Sand Body Connectivity Leederville Aquifer Perth Basin

By

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ABSTRACT

With demand on the water resources of the Perth Basin increasing due to impacts from population growth and climate change, groundwater resource management practices such as aquifer storage and recovery schemes will increasingly become an important component of the management of this resource. Within aquifers such as the Leederville, the heterogeneity of sediment grain size distribution can have an impact on the movement of groundwater within the aquifer body. This variation in grain size distribution can be imparted by depositional processes resulting in variable sand body connectivity which can impose an anisotropic flow field within the aquifer.

To investigate sand body connectivity within the Leederville aquifer, downhole geology logs from 19 bore holes drilled at through the Wanneroo Member at the site of the Water Corporations Beenyup Groundwater Recharge Trial were collected. From this downhole geology data, four hydrofacies classes were derived based on the logged sand to silt ratios. Using these hydrofacies, a geostatistical model was developed of the Wanneroo hydrostratigraphy at the Beenyup recharge site. This modelling utilised the markovian transitional probabilities approach as implemented in the TPROGS software (Carle 1999).

To account for the broadly westerly direction of sediment flux during deposition, the TPROGS model contained a preferential orientation of the sand bodies on a west to east orientation. The stochastic FloPy modeling in MODFLOW 6 conducted with these TPROGS hydrofacies realisations show that there is anisotropic flow between depositional dip and depositional strike directions due to the preferential orientation of these sand bodies. This anisotropic flow within the conceptual hydrofacies model highlights the potential control that aquifer geologic heterogeneity can have on site scale groundwater movement within the Leederville aquifer.

Consequently, a site scale in the Leederville aquifer groundwater flow driven laterally and vertically away from the orientation of preferential permeability (dip direction), by induced head gradients (such as from aquifer injection and abstraction induced localised ground water gradients), will likely be impeded by permeability contrasts on a local scale. These flow retardant zones are a result of juxtaposition of textural fabrics running parallel to the primary orientation of deposition within the aquifer.

This highlights the need for further high resolution geological investigations with the Leederville aquifer to accurately identify the higher conductivity zones, as it is these higher conductivity zones such as the coarse grained sands that will dominate the localised groundwater flow on a site scale.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Rick Jones

Date 19/10/2020

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To my girls Winona and Trudy, I know dad has been busy lately, but don’t worry, I’ll be able to play again soon.

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1. INTRODUCTION

1.1 Ground Water in the Southwest of Western Australia

In the southwest of Western Australia, including the Perth metropolitan area, groundwater is an increasingly important water resource (Ali *et al.*, 2012). This resource is utilised for potable water supply as well as for other domestic, agricultural, and industry uses. The Gnangara mound system represents a large and low cost source of potable water for the Perth metropolitan area. It extends over an area of 2200km^2 and encompasses the groundwater areas of Yanchep, Gnangara, Wanneroo, Swan, Mirrabooka, Gwelup and Perth (Department of water, 2009). It is a complex multi layered groundwater system with three primary aquifers that contribute to the groundwater resource. These aquifers are referred to as the unconfined superficial, semi confined Leederville and deep Yaragadee aquifers. There is also minor contribution from the Mirrabooka aquifer (Department of Water, 2017).

1.2 Climate

1.2.1 Current Climate

The south west of Western Australia (SWWA) is dominated by a Mediterranean style climate which is typified by dry and hot summers and cold wet winters (IOCI, 2012). This climatic trend is due largely to subtropical high pressure systems that can extend across this region in the summers reaching its southernmost position between January and February. Summer rainfall in this zone is highly sporadic, and generally associated with tropical cyclones. During the winter months this subtropical belt of high-pressure lies further to the north, almost completely outside the SWWA region. This winter weather in SWWA is characterised by moist, unstable winds and 80% of rainfall occurs from April to October, most of it during the cooler months of June and July (IOCI, 2012; Department of Water, 2014). The annual average rainfall in the SWWA area has declined since the 1970s, this downward trend in rainfall has intensified and expanded in recent times (Dey *et al.*, 2019).

Observed rainfall totals have continued to decrease since the 2000s with early winter (May to July) rainfall in many locations becoming lower than the 1969 to 1999 average for the same months (figure 1). This drying trend has also expanded in geographic extent and in addition the year-to-year fluctuation in winter rainfall in the far SWWA is also declining (IOCI, 2012). Modelling studies conducted by Delworth and Zeng (2014) indicate that this autumn–winter drying trend over southern and especially south Western Australia is expected to continue. These studies show that declines in rainfall by up to 40% from the 1911–1970 average by the later half of the twenty-first century will become evident. This drying trend is confirmed by work from Silberstein *et al.*, (2012) which concludes that future climate projections indicate a further decrease in rainfall.

