Accelerated gravity testing of aquitard core permeability and implications at formation and regional scale

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Abstract Evaluating the possibility of leakage through low permeability geological strata is critically important for sustainable water supplies, the extraction of fuels from coal and other strata, and the confinement of waste within the earth. The current work demonstrates that relatively rapid and realistic vertical hydraulic conductivity (K_v) measurement of aquitard cores using accelerated gravity can constrain and compliment larger scale assessments of hydraulic connectivity. Steady state fluid velocity through a low *K* porous sample is linearly related to accelerated gravity (*g*-level) in a centrifuge permeameter (CP) unless consolidation or geochemical reactions occur. A CP module was custom designed to fit a standard 2 m diameter geotechnical centrifuge (550*g* maximum) with a capacity for sample dimensions up to 100 mm diameter and 200 mm length, and a total stress of ~2 MPa at the base of the core. Formation fluids were used as influent to limit any shrink-swell phenomena which may alter the permeability. K_v results from CP testing of minimally disturbed cores from three sites within a clayey silt formation varied from 10^{-10} to 10^{-7} ms^{-1} (number of samples, n = 18). Additional tests were focused on the Cattle Lane (CL) site, where K_v within the 99% confidence interval (n =9) was 1.1×10^{-9} to 2.0×10^{-9} ms^{-1}. These $K_v$results were very similar to an independent in situ K_v method based on pore pressure propagation though the sequence. However there was less certainty at two other core sites due to limited and variable K_v data. Blind standard 1*g* column tests underestimated K_v compared to CP and in situ K_v data, possibly due to deionized water interactions with clay, and were more time consuming than CP tests. Our K_v results were compared with the setup of a flow model for the region, and considered in the context of heterogeneity and preferential flow paths at site and formation scale. Reasonable assessments of leakage and solute transport through aquitards over multi-decadal timescales can be achieved by accelerated core testing together with complimentary hydrogeological monitoring, analysis and modelling.

1. Introduction

Clay or other low permeability sediment and rock often dominate sedimentary sequences and can form important aquitards (Potter et al., 1980). These hydraulic barriers often overlie aquifers that yield strategically important fresh water resources and form important cap-rocks or seals between shallow aquifers and deeper strata targeted for depressurization during gas or mineral extraction (Timms et al., 2012). The current work compares the results of steady state centrifuge permeability testing of semi-consolidated drill core samples with column tests at standard gravity (1*g* at earth's surface, 9.8065 m s^{-2}). Results of laboratory tests were also compared with in situ permeability, based on analysis of pore pressure propagation at formation scale.

Thick, low hydraulic conductivity (*K*), un-oxidized, clay-rich aquitards represent important sites for waste confinement and disposal (including high-level radioactive waste and the sequestration of carbon dioxide and saline effluents) and act as protective covers for regional aquifers (Cherry et al., 2004). Effective shale and claystone flow barriers are required to disconnect shallow aquifer systems from underlying coal seams that are depressurized to produce gas (Timms et al., 2012; APLNG, 2013). Fine-grained geologic media are also commonly used as engineered barriers to limit horizontal seepage of mine water (Bouzalakos et al., 2014), for containment of tailings (Znidarčić et al., 2011), and disposal of municipal refuse and nuclear waste (Rowe et al., 1995). Low permeability material is defined by *K* of $<10^{-8}$ ms^{-1} (Neuzil, 1986). The US EPA requires low permeability waste barriers for hazardous waste landfills with *K* of $<10^{-9}$ m/s (US EPA, 1989).

Aquitards volumetrically constitute the bulk of sedimentary geologic deposits (Potter et al., 1980), and are typically assumed saturated if located below a watertable (Cherry et al., 2004). Water-saturated *K* and diffusion coefficients for aquitards are therefore not applicable to variably saturated or non-water saturated low permeability strata. Research is lacking for semi-consolidated clayey aquitards (eg. alluvial, colluvial and aeolian deposits), compared with aquitard research on glacial tills (Grisak and Cherry, 1975), claystones (Smith et al., 2013; Jougnot et al., 2010) and shale (Neuzil, 1994; Josh et al., 2012). Clay-bearing sediments formed via alluvial, colluvial and aeolian processes frequently occur in the geosphere. For example clayey silt aquitards account for 60% of the ~100 m thick alluvial sediment sequences in the Mooki catchment of Australia's Murray-Darling Basin (Farley, 2011). The relative lack of information on the dominant type of sedimentary deposit represents a key gap in the current theoretical understanding of clay mineralogy and geochemistry.

Aquitard research on alluvial sediments is important because recharge by slow seepage provides essential groundwater supplies for municipal water supply and crop irrigation in relatively dry inland settings (Acworth and Timms, 2009). Increased effective stress associated with aquifer drawdown for irrigation, may release saline water stored within shallow aquitards with implications for the continuation of high yields of fresh water. Characterising the effects of variable chemical composition of formation water on the hydraulic conductivity of such sediments is therefore essential to determine the long-term changes to fresh water.

As an example, revised calculation of hydraulic parameters based on water level recovery from a bore pump test in glacial till ($K = 10^{-11}$ ms^{-1}) has been required to improve the fit with the data emerging over a ~30 years (van der Kamp, 2011). Various field and laboratory methods are available to directly measure or indirectly calculate hydraulic conductivity along the horizontal (K_h) or vertical (K_v), and saturated and unsaturated or multi-phase flow (eg. liquid and gas). Obtaining realistic measurements of groundwater flow and solute transport within aquitards is by definition a slow process, requiring relatively time consuming and expensive field and/or laboratory studies.

Methods for measuring the in situ permeability of clay formations include: slug tests (piezometer tests, falling-head tests), aquifer pumping tests with piezometers in the aquitard, aquifer pumping tests with observation wells in the aquifer only, measurement of seasonal fluctuations of pore-pressure, measurement of pore-pressure changes and settlement due to surface loading, and numerical analysis of local and regional groundwater flow (van der Kamp, 2001). Neuman and Witherspoon (1968) developed generic analytical solutions for drawdown within an aquiclude, in which vertical flow occurs, but is sufficiently small to have no effect on water levels within an overlying or underlying aquifer. Type curves were presented for analytical solutions applying to an infinitely thick and a finite thickness aquiclude. In contrast, analysis of a leaky aquitard-aquifer system was presented by Neuman and Witherspoon (1972). The ratio method compares drawdown within an aquitard with drawdown in an underlying aquifer from which extraction was occurring. Drawdown data is then used to calculate hydraulic diffusion of pressure transients, and K_v, assuming a uniform, homogeneous aquitard.

Deconvolution of the pressure response to depth through an aquitard can be analysed with a Fourier transform or harmonic analysis (Boldt-Leppin and Hendry, 2003). The hydraulic diffusivity (hydraulic conductivity divided by specific storage) is expressed analytically, either based on the amplitude or phase shift of harmonic signals, assuming that the thickness of the aquitard is semi-infinite. Jiang et al. (2013) further developed the harmonic analysis method for finite aquitards in a multi-layer system in the instance of water level monitoring within aquifers above and below an aquitard, but not monitoring within the aquitard.. Coherence analysis of water level fluctuations in bounding aquifers from indeterminate stresses (eg. pumping, recharge, rainfall or earthquake) was used to derive K_v for deep rock aquitards on the basis of interpolated groundwater level data measured at irregular intervals of at least 10 days over a duration of several decades.

