1 = 1 subtracted from:

C1     Lower  Center   Upper  -----+---------+---------+---------+----
2    -0.1995  0.5307  1.2608            (--------------*-------------)
                              -----+---------+---------+---------+----
                                 -0.50      0.00      0.50      1.00
```

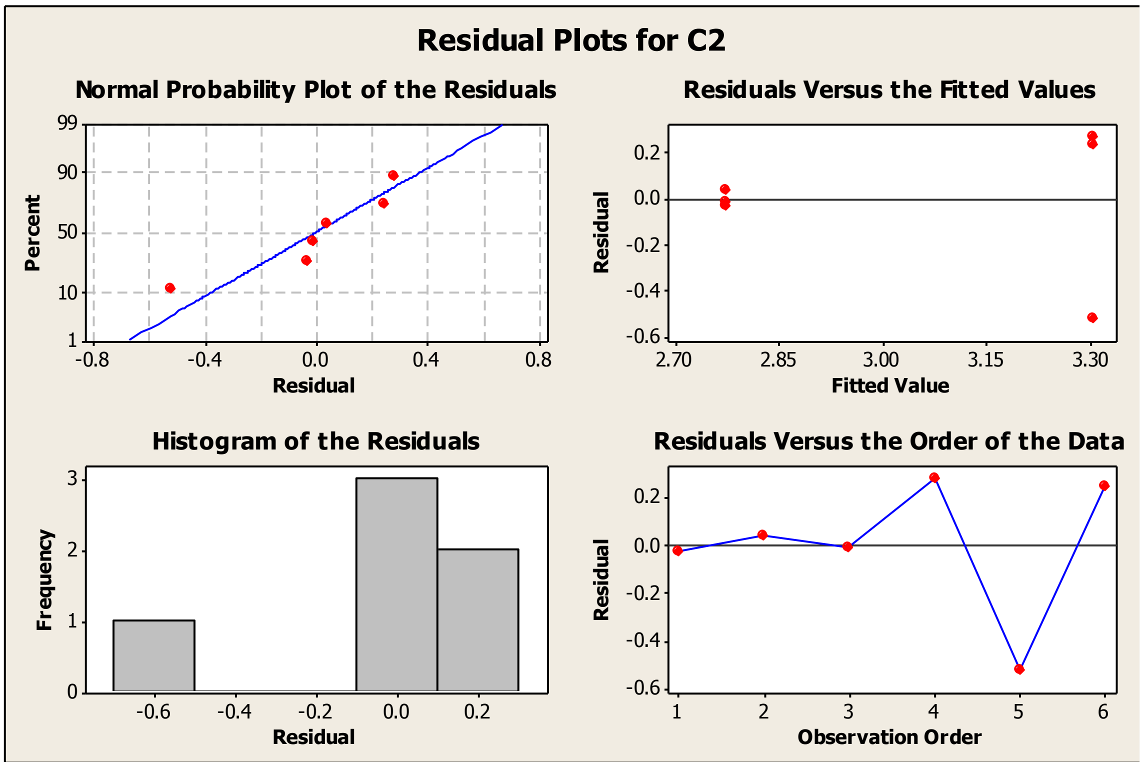

Figure D2: TSS Stats Example Plots