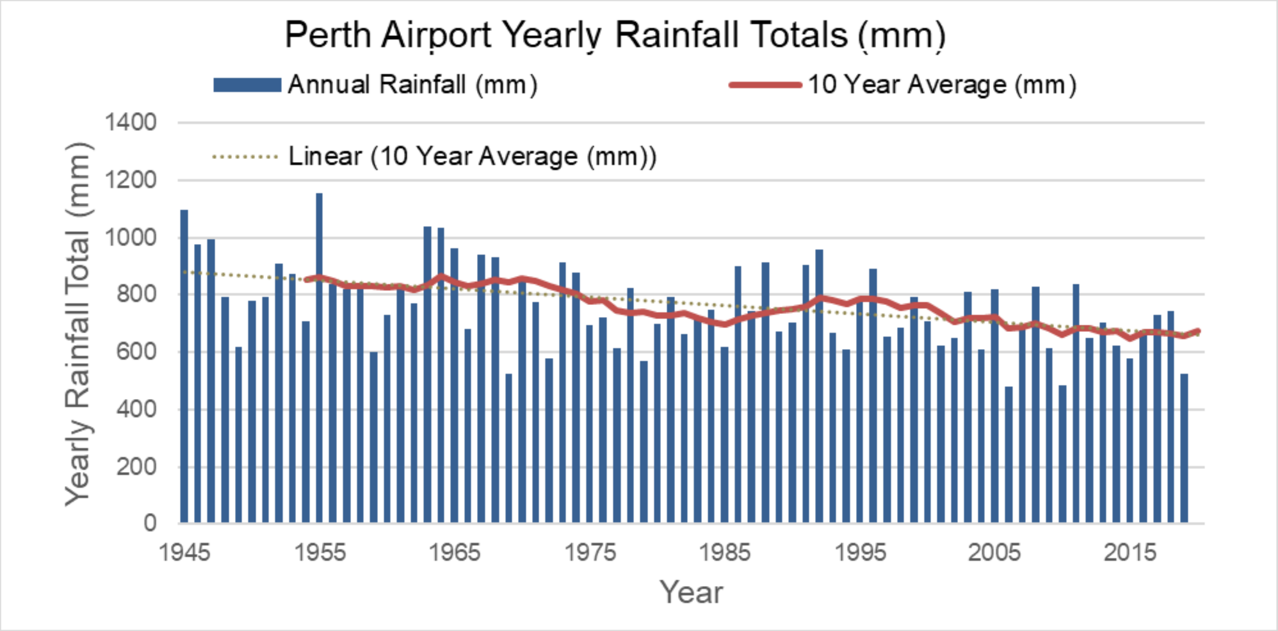


Figure 1 Rainfall trend for Perth Airport (BOM 2020)

1.2.2 Projected Climate Change

Within the SWWA the Global Climate Models (GCMs) indicate that temperatures will rise and rainfall will follow a falling trend into the 21st century. The projected dry scenarios show relative to baseline that the SWWA will undergo a 14% reduction in average daily rainfall by 2030 and a 0.7 degree rise in temperature. The median scenario shows a 5% reduction in total rainfall and the wet a 2% reduction. In the Perth metro region the annual rainfall trend over the last decade has aligned with the modelled trend for the dry scenario (Department of Water, 2014). As this climate modelling of SWWA indicates a general decrease in rainfall and an increase in temperature, the modelled climate projections will be useful for planning water availability into a drying future, (Department of Water, 2014).

1.3 Geology of the Perth Basin

1.3.1 Overview

The Perth Basin is a large north south trending sedimentary basin that covers an area of approximately 45000 km^2 onshore and 55 000 km^2 offshore, (Playford, Cockbain and Low, 1976). The Perth Basin was initiated as a rift along the continental margin of South West Australia as Australia and India separated during the Valanginian (mid – Neocomian), early Cretaceous breakup of Gondwana. This sequence is separated from the crystalline rocks of the Yilgarn Craton by the Darling Fault to the east and represents a sedimentary trough up to 15 km thick containing faulted sediments of Silurian to Pleistocene in age (Davidson, 1995; Mory and Iasky, 1996, Crostella and Backhouse, 2000).

During breakup with India and Australia, the Perth Basin underwent dextral strike slip deformation, uplift and erosion from the Late Jurassic to early Cretaceous. This resulted in northerly striking faults and north westerly transfer zones and the development of the intra – Neocomian breakup unconformity. These transfer zones have exhibited a control on the subsequent deformation of sedimentary cover, (Song and Cawood, 2000; Davidson and Yu, 2008).

The Swan Coastal Plain is approximately 36 km wide in the north and some 23 km wide in the south. To the east the Gingin and Darling rise to 200 m above sea level and represent the eastern most extent of marine erosion that occurred during the Tertiary and Quaternary (Davidson and Yu, 2008).

1.3.2 The Warnbro Group

Of the sedimentary sequences that have infilled the Perth Basin, the Warnbro Group represents terrestrial to shallow marine sedimentation deposited during the early cretaceous, and consists of the Gage Formation, South Perth Shale and Leederville Formation. This succession overlies the Jurassic syn rift sedimentary sequences of the Cattamarra Coal Measures, Yarragadee Formation or the Parmelia Formation on an erosional Neocomian (early Cretaceous 146 – 125 Ma) unconformity surface (Davidson, 1995).

The Leederville Formation is the largest portion of the Warnbro Group and was deposited after the Gondwanan continental breakup of Australia and India and the subsequent opening of the Indian Ocean. The development of the Western Australian passive margin at this time resulted in a change in drainage patterns and sediment provenance, from that of a north to northwest axial pattern, to a westerly topographically driven direction that persists to the present day (Olierook *et al.*, 2019). The Leederville Formation sediments as described by Descourvieres *et al.* (2011) were deposited proximally to source in a paralic/lacustrine depositional setting. To the base of the Leederville Formation this depositional environment was found to exhibit marine influences with terrestrial influence's becoming dominant at the formation top. The local granitoids of the Yilgarn Craton are considered the primary source for sediment of the Leederville aquifer in the Perth region. Leyland (2011) has divided the Leederville into five sequence stratigraphic units determined by correlation of common erosional/discordant surfaces. This has allowed stratigraphic units to be categorised into a common chronostratigraphic framework that reflects identifiable depositional conditions. These stratal packages from Leyland (2011) are as follows:

Gage Formation (Kwg)

A sand-rich sedimentary unit that was deposited from Valanginian to Early Hauterivian in moderate energy marine conditions.

South Perth Shale (Kws)

The South Perth Shale is a mud rich sequence that fines upwards and was deposited during a rise in relative sea level and a deepening of depositional conditions during the Valanginian to Early Hauterivian.

Mariginiup Member (Kwlm)

A mud-rich prograding delta front facies deposited as a fall in relative sea level occurred during the Early Hauterivian deposition of the Mariginiup Member.

Wanneroo Member (Kwlw)

As the Wanneroo Member was deposited in the Late Hauterivian an abrupt regional shallowing of depositional conditions occurred. This resulted in an influx of river-borne sediment from the north-east**.** This sediment influx resulted in the deposition of the heterolithic delta plain facies of the Wanneroo Member, (figure 2). The fall in sea level also resulted in the incision of 3-50m deep distributary valleys. These distributary valleys were then filled with channel fill sediment creating laterally extensive sand bodies of 5-10km. Due to the presence of well-connected sand bodies, the Wanneroo Member is the highest yielding sedimentary sequence within the Leederville Aquifer and is heavily exploited. It increases in sand content from east to a west.

The Wanneroo can be broken down from east to west into four broad north south trending stratigraphic units, these have been identified by Leyland (2011) as follows**:**

- Eastern Zone - A non-tidally influenced Fluvial Channel FA1 and Fluvial flood plain FA2.