A more direct method of determining in situ hydraulic parameters is possible using fully grouted vibrating wire transducers and high frequency data recording within deep formations, as recently demonstrated by Smith et al. (2013) for a bedrock claystone at up to 325 m below ground (BG). Pore pressure and barometric pressure were recorded at 30 minute intervals and analysed, assuming no leakage in the grouted system, for barometric response, earth tides, and rainfall events. Core samples from the same drill holes were vacuum sealed on site for consolidation testing and triaxial permeameter testing. The in situ compressibility and specific storage calculated from barometric pressure responses were as much as an order of magnitude smaller than laboratory results.

A variety of laboratory testing techniques for low K samples are also available, however the reliability of results may depend on factors such as the preparation and size of core samples, configuration of equipment and uncertainties of measurement, the influent water that is used and the stresses that are applied relative to in situ values, and whether permeability is directly measured from steady state flow, or subject to additional parameters and assumptions with alternative flow regimes. Laboratory testing of clayey-silt cores by standard rigid and flexible wall column techniques requires 1-2 weeks, compared with <1 week for centrifuge permeameter (CP) methods in unsaturated samples (ASTM, 2010). Constant or falling-head tests in rigid-walled column permeameters at natural gravity require a large water pressure gradient and/or long testing times for low-permeability samples. They are subject to potential leakage, and may not replicate in situ confining stresses. Column testing of core samples is possible for some test conditions in triaxial cells on both K_h and K_v, for example those used in geotechnical and petroleum studies (Wright et al., 2002). However standard practice for testing ultralow permeability cores (e.g. K_v <1×10^{-10} ms^{-1}) typically consists of applying a confining pressure to a watertight system and measuring small transient pore pressures with high resolution pressure transducers (API, 1998).

Geotechnical centrifuges are used to subject porous samples to high artificial gravities in order to characterise their hydraulic and/or consolidation properties (Conca and Wright, 1998; Nakajima and Stadler, 2006; Znidarčić et al., 2011), and for physical modelling as part of geotechnical design (Garnier et al. 2007; Parks et al. 2012). Accelerated gravity acts on both the solid particles and fluids within the porous sample without use of a large fluid pressure gradient to drive flow. The technique can be applied to investigate slow hydrogeological processes over shorter timescales, i.e. flow through low permeability layers that would take several years under in situ conditions can be reproduced in a geotechnical centrifuge within hours or days, depending on test conditions.

A CP, or a column mounted on a centrifuge strong box, is commonly used for hydraulic characterisation of porous media. Accelerated gravity achieves a steady state equilibrium for fluid flow through the CP within hours or days of instrument operation (for an unsaturated sample), while simultaneously applying stresses to the solid matrix. A permeameter column, mounted on a geotechnical centrifuge is rotated sufficiently fast to accelerate flow and approximate in situ total stresses, while the target *g*-level is designed to ensure that the matrix is not consolidated and chemical equilibrium is maintained. Steady state flow can provide more reasonable K results than transient flow techniques. Although transient tests are even more rapid than steady state tests in the centrifuge, more complex instrumentation is required to ensure reliable results (Zornberg and McCartney, 2010).

The geotechnical centrifuge system described in this paper is moderately sized and relatively economical to operate, whilst able to perform both unsaturated and saturated testing of porous media with real-time measurement of various parameters during flight (Table 1). These attributes mean that CP testing of relatively large diameter cores (up to 100 mm diameter) in this facility is comparable in cost to testing of small cores (38 mm diameter) using alternative methods such as He-gas permeation. The system has been successfully used for testing low permeability rock cores (Bouzalakos et al., 2013). To date, there were no other direct K_v measurements on these deep shales available (APLNG, 2013) and alternative laboratory methods were not successful in obtaining a K_v value from these very low K rocks (Bouzalakos et al., 2013).

This paper demonstrates novel CP techniques and equipment that have been specifically developed for characterizing semi-consolidated clayey silt cores. K_v results from CP methods are compared with standard 1g column methods and in situ measurements of permeability, based on harmonic analysis of the high frequency pore pressure propagation through a thick clayey sequence. The variability, confidence limits and overall reliability of the K_v results to constrain assessments of regional scale vertical connectivity are considered in the context of sampling and flow and stress conditions within the CP. This paper provides reasonable K_v for at least one local clayey-silt sequence and strategies for future testing that are important contributions towards evaluating flow connectivity at a range of scales. These K_v results can be complimented with hydrogeological data such as pore pressure and tracer data to better constrain numerical flow models.

2 Geology of study sites

Semi-consolidated sediment cores were obtained from three sites in the Australia Murray-Darling Basin, in the Upper Mooki subcatchment of the Namoi catchment (Fig. 1). Groundwater is extracted in this area for irrigation and town water supplies, with drawdowns of more than 10 m over 30 years. It can take years or decades for changing pore pressures to be transmitted through these mixed sediments that are heterogeneous, even though the effects of groundwater extraction were assumed to occur rapidly within homogeneous, high permeability sediments (Kelly et al., 2013). The alluvial sedimentary geology of the valley features significant heterogeneity but a general fining upwards which reflects climatic drivers of sedimentation (Kelly et al., 2014). This study found that the architectural features and the net (sand and gravel) to gross (total volume) line plot that identifies low permeability clays and silts of the valley-filling sequence are best represented by a distributive fluvial system. In this type of fluvial system, the avulsion frequency increases at a slower rate than the aggradation rate.

Core drilling was completed at three research sites (Fig. 1) including Cattle Lane (CL), located south of the town of Caroona (31° 31'9"S, 150° 28'7"E), the Breeza farm (BF) operated by the NSW Department of Primary Industries, southeast of Gunnedah (31° 10'32"S, 150° 25'15"E), and Norman's Road (NR), east-southeast of Gunnedah (31° 2'48"S, 150° 26'7"E).

Clayey silt sediments at the Cattle Lane site are approximately 30 m thick (Timms and Acworth, 2005) and extend throughout the valley (Wiesner and Acworth, 1999), as shown by numerous CCPT (conductivity cone penetrometer) profiles. The porewater salinity profile at the site, increasing from 10-30 m depth through the clay is consistent with a diffusion dominated transport over thousands of years (Timms and Acworth, 2006). The saturated zone fluctuates in response to rainfall events from between ground surface to approximately 2 m depth, while water levels in the confined gravel aquifer at >50 m depth display a delayed and dampened response to the same rainfall events. There is no groundwater extraction for irrigation from this aquifer in the vicinity of the site, and the valley has been artificially drained to prevent ponding of surface water and soil salinization. Detailed geological studies and particle dating have identified that the clayey silt in the top ~30 m at this site accumulated gradually at 0.2 – 0.3 mm/year by weathering of alkali basalts (Acworth et al., 2015). Flow testing of 100 mm diameter cores from the CL site, reported by Crane et al. (2015) has revealed evidence for dual porosity flow when a hydraulic gradient is imposed on the low permeability sediments, with further work in progress to identify the nature and significance of these potential flow paths.

Sediments at the Breeza farm and Norman's Road site are relatively heterogeneous, with mixed sandy, clayey sand, and clayey-silt alluvium overlying a semi-confined aquifer. The saturated zone is approximately 18 to 20 m below surface and extraction for flood irrigation of crops causes large fluctuations in groundwater levels in the confined aquifers at >50 m depth. Hydrogeological and hydro-geochemical evidence indicate a leaky aquifer-aquitard system, with the variability in groundwater level responses controlled by a fining upward alluvial sequence (Acworth and Timms, 2009). At the Norman's Road site, highly saline porewater (15 mS cm^{-1}) in the clayey silt in proximity to the surface (<20 m) appears to have leached into the underlying aquifer, causing a significant increase in salinity of the aquifer (Badenhop and Timms, 2012).

3 Study site characterisation and sampling

3.1 Drilling and core sampling

Equipment and procedures for coring were compliant with ASTM D1587-08, 2008 to obtain samples which were as undisturbed as possible. A rotary drilling rig equipped with Triefus triple core barrels, lined with seamless clear PET, was used in push coring mode. Local creek water was used as a drilling fluid and casing was used to stabilise the hole behind the push core barrel such that drilling fluid additives were not required. The holes were therefore fully cased to the maximum depth of push core drilling at up to 40 m BG.

The non-rotating core barrel was forced into the formation whilst a rotating device on the outside of the tube removes the cuttings as the barrel was advanced. The cutting edge of the non-rotating sample tube projects several millimetres beyond the rotary cutters. The thin walled core barrel complied with the standard for undisturbed sampling, with an area ratio of less than 25% for an open drive sampler. The area ratio of 16% was based on a core barrel design with an external diameter of 110 mm and internal diameter of 101 mm (C size). The 1.5 m length core barrel was a composite open sampling system with a core nose screwed on the base with a bevelled end to cut the core as the barrel pushed into the formation. After the core was extracted from the ground, an air supply was connected to the top of the core barrel to slide the core out of the barrel whilst it remained in the clear PET liner without rotation, distortion or compression.

The cores contained within PET liners were transferred directly from the core barrels to a cool room on site, and thence to a laboratory cool room, reducing the potential for moisture loss. Semi-consolidated clay cores were selected from below the saturated zone for CP tests, at depths up to 40 m BG. Sediment core samples of lengths between 50-100 mm were prepared for CP testing. The moisture content and bulk density of cores was measured using methods adapted from ASTM D7263-09 (2009). These measurements were completed immediately on the drill site.

The preferred method for preservation of drill core was double plastic bagging of sections of core within their PET liners using a food grade plastic sealing system (with brief application of a vacuum to extract air from the plastic bag). Alternatively, core within PET core barrel liners were trimmed of air or fluid filled excess liner immediately after drilling, sealed with plastic tape. All cores were stored at 4 ˚C in a portable cool room on the drill site and then at the laboratory. Sections of cores, particularly at the nose end, that appeared to be damaged or disturbed were excluded from permeability or bulk density testing. Additional steps that were taken in the laboratory to ensure core testing was representative of in situ conditions are described in Section 4.1.

After coring, the holes were completed as monitoring piezometers and the casing was jacked out. The piezometers were constructed of screwed sections of 50 mm PVC casing with O-ring seals, with a 1.5 m machine slotted screen packed with pea-sized washed gravel. The annulus was then filled with a bentonite seal, backfilled to the surface and completed with a steel casing monument and cement monument pad.

3.2 Groundwater sampling for influent

Fluid for *K* testing (influent) should be taken from the formation at the same depth as the core. Formation water can be synthesized if it is not possible to sample directly from aquitard strata, by estimating the ionic strength, Na/Ca ratio and pH. In this study, groundwater from piezometers at a similar depth to the core was obtained using standard groundwater quality sampling techniques (Sundaram et al., 2009). A 240V electric submersible pump (GRUNDFOS MP1) and a surface flow cell were used to obtain representative samples after purging stagnant water to achieve constant field measurements of electrical conductivity and other parameters (Acworth et al., 2015 and unpublished data).

4. Centrifuge permeameter methods and calculations

4.1 Preparation of cores

To ensure that cores weretested under saturated realistic conditions, drill cores were adequately preserved, stored, prepared and set on a vacuum plate prior to centrifuge testing. Cores from PET drill core liners were trimmed and inserted into an acrylic liner for the CP using a core extruder. The custom made core extruder had 5 precision cutting blades driven by a motorised piston suitable for a 100 mm diameter core. Cores for CP testing in this study were 100 mm diameter C size core, with a length of 50-100 mm. A close fit between the clay core and the liner was achieved using this extruder.

A vacuum plate system for core samples was designed to ensure fully saturated cores, remove air at the base of the core, and ensure an effective seal between the CP liner prior to testing at accelerated gravity. The vacuum plate device was designed to fit the CP liners containing the cores, drawing ponded influent from the top to the base of the cores using a standard laboratory vacuum pump at 100 kPa of negative pressure. After 12 to 48 hours, or upon effluent flow from the base, the acrylic liners containing the prepared cores were then transferred directly to the CP module without disturbing the sample.

Furthermore, the moisture content and degree of saturation was monitored by measuring weight change of the permeameters during testing, and direct moisture tests of samples before and after CP testing. There was negligible difference observed between the moisture content of the core tests and in situ conditions, and the results were not associated with the time between sampling and testing of the core. Moisture content was not affected by the use of vacuum to expel air from sealing bags or from the top or base of the cores fitted into the CP liners.

A self-seal was observed forming from material swelling at the interface with the liner within minutes of introducing the influent solution. Prior to the self-seal development, leakage along the liner interface was identified by a flow rate of several orders of magnitude higher than the steady state flow K_v value. The swelling that occurred to self-seal the core was estimated at less than 0.02% of the cross-sectional area of the core by comparing flow rates through the CP drainage hole (described in Supplement S3). It was calculated that this area of swelling was sufficient to seal an annulus aperture of ~0.01 mm between the clay core and the acrylic liner.

Given the relatively shallow depth of these cores, and the semi-consolidated status, the maximum g-level in the centrifuge was limited to prevent structural changes in the core matrix. To minimise changes in porosity of the core during testing, the g-level and the weight of ponded fluid on the cores were therefore designed to ensure that total stress was less than estimated in situ stress at the depth from which the core was drilled.

Blind permeability tests were carried out by an independent laboratory, who adapted a constant/falling head method (AS 1289 6.7.3/5.1.1) with methods from Head (1988). For these 1g column tests, a sample diameter of 45.1 mm and length 61.83 mm was used, and a confining pressure of 150 kPa and back pressure of 50 kPa was applied, providing a vertical uniaxial stress of 100 kPa. The test time was up to 100 hours. These standard 1g column tests used deionised water as the influent.

4.2 Centrifuge permeameter testing

The Broadbent CP module and some unique systems developed as part of this study are described in this section, with further details in Supplement S1 and S3. A conceptual plan of a CP is shown in Fig. 2. The CP contains a cylindrical clay sample with length L and diameter D, and is spinning in a centrifuge around a central axis at an angular velocity ω. The permeameter has an inlet face at a radius r, and a drainage plate at a radius of r_0. The co-ordinate z is defined as positive from the base of the sample towards the central axis of rotation, consistent with definitions in 1g column testing (McCartney and Zornberg, 2010). This frame of reference is in an opposite direction to that defined by Nimmo and Mello (1991), but is convenient for interpretation and comparison of column flow tests.

Influent was fed from burettes located next to the centrifuge via a pair of custom designed low voltage peristaltic pumps mounted either on the centrifuge beam, or outside the centrifuge and through the low flow rotary union. In this study, the outlet face was a free drainage boundary, and is discussed further in Supplements S2 and S3.

The K value is based on flow rate, flow area, radius and revolutions per minute (RPM), although the method was adapted from a UFA centrifuge to this CP system (Section 4.3). Importantly, both testing systems are for steady state flow with free drainage due to zero pressure at the base of the core.