- Central Zone – High sand content tidally influenced distributary channels (FA5), intertidal interdistributary bay’s (FA6) and subtidal interdistributary bays (FA7).

- Western Zone - Prograding delta front consisting of subtidal interdistributary bay (FA7) to tidal mouth (FA4). Tidally influenced stacked distributary Channels (FA5).

- The Wave - Influenced upper and lower shore face facies (FA3) are also of interest.

Pinjar Member (Kwlp)

From the Barremian to Early Aptian, a prograding wave dominated delta supplied with sediment from the Yilgarn craton to the east formed as sea levels rose after deposition of the Wanneroo Member. The sands deposited at the prograding shore face to the east represents a bedload type deposition with suspended silts and sands deposited further offshore resulting in the deposition of stacked silt rich bars.

1.4 Leederville Aquifer

The Leederville Formation comprises of the Pinjar, Wanneroo, Mariginiup members of the Warnbro Group and contains a high sand percentage and is considered a significant semi-confined groundwater resource for the Perth region (Davidson, 1995). Typically the potentiometric head distribution within the Leederville aquifer is on a broad shallow gradient from the north east to the south west (figure 3).

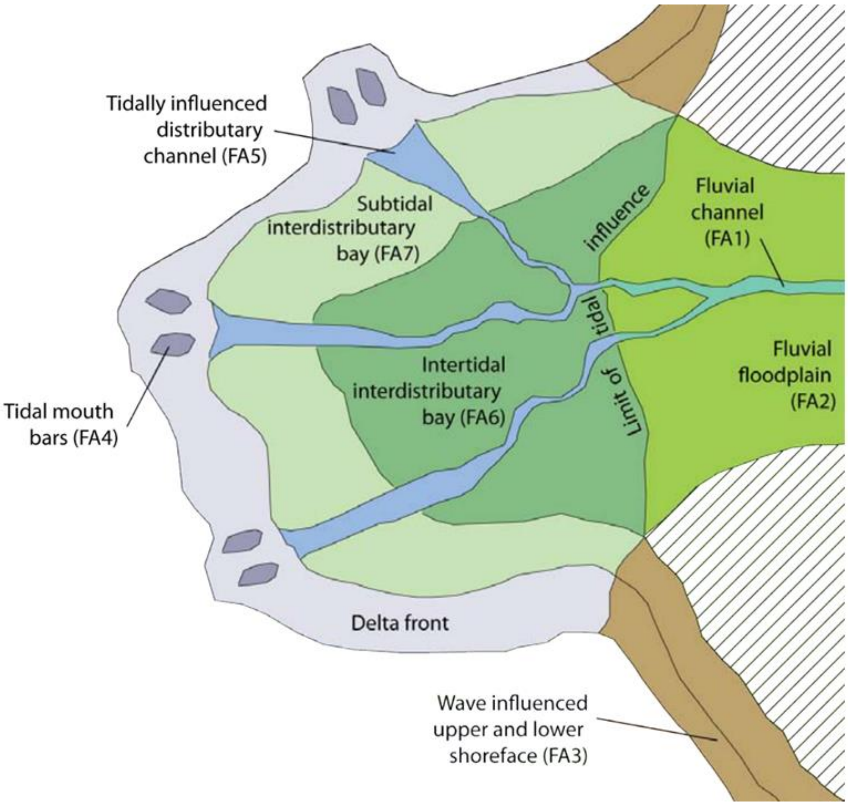


Figure 2 Conceptualisation of the Wanneroo Member Leederville Aquifer, Leyland (2011).

Hence forth the Leederville Formation will be referred to as the Leederville Aquifer in the context of these three sedimentary members. The sandstone units as described by Davidson (1995) that comprise the Leederville Aquifer vary in thickness. They comprise of poorly sorted sands fine to coarse grained, and angular to subangular in shape. Individual units are typically between 6 and 20 m thick, but south of Perth may reach 60 m in thickness. The author also recognised that the thickest sandstone beds are not always featured in the areas of greatest formation thickness. The Wanneroo Member as described by Leyland (2011) is the most significant component of the Leederville Aquifer, it is 100-400m thick and is comprised of tidally influenced sand bodies interpreted to represent a delta plain deposit.

Due to the rapid population and economic growth that the SWWA has undergone and the climate continuing to trend along the drier of modelled climate scenarios, there has been increased demand and reduced recharge to the groundwater resources within the SWWA (Ali *et al.*, 2012). This increased stress is compounded where the confined aquifers are connected to the Superficial Aquifer such as within the extent of the Gnangara mound, where the environmental impact of abstraction under changing climatic conditions is expected to be the greatest.

This reduced recharge, along with the increased demand from population growth, requires careful management to ensure that the many competing demands on the groundwater resource are met. This is an important consideration as the persistence of a hotter and drier climate will place a greater reliance on groundwater into the future. With the modelled increase in temperatures, surface water storages come under increased pressure due to decreased run off. This increased heat will also require increased irrigation rates to maintain vegetation growth during the summer months; these factors will exacerbate this issue of resource demand management due to population growth.