The mass of two core samples were balanced to the nearest 100g and tested simultaneously at either end of the centrifuge beam. The CP was operated at 10g for 30 minutes, and if no rapid flows due to leakage were detected, this was gradually increased to 20g, 40g and so on, until the maximum total stress on the core approached the estimated in situ stresses of the material at the given depth in the formation. The upper permissible g-level was designed to be less than the estimated in situ stress from the depth at which the core was obtained. It was also important to ensure that effective stress (Section 4.4) was acceptable, as variable pore fluid pressures during testing could cause consolidation of the core matrix. Influent volume was measured using both a calibrated continuous time record of pump rotations, and manual burette measurements, and effluent volumes were measured by weight. Steady state flow was defined as ±10% change in discharge over subsequent measurements in time, provided that influent flow rate was within ±10% of the effluent flow rate. Both of these conditions were required for the testing to be considered as a steady state flow condition. This protocol provided additional quantitative measures to the ASTM D7664 which states that steady state conditions have been attained "if the outflow is approximately equal to the inflow". Supplement S4 discusses the uncertainty of the measured data in more detail.

4.3 K_v calculations and statistical analysis

Hydraulic conductivity calculations for the CP in this study were based on ASTM D6527 (ASTM, 2008) and ASTM D7664 (ASTM, 2010) with a form of Darcy's Law that incorporates the additional driving force within a centrifuge. The gradient in the centrifuge elevation potential (Nimmo and Mello, 1991), or the gradient in centrifuge "elevation head" (Zornberg and McCartney, 2010) due to the centrifuge inertial force driving was defined as flow away from the centre of rotation (or in the opposite direction to z in Fig. 2). The g-level was defined at the mid-point of the core. A ponded influent above the top of the core prevented loss of saturation along the core (Nimmo and Mello, 1991). The centrifuge inertial (elevation) head gradient and hydraulic head gradient (stationary centrifuge at 1g) were calculated at 0.005 m increments through the core.

Statistical analysis of the data followed basic small-sampling theory using the student t-distribution, following the approach of Gill et al. (2005) and extending the approach of Timms and Anderson (2015) for estimating sample numbers required for CP testing. Upper and lower confidence intervals (UCI, LCI) were calculated from the mean ± $t_{(n-1)}$. s_n /$n^{1/2}$, where s_n is the sample standard deviation and $t_{(n-1)}$ is the value of the student t-distribution at the selected confidence limits (CL) of 90% and 99%. The confidence intervals were calculated for increasing number (n) of K_v data from each core.

4.4 Fluid pressure and total stress calculations

Fluid pressures and hydraulic gradient through the centrifuge core were determined following the approach of Nimmo and Mello (1991). The total fluid pressure P (kPa) was calculated, in Eq. (1):

$$P = \rho_w \int_{r_0}^{r'} r\omega^2 \, dr \qquad (1)$$

assuming a fluid density ρ_w, of 1.0 g cm^{-3} and where r is the radius of rotation (cm), and ω is the angular velocity (s^{-1}). The total stress S (kPa) was determined through the centrifuge core, following Eq. (2):

$$S = \rho_s \int_{r_0}^{r'} r\omega^2 \, dr \qquad (2)$$

assuming core bulk density ρ_s, of 1.9 g cm^{-3}. The total stress and fluid pressure were calculated at 0.005 m increments through the core. The effective stress was then calculated as the difference between total stress and fluid pressure. An increase in effective stress associated with decreased fluid pressures near the base of the free draining core may cause consolidation of the core matrix near the boundary.

The total stress applied to the core, relative to stress, may affect the porosity of the core sample, depending on the stress history. In situ stress of the cores (S_i) at the sampling depth below ground (D) was calculated using Eq. (3):

$$S_i = \rho_s D g \qquad (3)$$

It was assumed that the overlaying formations were fully saturated and of a similar bulk density to the supplied core samples.

5. Results and discussion

5.1 Core properties and K_v results from CP testing

Index properties for five representative cores are provided in Table 2. The cores were typically silty clay (where the clay-silt size boundary is defined at 0.002 mm), except for one sandy clay core. The large proportion of silt relative to clay is an important characteristic of this formation, with clay mineralogy dominated by smectite (Timms and Acworth, 2005; Acworth and Timms, 2009).

Moisture content varied from 24.7 to 36.4% by weight, and was consistent with site measured data on the core (Supplement S5), although not all the cores were fully saturated as received by the external laboratory. Bulk wet density varied from 1.71 to 1.88 g cm^{-3} and particle density from 2.47 to 2.58 g cm^{-3}. The K_v of cores tested in the CP module (Table 3) varied from 1.1×10^{-10} to 3.5×10^{-7} ms^{-1} (n = 18). Accelerations up to 100*g* were applied during CP testing of semi-consolidated sediment cores and were more typically limited to 30-40*g*. Fig. 3 shows the measured influent and effluent rates and the calculated K_v values during a typical CP test as the *g*-level was gradually increased. Steady state flow (±10 % change over time with influent rate equal to effluent rate) was achieved at ~20 hrs (Fig. 3). However, a lower K_v value that was observed overnight (>12 hrs interval between samples) than was observed during the day (~1 hr intervals between samples). The K_v values over shorter time periods, with minimal evaporative losses were considered to be more reliable. Further experimentation and numerical modelling is required to adequately explain this anomalous data which may be associated with evaporative losses over longer time periods of flow measurement or other transient processes within the system.

Anomalous flow via preferential pathways could be readily identified by a flow rate of several orders of magnitude greater than otherwise observed. Anomalous flow was often observed along the interface of the cores and the liner during the early minutes of a test before sealing occurred and steady state conditions were established. On one occasion a preferential flow path developed during the test which caused very fast flow at accelerated gravity that was easily detected. A test failure like this could be readily identified and excluded from further evaluation.

A small uncertainty in K_v results for the CL site was calculated at a confidence limit of 99% using the methods described in Section 4.3. By increasing the number of samples, the confidence bounds for K_v were narrowed from a range of 4.8×10^{-10} to 2.4×10^{-9} m/s (n=5) to a range of 1.1×10^{-9} to 2.1×10^{-9} m/s (n=9). Increasing the number of samples from five to nine decreased the standard deviation, although asimilar geometric mean occurred with the increased sample number (Table 4). However there was less certainty at two other core sites (BF and NR) due to limited and more variable K_v data. At the BF site the 99% confidence interval had relatively wide K_v bounds for n = 6, while at NR site, a confidence interval of 90% results in similarly wide K_v bounds for n = 3. However, such a small number of samples is not considered sufficient for statistical analysis. This evaluation of the results highlights the relative K_v variability and small sample set for the BF and NR sites, and the need for further testing, particularly at the NR site. This issue will be expanded in the following discussion.

5.2 Pore fluid pressure and stress conditions at accelerated gravity

How realistic the K_v measured by CP testing is of in situ conditions depends in part on the magnitude of stress and any structural changes that occur within the core matrix. Supplement S2 provides background on the definition and significance of hydrostatic pore pressure, centrifuge inertial (elevation) head, and gradients driving fluid flow. Supplement S2 also discusses the possibility that K values reported in this study could be biased on the high side, considering total stress at the base of the core under steady state conditions.

During centrifuge testing effective stress is maximum at the base of the free draining core, where fluid pressure is zero, and thus effective stress is equal to total stress under hydrostatic conditions (no flow). In both testing methods in this study, the total stress was less than estimated in situ stress, however the stress history of the core sample and effective stress dynamics were uncertain. It appears that the stresses during these tests were likely within an acceptable range to minimise structural changes including swelling and consolidation. There was no evidence of significant changes in core length due to consolidation of the samples during spot checks of core length with a digital calliper. However further attention on these processes, including instrumentation to measure fluid pressures and core matrix changes during testing is required in future studies. A separate geotechnical study of these semi-consolidated sediments, including oedometer testing is in progress to better quantify the relationship between stress and permeability in these semi-consolidated materials. In future studies of semi-consolidated materials, measurement of consolidation state (over consolidation ratio) and pre-consolidation stress is recommended prior to centrifuge testing to ensure that an appropriate centrifuge stress is applied.

5.3 Comparison of in situ K_v and column testing methods at the CL site

A comparison of K_v from in situ and column testing methods are shown in Fig. 4 for the CL site. Results from the CP method (1.1×10^{-10} to 3.5×10^{-9} ms^{-1}, n = 9) were similar to K_v values from the independent and in situ method (1.6×10^{-9} to 4.0×10^{-9} ms^{-1}) confirming that the sequence is of low permeability at the CL site with a reasonable level of confidence (Table 4). However, K_v from both in situ and CP methods were higher than 1g column tests of core from 11.27-11.47 and 28.24–28.33 m BG from this site (1.4×10^{-9}, 1.1×10^{-10} and 1.5×10^{-10} ms^{-1}, n = 3).

In situ K_v of the clayey-silt at the CL site were based on observed amplitude and phase changes of pore pressures (at hourly or 6-hourly intervals) due to five major rainfall events over four years (Timms and Acworth, 2005). The phase lag at the base of the clay varied between 49 and 72 days. The phase lag pore pressure analysis resulted in a K_v value of 1.6×10^{-9} ms^{-1}, while the change in amplitude over a vertical clay sequence of 18 m (from a 17 m depth piezometer to the inferred base of the aquitard at 35 m depth) resulted in a K_v value of 4.0×10^{-9} ms^{-1}.

It is noted that the reliability of harmonic analysis related methods may be compromised by specific storage measurements. Jiang et al. (2013) relied on indirect specific storage values derived from downhole sonic and density log data from boreholes in the region, while Timms and Acworth (2005) calculated specific storage from barometric and loading responses that were recorded in the same groundwater level data set and boreholes used for harmonic analysis.

The reduced test times of CP testing may be attributed to the reduced time required to achieve steady state flow with centrifugal forces driving flow. Alternatively, the relatively longer time required for 1*g* column testing may be attributed to deionized water interaction with clay that reduced infiltration rates into the cores (10 to 100 lower K_v result for 1*g* column tests compared with CP tests). It is known that decreased ionic strength of influent (eg. deionized water) causes a linear decrease in permeability, and that the relative concentrations of sodium and calcium can affect permeability due to swelling and inter-layer interactions (eg. Shackelford et al., 2010; Ahn and Jo, 2009). Differences in K_v values from the two laboratory testing methods could be due to differences in test setup (eg. 45 vs. 100 mm diameter core) and stress changes that occur as discussed in Section 5.2 and Supplement S2.

CP testing was relatively rapid, typically with a few hours, up to 24 hours required for steady state flow CP, compared with an average of 90 hours (73, 96 and 100 hours for the tests reported here) for 1*g* column testing. In addition, an extended test of 830 hours in the CP (unpublished data) verified that no significant changes occurred over extended testing periods. The CP technique can therefore reduce average testing time to ~20% of the time that would be required in 1*g* laboratory testing systems, similar to the reduced time requirement of centrifuge methods for unsaturated hydraulic conductivity functions compared with 1g column tests ASTM (2010). The relative time advantage of testing cores at accelerated gravity may be greater at lower K_v, due to the increased time required to establish steady state flow conditions. The relative time advantage could be significant for contaminant transport testing which requires several pore volumes of steady state flow, compared to permeability testing where steady state flow is established before one pore volume.

The similarity of K_v measurements with different scales at the CL site (Fig. 4) indicates that in this part of the alluvial deposit K is independent of vertical scale from centimeters to several meters. These K_v results from both in situ and laboratory methods provide an important constraint for evaluations of hydraulic connectivity, particularly as there is a general lack of K_v data for these sediments. Complimentary studies of hydraulic connectivity to quantify leakage rates include pore pressure monitoring and piezometer slug testing at various depth intervals along with hydrogeochemical and isotope tracer data. Recent geological studies of the alluvial sequence (Acworth et al., 2015) outlined in Section 2, and identification of dual porosity structures in the large diameter cores (Crane et al., 2015) indicate that it may be possible for vertical leakage to occur through clayey silts if a vertical hydraulic gradient were to be imposed. A diffusion dominated salt profile through the sequence suggest negligible vertical flow (Timms and Acworth, 2006), however, a proper assessment of flow connectivity requires vertical hydraulic gradients to also taken into account any salinity variations with depth and pore pressure variations that have occurred over at least the past decade.

5.4 Geological and regional context for permeability of a clay-silt aquitard

The K_v measurements reported in this paper are important because there is a lack of aquitard data for alluvial groundwater systems globally. Even where many groundwater investigations have been completed (eg. Murray-Darling Basin) there continues to be a lack of information on the thick clayey-silt sediments at various spatial scales.

The core samples for testing were randomly selected from the same lithostratigraphic formation, the upper 30 m of the alluvial sequence as described in Section 2. Although the alluvial sequence extends to over 100 m depth, we focused this study on sediments defined by a low net-to-gross ratio (Larue and Hovadik, 2006) of <0.4 that reflects that clay rich part of the sequence (Timms et al., 2011). We assumed a log-normal distribution of K_v within this formation, which as noted by Fogg et al. (1998) might be justified within individual facies, but not over the full stratigraphic section. It was also assumed that the standard deviation of the samples tested is similar to the standard deviation of the total population of K_v results from the formation, which may only be known if a significantly large number of samples are tested.

K_v values for cores from the NR and BF sites were significantly larger than for the CL site, although additional data from the NR site is required to increased confidence intervals (Table 3, Table 4). Based on the dataset currently available for each site there did not appear to be any significant K_v trend with depth, except at the CL site, with a possible decrease of K_v by a factor of 3 with depth increasing from 11 to 28 m BG. Further testing is in progress to better identify any spatially significant trends in K_v.

K_v results obtained from the CP for these clayey silt aquitards were significantly larger than K_v for consolidated rock cores tested in this system (Bouzalakos et al., 2013). The relatively low g-levels in this study (up to 80g), compared to rock core testing (up to 520g, Bouzalakos et al., 2013) were necessary for the shallow and semi-consolidated nature of the clayey-silt cores. In fact, steady state flow was achieved at low g-levels for K_v values that were at least 100 times higher than the current detection limit and uncertainty of the CP system (Supplement S4).

The vertical permeability of the clayey-silt aquitards in this region, and the relative importance of matrix flow and preferential flow through fractures and heterogeneities are critical to the sustainability of the groundwater resource. The K_v data reported in this study for these silty and semi-consolidated sediments are higher than reported for regional flow modelling in this area (McNeilage, 2006), indicating that the aquitards allow significant recharge to underlying aquifers.

A regional groundwater flow model developed by McNeilage (2006) with a 2 layer MODFLOW code, determined the dominant source of recharge to be diffuse leakage through the soil (and aquitards) in the Breeza groundwater management area. As in typical groundwater modelling practice (Barnett et al., 2012) the aquitard was not explicitly modelled, with water instead transferred from a shallow to a deeper aquifer using a vertical leakance value (units in day^{-1}).

The calibrated groundwater model indicated that approximately 70% of the long-term average groundwater recharge (11 GL year^{-1}) was attributed to diffuse leakage in this area that included the CL and NR sites. This volume is equivalent to 20 mm year^{-1}, or a K_v of ~6×10^{-10} ms^{-1} assuming a unit vertical hydraulic gradient over an area of approximately 500 km^2. The actual K_v or leakance values were not reported. The calibrated leakance values were found to vary over three orders of magnitude across the Breeza area, with relatively high values in isolated areas in the south, centre and north. In comparison, the K_v results on clayey-silt cores appear to be higher than the apparent K_v of the regional groundwater model, but with a similar degree of heterogeneity. The reasons for this discrepancy are not yet clear, but may be attributed to non-unique calibration of the regional flow model (eg. underestimation of inter-aquifer leakance) or the lack of representative K_v values for this aquitard at a scale that accounts for heterogeneities and preferential flow paths.