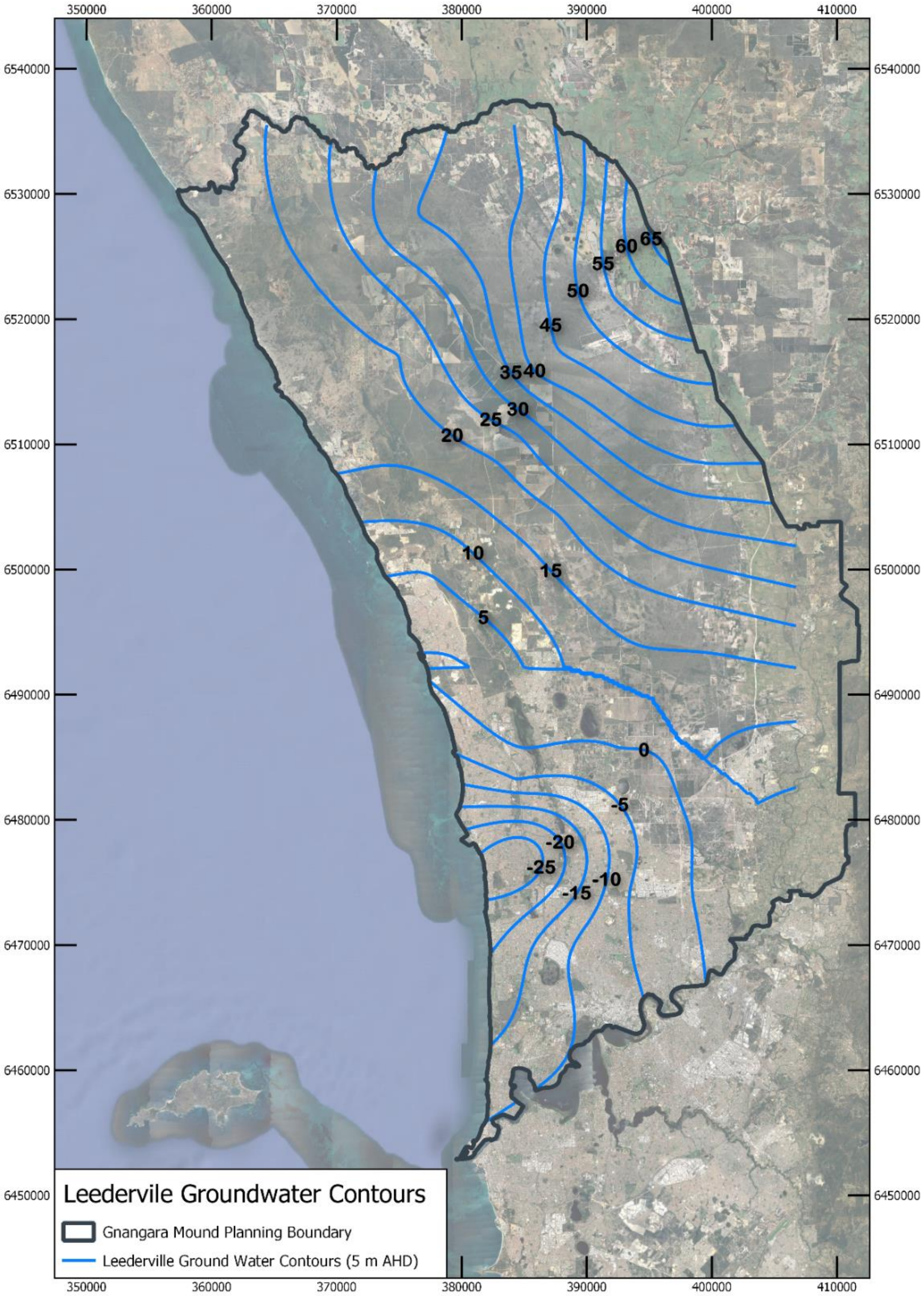


Figure 3 Regional Hydraulic flow within the Gnangara Mound extent of the Leederville aquifer.

1.4.1 Management Issues

The reduced rate of recharge has resulted in reduced storage, resulting in an overall potentiometric head reduction within the shallow unconfined aquifer. As a result there has also been acidification and seawater intrusion into the surficial aquifer along with impacts to ground water dependant ecosystems (GDEs). (Clohessy, 2014). Due to this increasing stress on the system, detailed water-balance studies of the unconfined aquifers were initiated in the 1980s, the results of which resulted in the licensing of non-domestic groundwater use being extended across all of the Perth Region (Davidson, 1995).

Changes in pressure within the Leederville and the Yaragadee aquifer have an impact on the unconfined superficial system, predominantly where confining units are absent. These impacts are highlighted by Karelse *et al.* (2019), who state the vital need to improve understanding of the interconnectivity between the surficial aquifer and the deeper aquifers within the Perth basin. The authors have identified that with increased abstraction from the deeper aquifers from the mid-nineties onwards there has been a reduction in pressure, resulting in both the Leederville and Yaragadee aquifers achieving new static levels. The authors state that where connectivity to the superficial aquifer is present the positive pressure exerted by the Leederville and Yaragadee aquifers on the superficial aquifer helps to reduce leakage from superficial to connected Leederville Yarragadee systems.

This variation in aquifer pressure can be managed through the adjustment of abstraction rates and aquifer storage and recovery schemes (Karlse *et al.,* 2019). For these to be effective mitigation methods, a greater understanding of the groundwater flow systems in the Leederville and Yaragadee aquifers are required. This is especially relevant to flow barriers that act to compartmentalise the aquifers such as faults and local geological discontinuities.

This increased stress upon surface water and shallow groundwater resources over at least the last 30 years has increased demand upon the deeper potable groundwater resources from the Leederville and Yarragadee aquifers. Due to this increased pressure, the need to improve the management of the deeper groundwater resources is becoming increasingly apparent as balancing the needs for potable water, the preservation of cultural amenity and environmental concerns (GDEs) are becoming increasingly difficult (Clohessy, *et al.,* 2014).

1.4.2 Management Strategies

To effectively manage Perth's water supply the integrated water supply scheme (IWSS) was instigated. From the 1900's the IWSS sourced all of its water from dams that were heavily reliant on stream flow with stable rainfall run off. Now as the impacts of climate change are becoming increasingly evident with a drying climate the water source of potable water for the IWSS has had to diversify. As of 2019/20 to breakdown for this water source is as follows 43% Desalinated Water, 39% Groundwater, 15% Rainfall and 3% groundwater replenishments, (Water Corp 2020)

Despite groundwater currently only contributing 39% of total requirements, it is expected that Managed Aquifer Recharge (MAR), particularly in relationship to recycled water sources will play an increasing role in maintaining the required demand from the IWSS into the future. (Department of Water, 2014, Water Corp, 2020). The development of MAR schemes utilising the deeper semi-confined aquifers (Leederville) will act to climate proof the water source if the future dry trends play out. This provides an opportunity as a management tool to balance pressures within the confined aquifers (Clohessy, *et al.*, 2014). An improved understanding of the groundwater system and how aquifers are connected will be required to properly manage the current and expected stresses to the groundwater system as a whole (Department of Water, 2017). To this end via consolidation of various subsurface data sets the Perth Region Confined Aquifer Capacity (PRCAC) study was initiated to improve the conceptual understanding of the groundwater system and to address regional scale groundwater management issues as follows (Department of Water, 2017):

- A decline in groundwater levels and reduced storage in the superficial aquifers.
- A decline in potentiometric heads in large areas of the Leederville and Yarragadee aquifers.
- Reduced water availability to numerous GDEs of conservation value; and increased potential for groundwater acidification and seawater intrusion in the superficial aquifer.
- Investigate the potential groundwater resources that are outside of the current IWSS and better optimise groundwater use in the current IWSS network.
- Better qualify the impacts and benefits of potential managed aquifer recharge (MAR) and assess the depth of fresh water and manage movement of the seawater interface in the deep aquifers.