The K_v results in this study are within the range of values reported elsewhere for semi-consolidated clay silt sediments. For example, Neuzil (1994) reviewed aquitard K_v values for intact muds and lacustrine clays (10^{-8} to 10^{-11} ms^{-1}) compared to consolidated materials such as shale with values as low as 10^{-16} ms^{-1} for argillite. A detailed study of a clayey marl and limestone aquitard in France (Larroque et al., 2013) found a quasi-systematic bias of one order of magnitude between petrophysical K_v estimates (10^{-8} to 10^{-10} ms^{-1}), compared with values (10^{-9} to 10^{-11} ms^{-1}) from hydraulic diffusivity monitoring between 30 and 70 m BG. However, the empirical petrophysical relationships between porosity, pore size and intrinsic permeability do not adequately account for structural effects of clay materials. Field piezometer rising head tests (n = 225) indicated that K_v of a lacustrine clay aquitard around Mexico City was 10^{-8} to 10^{-9} ms^{-1} in two areas, one hundred times greater than matrix scale permeability (Vargas and Ortega-Guerrero, 2004). However, in a third area of the Mexico City aquitard, the field tests were 10^{-10} ms^{-1} indicating the regional variability that can occur within clayey deposits.

Studies of glacial till aquitards in Canada, the US and Denmark find that regional permeability is typically at least two orders magnitude greater than laboratory tests (Van der Kamp, 2001; Fredericia 1990; Bradbury and Muldoon, 1990; Gerber and Howard, 2000), although one study (Husain et al., 1998) showed that for a thick glacial till aquitard in southern Ontario, Canada, the regional permeability is similar to the laboratory-obtained measurements, indicating the absence of significant permeable structures.

There is evidence of fracturing near the surface of the clayey aquitards that are the focus of this study. Fracture flow to a shallow pit and the freshening of porewater in the aquifers at 16 and 34 m depth during the irrigation season indicated rapid leakage had occurred at the BF site (Acworth and Timms, 2009). The dynamics of fracturing within ~2 m of the ground surface in these sediments was described by Greve et al. (2012). However, beyond the zone of fracturing near the ground surface, there appears to be insignificant groundwater flow. Solute profiles through the 30 m thick clayey deposit at the CL site indicate that downwards migration of saline water is limited to diffusion and that flow is insignificant (Timms and Acworth, 2006). On the basis of available evidence, the clayey sediments in this region may lack preferential flow paths at some sites, and in other areas preferential flow may occur through features such as fractures and heterogeneity at a range of scales (Crane et al. 2015). Further work is required to determine permeability at a range of scales, and to better understand preferential flow paths. The current conceptual model on which the numerical models in this region are based (simple layered aquitard overlying an aquifer) do not allow for spatial variability in connectivity mechanisms that could be important across a large valley alluvial fill sequence. Multiple mechanisms for vertical connectivity including matrix flow, fracture flow and sedimentary heterogeneity could be important in aquitards. The relative importance of each of these pathways for vertical flow would depend on the spatial scale and local setting in each aquitard.

5.5 Groundwater flow at natural gradient and accelerated conditions

To determine if accelerated flow conditions are realistic for hydrogeological environments, the linear flow velocity for various CP setups was compared with other flow scenarios. The rationale behind this comparison was that if the flow rate was consistent with scaling laws for physical modelling, with a unit gradient as a point of reference, then the results could be consider realistic for atypical in situ vertical hydraulic gradient. In Table 5, an in situ hydraulic gradient of 0.5 is compared with CP setups for 100 mm and 65 mm diameter cores of various lengths for an aquitard material with K_v of 10^{-8} ms^{-1}. The vertical flow rate varies from 0.3 mL $hour^{-1}$ under in situ conditions, to 8.5 mL $hour^{-1}$ in the CP, such that linear flow velocities remain very low at 10^{-8} to 10^{-6} ms^{-1}. The flow rate during centrifugation was N times greater than if a hydraulic gradient of 1 was applied to the core samples at 1g. This increase in flow rate is consistent with scaling laws for physical modelling (Tan and Scott, 1987) providing further evidence that the K_v results are realistic.

The accelerated flow conditions, whilst realistic for hydrogeological environments can also be an advantage for experimental studies of solute transport. K_v results in the order of 10^{-9}

ms^{-1} were obtained in ~20% of the time required for 1*g* column permeameter tests. Solute breakthrough experiments require longer testing periods of steady state flow than for permeability testing. For example, Timms and Hendry (2008) and Timms et al. (2009) describe continuous CP experiments over 90 days to quantify reactive solute transport during several pore volumes (PV) of flow. The comparisons of time required for one PV provided in Table 5 illustrate the possible advantages of CP for contaminant flow that may affect the structural integrity of the material.

6 Conclusions

Accurate and reasonable measurement of the vertical hydraulic conductivity (K_v) of aquitards is a critical concern for many applications. For example, following an empirical analysis of selected case studies, Bredehoeft (2005) reported that collection of new field data may render the prevailing conceptual hydrogeological models invalid in 20-30% of model analyses. Bredehoeft (2005) coined the term 'conceptual model surprise' to explain this phenomenon. He then went on to explain that 'often one does not have hydraulic conductivity values for confining layers because of the difficulties associated with acquiring such data'.

The centrifuge technology described within this paper helps investigators to overcome some of the modelling limitations identified by Bredehoeft (2005). With centrifuge technology realistic point-scale measures of hydraulic property data can be collected to develop more realistic numerical flow models to quantify the significance of transient drawdown, the associated release of water into adjacent aquifers over long time periods, and the possibility of preferential flow. t Realistic information on aquitard hydraulic properties could improve confidence in conceptual and numerical hydrogeological models of aquifer-aquitard systems

In the absence of direct measurement of aquitard permeability there is a real risk that aquitard parameters may be ignored or misrepresented in analyses resulting in a corresponding under-prediction of vertical connectivity via preferential flow paths and/or over-prediction of aquifer storage and transmissivity. This is an especially important consideration in the analysis of aquifer tests that may not have been conducted for sufficient periods of time to identify distant boundary conditions or the characteristic effects of aquitard leakage and/or storage (Neuman and Witherspoon, 1968). In very low permeability strata however, there are practical limitations to pump tests and packer testing below about 10^{-8} ms^{-1}, depending on the equipment and the thickness of strata that is subject to testing. It is recognised that in many heterogeneous systems time lags for the propagation of drawdown responses through an aquitard can be significant (Kelly et al., 2013).

Core scale measures of aquitard hydraulic conductivity are an integral component of hydrogeological studies concerning aquifer connectivity. The availability of core scale facies measurements enables the up-scaling of bore log and geophysical data to determine upper and lower hydraulic conductivity bounds for regionally up-scaled aquitard units. Any differences between K values at various scales are important for indicating the possibility of preferential flow through heterogeneous strata or aquitard defects (eg. faults and fractures). The availability of these bounded estimates helps to constrain the uncertainty analyses conducted on regional groundwater flow models to yield more confident predictions (Gerber and Howard, 2000).

Nevertheless, regional groundwater flow models generally use hydraulic resistance (leakance) values to transfer water vertically between aquifers (Barnett et al., 2012) rather than spatial discretization of aquitards that control this transfer. While this simplification is justified in many models, such an approach is not capable of identifying rapid flow pathways through defects in the aquitards or the release of stored water from an aquitard to an aquifer and cannot resolve the vertical hydraulic head distribution across the aquitard to verify drawdown responses. An aquitard should be subdivided into at least three thinner layers to effectively model transient pressure responses (Barnett et al., 2012). Rather than assigning constant theoretical values for aquitard properties through these multiple layers a combination of realistic and rapid laboratory measurement and direct in situ measurements couldimprove confidence in conceptual understanding and model predictions.

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Tables

Table 1. Specifications and performance details of the Broadbent GT-18 centrifuge permeameter (CP) system as constructed by Broadbent (2011).

Dimensions/mass	
Diameter (lower rotary stack)	200.0 cm
Radius to top sample chamber	45.0 cm*
Radius to base sample chamber	65.0 cm**
Total mass	4800 kg
Performance	
Rotational speed	10 – 875 RPM
Maximum sample length	20.0 cm
Maximum sample diameter	10.0 cm
Maximum sample mass	4.7 kg
Maximum sample density	SG 3.0
Maximum effluent reservoir capacity	1000 mL
Maximum payload	18.11 kg

* 385 G at 875 RPM; ** 556 G at 875 RPM; *** 471 G at 875 RPM;

Table 2. Core descriptions and index properties

Core ID	BF C2.8	BF C2.16 & C2.15	CL C4.8a	CL C4.20a	NR C3.23
Depth (m BG)	11.00-11.35/ 11.35-11.68	22.50-22.90/ 21.93-22.18	11.27-11.47	28.50-28.70	33.00- 33.35/ 33.35- 33.68
Description	Sandy clay - brown	Clayey silt - brown	Silty clay - brown	Silty clay – pale brown	Clayey Silt - Brown
Moisture (% wt.)	24.7	28.2	45.7	36.4	-
D_{50} (mm)	0.025	0.0068	-	-	<0.0013
Bulk wet density (g cm^{-3})	1.88	1.81	1.71	1.77	1.72
Particle density (g cm^{-3})	2.52	2.47	2.58	2.50	2.58
Initial void ratio	0.67	0.75	1.20	0.93	0.89
Initial degree of saturation (%)	93	95	96	99	74

Table 3. K_v results from CP tests indicating *g*-level maximum and testing time. The influent source column identifies the site (NR, CL, BF) and depth (P20 is piezometer screen at 20 m depth) of groundwater sampling. Calculations were based on Eq. (3) for in situ stress.

Site	Depth (m BG)	K_v (ms^{-1})	*g*-level maximum	Estimated in situ stress (kPa)	Testing time (hrs)	Influent source
NR	33.8	4×10^{-9}	10	615	~144	NR P30
NR	33.90	2×10^{-9}	10	615	~144	NR P30
NR	34.68	2.4×10^{-7}	10	646	2.6	NR P30
CL	11.75	3.5×10^{-9}	80	219	24	CL P15
CL	14.00	2.2×10^{-9}	80	261	1	CL P15
CL	19.25	2.0×10^{-9}	80	359	24	CL P20
CL	21.70	5.1×10^{-9}	80	404	1	CL P20
CL	26.01	2.4×10^{-9}	80	485	21	CL P40
CL	26.10	1.1×10^{-10}	80	486	21	CL P40
CL	28.33	2.0×10^{-9}	10	526	24	CL P40
CL	28.52	2.7×10^{-9}	80	532	1	CL P25
CL	31.36	1.6×10^{-9}	40	585	24	CL P40
BF	24.07	5.9×10^{-9}	40	449	3	BF CP25
BF	24.14	3.4×10^{-8}	40	450	3	BF CP25
BF	31.40	1.3×10^{-9}	30	585	11	BF CP40
BF	36.46	3.5×10^{-7}	10	680	2.5	BF CP40
BF	40.00	1.5×10^{-9}	30	746	23	BF CP40
BF	40.10	4.3×10^{-8}	30	746	23	BF CP40

Table 4 Geometric mean, standard deviation (s_n) and confidence limits (C.L. %) analysis for K_v data using the CP method to test core from the clayey-silt formation at the CL, BF and NR sites.

					K_v confidence intervals (m/s)	
Site	n	K_v geometric mean (m/s)	s_n log K_v	C.L. %	Lower bound	Upper bound
CL	5	1.3×10^{-9}	0.21	99	4.8×10^{-10}	2.4×10^{-9}
CL	9	1.6×10^{-9}	0.14	99	1.1×10^{-9}	2.0×10^{-9}
BF	6	1.3×10^{-8}	0.19	99	6.5×10^{-9}	2.1×10^{-8}
NR	3	1.2×10^{-8}	0.34	99	1.5×10^{-10}	8.5×10^{-8}
				90	3.4×10^{-9}	4.6×10^{-8}

Table 5. Linear flow velocity at natural gradient, unit gradient and for various centrifuge permeameter setups

	Natural gradient	Unit gradient	Centrifuge permeameter		
Vertical hydraulic conductivity (ms^{-1})			1.0×10^{-8}		
Core type		C core - long		C core - short	HQ core - short
Core length ×diameter (mm)		200 × 100		30 × 100	30 × 65
RPM	n/a	n/a	202	202	310
g-level	1	1	30	30	70
Vertical fluid head gradient ($m\ m^{-1}$)	0.5	1	~0.2#	~0.5#	~0.5#
Flow ($mL\ hour^{-1}$)	0.3	0.6	8.5	8.5	8.5
Linear flow velocity (ms^{-1})	1.7×10^{-8}	3.3×10^{-8}	1.0×10^{-6}	1.0×10^{-6}	2.4×10^{-6}
Time for 1 pore volume (hours)	3333	1667	55.4	8.3	3.5
			Normalised		
Increased linear flow velocity			30	30	71
Reduced time for 1 PV			30	200	474

Fluid head gradient depends on the depth of influent on the core, and the length of the core

Figures

Fig. 1 Location of study sites in Eastern Australia, state of NSW. The Norman's Road (NR), Breeza Farm (BF) and Cattle Lane (CL) sites are shown within the Namoi catchment.

Fig. 2 Cross-sectional diagram of a core sample subjected to centrifugal force, with a free drainage boundary condition at the base of the core.

Fig. 3 Centrifuge permeameter testing at low stresses of a semi-consolidated clayey-silt core sample (CL 26.1 m depth, Test 39-1) showing variation of *g*-level, K_v and influent and effluent flow rate during the test (after Timms et al., 2014).

Fig. 4 Vertical hydraulic conductivity (K_v) measurements by centrifuge permeameter and column permeameter compared with in situ K_v derived from pore pressure data at 6 hourly intervals over 4 years interpreted with harmonic analysis (after Timms and Acworth, 2005) for the Cattle Lane site with massive clayey-silt from the surface to 35 m depth.