Due to the complex confined (semi-confined) nature of the Leederville and Yarragadee aquifers further work will be required to improve understanding of how the impact of this complex geology will impose upon the MAR efforts, especially within the Wanneroo Member of the Leederville Aquifer.

1.5 Problem Statement and Research Aims

Tidally influenced deltas are described as complex heterogeneous systems that can be compartmentalised by sedimentary depositional relationships of varying scales which can truncate the high conductivity sand bodies within. This apparent compartmentalization of sand body interconnectedness is a very large source of uncertainty in complex heterogeneous aquifers, as this interconnection (or disconnection) of high conductivity material can result in varied fluid pathways, (Galloway and Hobday, 1996; Fogg, 1986).

1.5.1 Problem Statements

Due to a tidally influenced depositional environment attributed to the Leederville aquifer (Leyland, 2011), an understanding of the distribution of matrix poor (and matrix rich) lithologies is important if the degree of compartmentalisation and the associated impacts on groundwater flow is to be understood and addressed. This is especially so when developing conceptual and numerical models of the aquifer. The interconnectedness of the coarse-grained size fraction has the strongest influence on the spatial variation in hydraulic properties within an aquifer (Koltermann and Gorelick, 1996; Miall, 2015). Therefore a means to understanding the inter-connectedness and spatial variability of the higher conductivity sediments within the Leederville Aquifer is clearly important from a resource management perspective.

In some sections, especially in the eastern and central zones, the Leederville aquifer can be observed to have high geologic intra hole variability between downhole geology logging (Leyland, 2011). There is also evidence of facies boundaries within the Leederville that may act as permeability barriers within the aquifer which may influence flow regimes at a local scale (Water Corp, 2009, 2011 and 2016) as well as regionally (Department of Water, 2017).

As sediments deposited in tidally influenced deltas such as the Leederville aquifer can be highly heterogeneous in nature due to the inherently high incidence of textural juxtaposition is these depositional environments. Aquifer heterogeneity is not always apparent when data is attained from a limited number of points. Consequently, hydraulic conductivity determined for an aquifer may not be reflective of the geological complexity. This study will utilise data from the Department of Water and Environmental Regulation (DWER) and the Water Corporation with the aim of investigating the extent of sand body connectivity within the Wanneroo Member at the Beenyup Recharge site. To undertake this work the following questions will guide the research effort for this project.

1.5.2 Research Aims

1. To what extent are the sand bodies within the (Wanneroo Member) Leederville aquifer connected (or disconnected) at the Beenyup study site. Are there spatially persistent boundary conditions evident due to the depositional setting and grain size variation that may impede flow and act to compartmentalise the aquifer.

2. What impacts could this sand body interconnectedness (or disconnection) have on fluid flow and solute transport rates at the Beenyup MAR sites. What are the potential issue for management of

the resource and what could be the implications for aquifer storage and recovery efforts and the IWSS.

2. LITERATURE REVIEW

2.1 Introduction

Sanchez-Vila, Guadagnini and Carrera (2006) state it is the presence of connected high conductivity zones that will have the biggest influence on groundwater flow within an aquifer. The authors state that it is the manner in which these high conductivity zones are connected that will influence the overall transmissivity of a heterogeneous system. They state that the observed geology of aquifers suggests that high conductivity zones exhibit a higher degree of interconnectedness than do average and or low connectivity zones. This variable connectivity is inconsistent with multi-gausian assumptions made in many theoretical assessments of aquifer connectivity.

Investigating this control of connectivity further, Neild (2008) developed a simple model to explain the apparent control high conductivity zones have on bulk transmissivity values. The author proposed that if a high conductivity (low resistivity) conduit is present in a domain in the direction of flow of the system then the effective resistance of the system will be low (high transmissivity), regardless of the conductivity of the surrounding material. Sanchez-Vila, Guadagnini and Carrera (2006) concluded that the development of geologically realistic conductivity fields is needed to better understand the practical implications of connected high conductivity networks have on groundwater movement in aquifers and that these improved conductivity fields should be used in conjunction with stochastic approaches in future investigations.

2.2 Geologic Heterogeneity in Sedimentary Aquifers

The work undertaken by Fogg (1986) within the complex sedimentary Wilcox aquifer described the discontinuous nature and complex three-dimensional structure of the sand bodies within the aquifer. From this work the author determined that lateral well-connected sands influence groundwater flow differently than variably-connected sand bodies. Due to this variable hydraulic interconnection of sand bodies the author states that there is a need to incorporate geologic data into groundwater models. As models calibrated to hydraulic head cannot be assumed to depict hydraulic continuity within an aquifer, consequently, the model may lack the necessary detail to infer fluid and solute transport processes.

This geologic heterogeneity at the facies scale can also be described as macro scale heterogeneity. In aquifers Hobday and Galloway (1996) describe site specific heterogeneity (Macroscopic heterogeneity) as the delineation of all the transmissive and bounding units in a three-dimensional volume. These macroscopic heterogeneities include the following:

Aquifer compartmentalisation - Can occur where vertically and laterally deposited facies within a sequence can be separated by bounding depositional or erosional surfaces. In these environments most sand bodies are considered to be three-dimensional composite of individual facies within the system.

Permeability distribution – Textural gradients due to vertical and lateral variation can impart a distinct permeability distribution within an aquifer. Sandstone facies may have distinct structures (bioturbidation) that influence permeability with an aquifer. The impact of textural variation can occur within depositional settings, for example, where high permeability coarse grained units are juxtaposed against fine grained, low permeability units.

Stratification – Horizontally interbedded facies can form sheetlike, lenticular units that can be separated by permeability changes (mud drapes) between neighbouring units. This type of horizontal bedding can impart a high degree of anisotropy into the aquifer system.

To better account for this heterogeneity in the modelling of complex sedimentary aquifers, Anderson (1989) defined the concept of hydrofacies. The Author described hydrofacies as “a homogeneous but anisotropic unit that is hydro geologically meaningful for purposes of field experiments and modelling”. In this work Anderson (1989) states there are two definitions of what constitutes a hydrofacies in a sedimentary aquifer. They can be considered as either an ordered (layered) sedimentary sequence or as a highly disordered sequence contained in a matrix of finer material.

These observations regarding geologic heterogeneity are reinforced by Poeter and Gaylord (1990). The authors state that utilising standard lithofacies models to interpret the hydrogeologic features within a sedimentary aquifer can be useful. However, they recognise post depositional events such as erosional reworking of sediments that destroy the original depositional fabric can greatly impact the hydraulic properties of the original lithology.

To improve the relevance of geologic data into modelling efforts the authors recognise the need for the inclusion of geologic parameters that are correlated with hydraulic properties, for example, particle size distributions and degree of cementation. The inclusion of the hydraulically relevant properties the authors argue should be considered an improved means of identifying lateral and vertical interconnectedness, compared to just a qualitative textural description of the lithofacies.

2.3 Importance of High Conductivity Facies

Marsily and Gonçalv (2005) state that the way in which heterogeneity in hydrogeology is dealt with can be improved. The authors claim this is evident in the way geological features are typically homogenised in hydrogeology, which is an approach they claim has some limitations. The authors stipulate that detailed studies are required on out cropping analogues with comparison of facies models to the characterised study sites. For these studies to be effective all the (hydro) facies need to be identified including the high and low conductivity as well as the intermediate mixed texture facies. This is essential along with developing methods to determine material properties at the facies scale.

Via three-dimensional modelling of heterogeneity at the facies scale in a braided gravel alluvial aquifer, Zappa *et al.*, (2006) demonstrate the importance of understanding the distribution of high conductivity facies within an aquifer. The authors determined it was not only the proportion of the high conductivity facies, but the organisation of those facies that controlled preferential flow. In this modeling study Zappa *et al.*, (2006) identified that the connectivity of the most permeable units is controlled by conductivity contrasts between textural changes and the relative abundance and number of facies. As such it was observed that domains with low proportions of high conductivity facies could still have a large impact of groundwater flow due to the facies depositional fabric favouring connectivity.

Fogg and Zhang (2016) also clearly state that deriving an understanding of the aquifer geology is vital as without it the important characteristics can be misinterpreted or not identified. This is apparent in the study undertaken by Bianchi *et al*. (2016) where a sedimentary textural analysis of the heavily studied research site known as the Macro dispersion Experiment (MADE) in Columbus (Mississippi, USA) resulted in the identification of a previously unknown highly connected high conductivity facies. The identification of this high conductivity facies has in some ways explained the anomalous behaviour of the plume that had been studied at the MADE site for over a 30 year period.

2.4 Aquifer Connectivity

In clastic sedimentary aquifers where geologic discontinuities such as faults and unconformities are not prevalent, geologic facies that comprise at least 18% of the total system volume have a tendency to percolate and form connected pathways in three dimensions (Fleckenstein and Fogg, 2008). Fogg *et al*. (2000) state that this concept of a three-dimensional connected network can be useful where the traditional “layer cake” style aquifer conceptualisations are utilised. In these scenario’s vertical connection between layers is typically assumed to only occur via leakage between adjacent units. Whereas if a connected network in three dimensions is considered it is the higher permeability sediments that provide the significantly greater fluid pathways between zones, than otherwise would occur by “leakage” in the standard layered conceptualisations. This is significant in that contaminate transport models based on the traditional layer cake models will result in inaccurate results.

Fogg *et al.* (2000) have identified that the over reliance of analytical test pumping models in geologically complex aquifers typically results in an oversimplification and underestimation of the inherent heterogeneity of the aquifer. However, it is recognised that this oversimplification may not be detrimental to groundwater flow modelling and will more so have an impact on contaminant transport models. The authors identify that the estimation of log – k variance which is reliant on traditional field tests and typically ignores hydro facies will be too low if the leakage is more so via the connected network of high K facies than slow leakage across laterally extensive aquitards.

Knudby and Carrera (2005) identify the need for quantitative measures of connectivity for flow and transport studies in complex sedimentary aquifers. The authors recognise that there is a conceptual difference between flow and transport connectivity and as such connectivity within aquifers should be considered process dependent. The authors found that flow connectivity metrics are more sensitive to aquitard material within an aquifer than were the transport connectivity metrics.

This importance of aquifer connectivity is reinforced by Renard and Allard (2013), who confirm that connectivity strongly influences groundwater flow and transport processes. However, they determine that connectivity itself is not sufficient to completely describe the processes within a groundwater system. The authors indicate that the extent to which the hydro stratigraphy is connected or disconnected, including the facies proportions and the geometry of the sand bodies is extremely important because it controls indirectly the degree of connectivity.

2.5 Impact of Geologic Heterogeneity on Aquifer Modelling

Through the groundwater modelling process, it is the initial conceptual model that provides the foundation for developing the numerical model then used to solve the groundwater problem at hand (Anderson *et al*., 2015). Considering this, it is reasonable to state that the greater extent to which the conceptual model captures the natural state of the site under investigation including the geologic heterogeneity, the greater the forecast accuracy of the resulting numerical model.

In their review of the current literature, Enemark *et al*. (2019) concluded that the current hydrogeological model prediction methodology assumes there is a single conceptual outcome. They state that there needs to shift towards considering a range of outcomes (stochastic), and also that it has to be acknowledged that unknown unknowns exist. As conceptual issues are uncovered alternative conceptual models should be developed that can be falsified. Enmark *et al.* 2019 consider hypothesis testing as essential in avoiding conceptual surprises in the modelling process.

This process of utilising multiple models to Improve the conceptual understanding have been utilised in the model testing and evaluation of predictive errors within the Valco San Paolo area by La Vigna *et al.* (2014). The authors have determined that although the use of a single model may result in reduced uncertainty and increased confidence in the model simulations, is very likely prone to statistical bias. Therefore they state it is best to develop multiple alternative conceptual models and scenarios to obtain predictions that are more realistic.

From aquifer model calibration and geostatistical studies, Koltermann and Gorelick (1996) describe how increasing the amount of information about aquifer behaviour to the calibration procedure can produce a better definition of heterogeneity.