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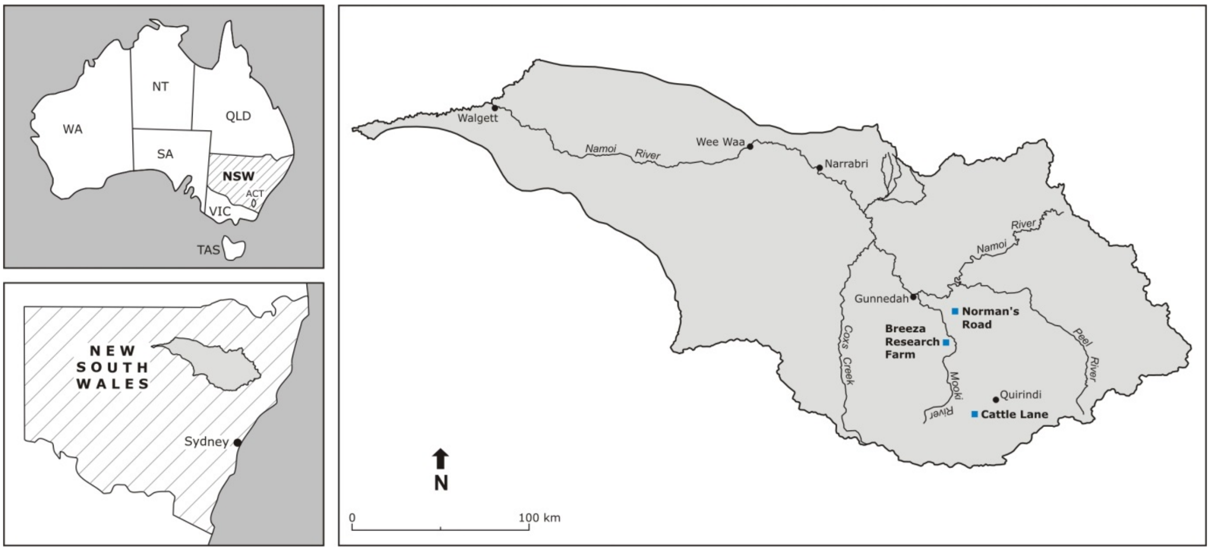

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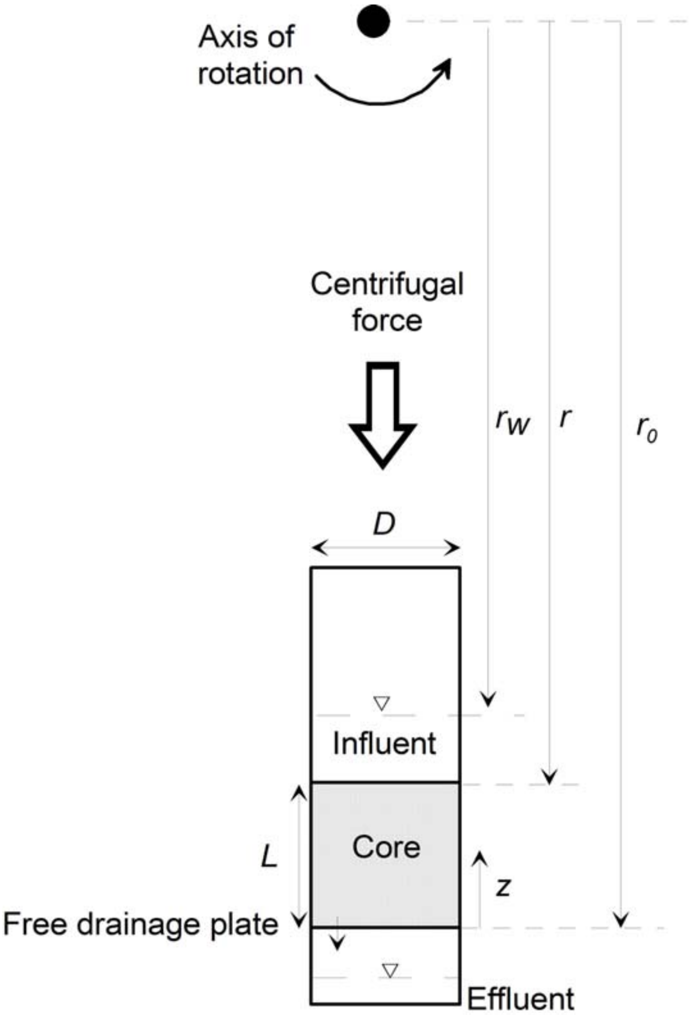

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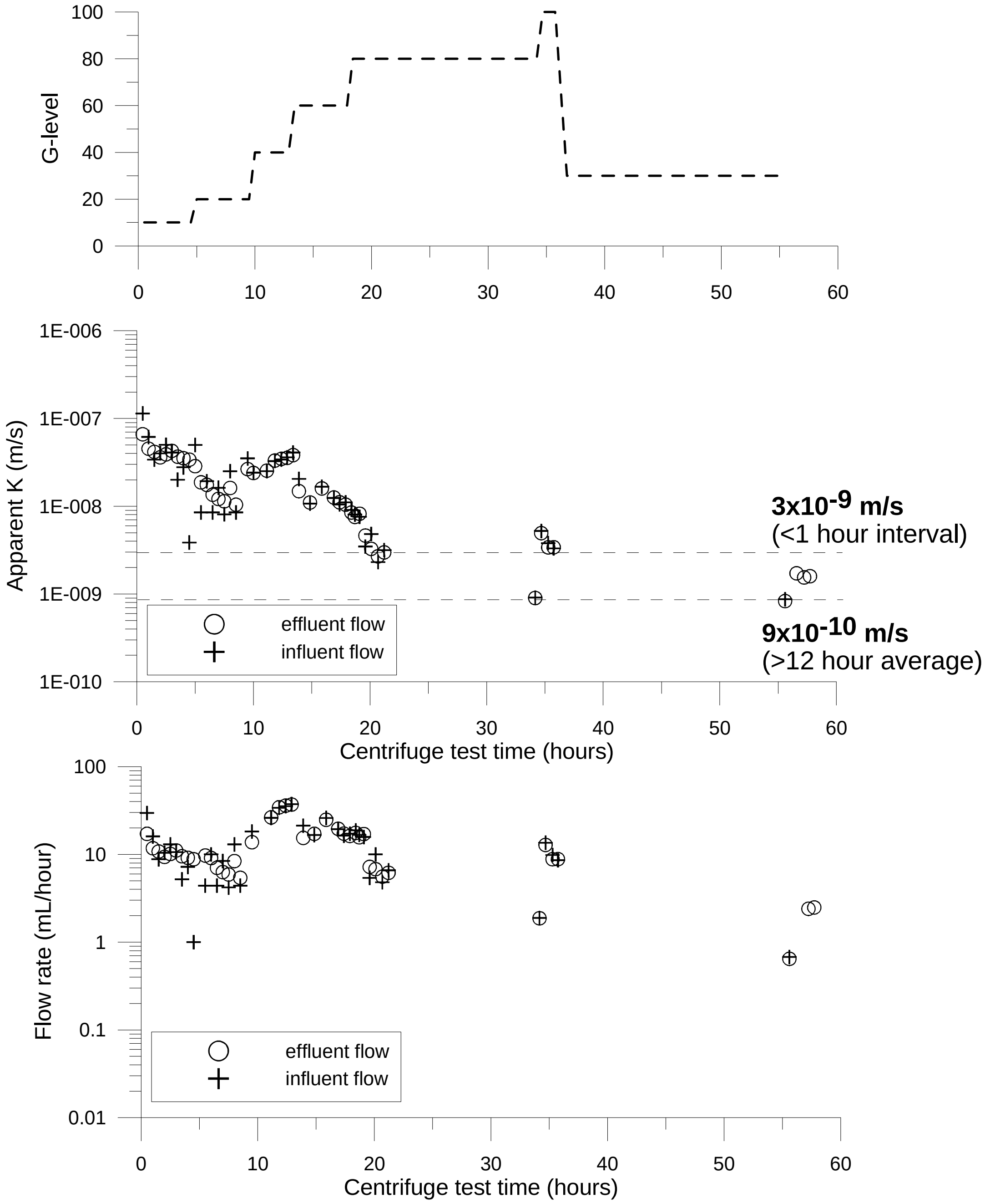

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