In work undertaken on geologic uncertainty in groundwater flow models Refsgaard *et al.*, (2012) found that if predictions are confined to the same variable used for calibration and if under a similar climatic and abstraction regime. A hydrogeologic model is less sensitive to geologic heterogeneity within the aquifer. In these situations the authors claim the unknown errors inherent within the geologic interpretation can be compensated for. The authors identify there is a caveat that is; if the groundwater model is extrapolated past its calibrated base, geologic uncertainty will start to impart a large impact on prediction accuracy.

This impact on forecast accuracy imposed by geologic heterogeneity is observed in contaminant transport and future climate and abstraction demand modelling where Refsgaard *et al.*, (2012) state that if the only data available for calibration are head and flow rates, and the extrapolation occurs outside of the calibration base, it is highly likely that geologic heterogeneity will become the dominant source of uncertainty in the model.

2.6 Geostatistical Modelling of Aquifer Heterogeneity

The primary mathematical models used in investigating the natural sciences as described by Renard, Alcolea and Ginsbourger (2013) can be grouped into three broad categories and described as either statistical, deterministic or stochastic in nature. These modelling approaches have traditionally been utilised separately with some rivalry. However the authors state these approaches should be viewed as complimentary and used together. Renard, Alcolea and Ginsbourger (2013) outline how these three model types should be utilised at different stages of a project, as no one single characterisation of a system will adequately describe the inherent complexity within. A point that is made by the authors is that complex patterns at a small scale are difficult to model deterministically as the number of unknown parameters is overly large.

A geostatistical approach to account for geological uncertainty is reinforced by Marsily *et al*. (2005) in a review of heterogeneity in sedimentary aquifers. The authors identified that the Markov Chain transition probability approach is a simple and flexible means to account for spatial cross correlation such as juxta positional relationships and finning upwards tendencies of different facies compared to other geostatistical approaches for modelling complex heterogeneous aquifers. Marsily *et al.* (2005) state that one of the primary advantages of the Markov Chain transition probability method is the is that it ensures that a specific facies can be preferentially found close to another facies as is the case with sedimentological principles.

In lithology modelling studies Weissmann and Fogg (1999) show that incorporating the transition probability methodology that is applied in TPROGS along with sequence stratigraphic modelling can be advantageous.

In this study it was found that published stratigraphic information could be easily incorporated into the transition probabilities as soft data. This resulted in the preservation of fining upwards, tendencies of fluvial deposits, the fining outwards tendencies of channels and the preservation of facies continuity along depositional dip directions (Weissmann and Fogg, 1999).

In comparison studies between TPROGS and other geostatistical models Lee, Carle and Fogg (2007) show the applicability of the transition probability approach. The TPROGS output preserved the spatial structure of the data, with a high level of conformance to geologic processes. The realisation were also shown to exhibit a large variance in log K due to the tendency of TPROGS simulations to include both aquifer and aquitard materials. The authors have also shown that the realisations generated by TPROGS were better at creating hydraulically connected networks with a strong spatial continuity in channel deposits compared to a gaussian based methodology.

A study utilising transition probability geostatistics by Fogg *et al*. (2000) involved the simulation of the alluvial basin within the Lawence Livermore National Laboratory (LLNL) California USA. The effective hydraulic conductivity was found to be sensitive to facies architecture with the facies juxta positional tendencies asserting a dominant influence on the preferential fluid flow pathways. The authors were also able to determine that observed draw down at wells exhibited a high sensitivity to the presence of aquitard materials within the LLNL study area.

Langousis *et al.* (2017) have tested the applicability of Markov based transition probability geostatistics in a two-dimensional form against a large number of stochastic realisations. The authors consider that as aquifers are complex and three-dimensional, the simple two-dimensional test case allowed a direct comparison between stochastic realisations between different modelling runs. The result of this testing revealed that the Markov chained transition probability methodology does simplify assumptions. From this review Langousis *et al.* (2017) conclude that although this methodology can be easy to implement and understand there are other methodologies that could be more applicable depending on the nature of the hydrological system under investigation.

Fogg, Noyes and Carle (1998) identify that this categorical approach to characterising aquifer geologic heterogeneity is not without problems. Some geologic units can be misidentified and the inherent geologic variability is not necessarily accounted for due to the limited number of hydrofacies categories allowed, and the hydraulic conductivities for each hydrofacies may not be easy to estimate. Despite these stated caveats the authors claim that the transition probability approach is better than other approaches that utilise interpolation and or kriging of conductivity and transmissivity values. As these approaches due to typically high intra well geologic variability typically lead to the unrealistic smoothing of the hydraulic property heterogeneity within the aquifer.

2.7 TPROGS Implementation

2.7.1 Overview

The transition probability approach of the TRPOGS software utility is an effective means of representing the inherent complexity of clastic sedimentary aquifers via conditional (stochastic) simulation of the spatial distribution of categorical variables (Carle, 1999). This transition probability approach has advantages over the traditional indicator kriging geostatistical methods common in other resource management fields such as minerals extraction (Jones, Walker and Carle, 2005). This is because transition probability is better at accounting for the asymmetry in geologic data than the indicator cross variogram. Therefore, unlike with kriging, the transition probability geostatistic approach can incorporate observable geologic attributes (Carle and Fogg, 1997). These obervable geologic attributes are described by Carle and Fogg (1997) as:

- Volumetric proportions
- Mean thickness and geologic unit (lens) length
- Juxta positional tendencies between the units
- Vertical and horizontal Anisotropy

This capacity to include geologic observation into the geostatistical model not only improves the understanding of spatial continuity but also helps in the development of models that are realistic in a geologic context especially when data is sparse or non-existent (Jones, Walker and Carle, 2005), (Carle and Fogg, 1996), (Carle and Fogg, 1997).

2.7.2 Conditional Simulation

Carle (1999) identifies that conditional simulation is quantitatively analogous to constructing a 2D geologic cross section between bore holes, that requires a reconciliation with the observed geologic phenomena before an acceptable geologic representation can be achieved. The author states that if geostatistic realisations are not reconciled against geologic phenomena then although equably probable in a stochastic sense they may well be highly improbable and of no practical use.

In He *et al.* (2014) the authors describe three key steps for developing a stratigraphic model utilising TPROGS. These steps are:

1. Obtain the transition probabilities from the observed data (bore hole data).
2. Representation of spatial variability observed in in x, y and z (up) directions by the development of Markov chain models.
3. Sequential indicator Simulations (SIS) and quenching used to stochastically generate the geologic realisations.

2.7.3 Transition Probability

To determine the strike (x) dip (y) transition probability for the hydro facies, the vertical (z) transition probabilities need to be developed, (GMS, 2016). To initiate this Carle (1999) states that a sample matrix is developed in the z up direction, representing the probability of the transition from material j to material k.

$$\boldsymbol{t_{jk}(h) = \mathrm{Pr}(k\ occurs\ at\ x + h|j\ occurs\ at\ x)} \qquad \textbf{Equation 1}$$

Where x is spatial location, h is the lag and j and k represent the hydro facies categories to be simulated. Carle (1999) gives the definition for this as “if facies j is present at location x then what is the probability that another or same facies k occurs at location x + h”. Schematically this can be observed in figure 4 from Carle (1999) bellow.

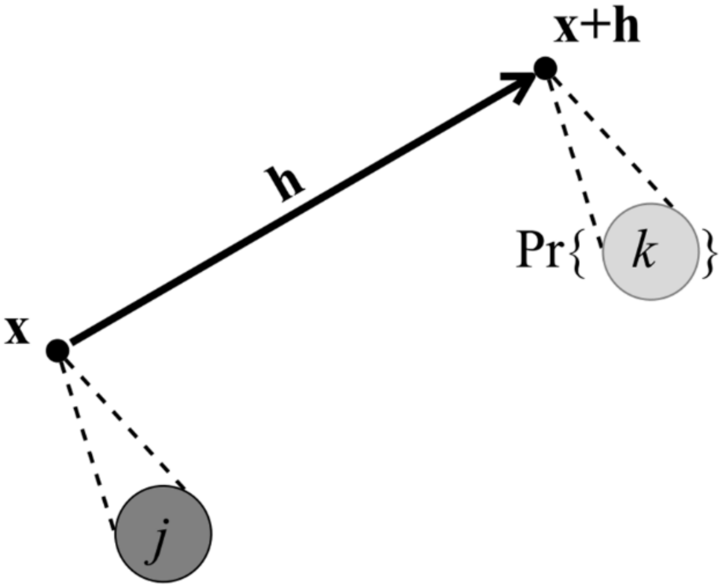


Figure 4 Transition probability schematic (Carle 1999).

In TPROGS the spatial statistics for the hydrofacies units are generated via the GAMEAS utility which calculates the transition probability, covariance and variagram. This utility then develops a sequence of transition probability curves as a function of lag distance for each category for a given sampling interval (Carle, 1999; (Jones, Walker and Carle, 2005).

As observed in figure 2 the self transition curves on the diagonal start at a probability of 1.0 and decrease at distance. The off diagonal curves start at a probability of zero then increase with distance. Where the curves flatten represents the mean proportion of the material, with all curves of a column flattening out at the same column, (GMS, 2016). The lag distance is where the tangent line taken from the start of the curve intersects at the horizontal, this intersection represents the mean lens length of the hydro facies.

The slope at the beginning of each Markov chain represents the transition rate. These combined mean lens lengths, proportions and transition rates define the Markov chain (GMS, 2016). With the transition probabilities in the z up direction generated, the Markov chain model needs to be developed for the strike, dip and vertical datasets dataset (Jones, Walker and Carle, 2005).

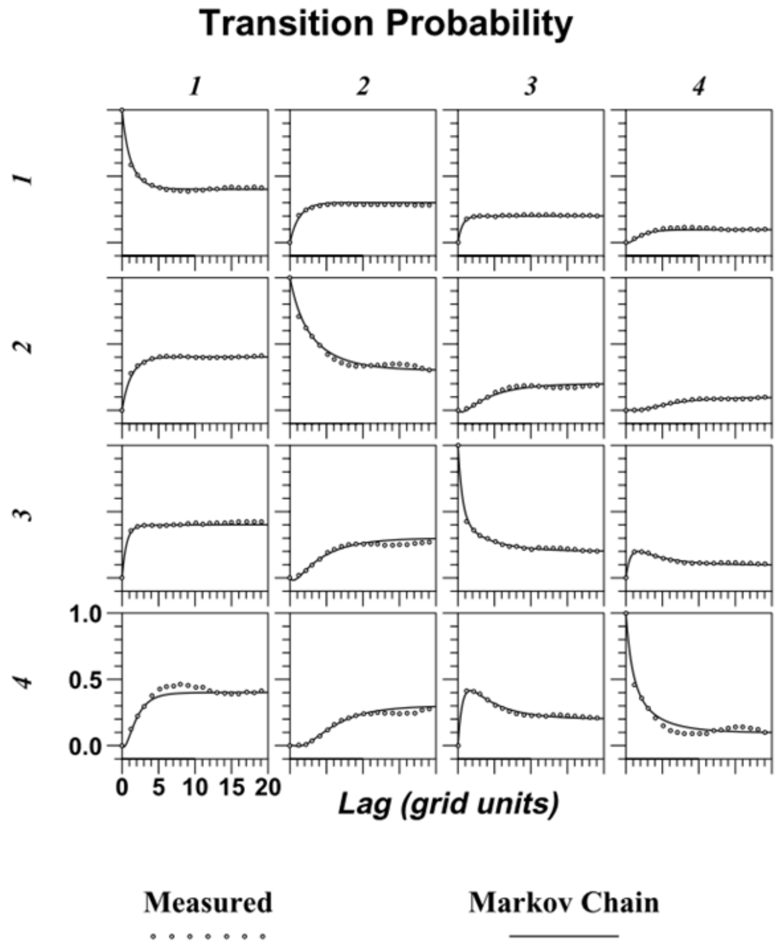


Figure 5 Transition probability curves (Carle 1999).

2.7.4 Markov Chains

To generate the facies realisation in TPROGS, three-dimensional Markov chain models need to be developed (GMS, 2018). As Markov chain models represent the spatial variability inherent within the transition probabilities derived from the data set (He *et al.*, 2014), they can be utilised to determine the mean lens lengths and proportions of the down hole lithology. In developing the Markov chain models the objective is to fit the curves as accurately as possible to the measured transition probability curves derived from the borehole geology, (GMS, 2018).

Krumbein (1969) states that in geology the application of a Markov chain assumes that the lithology at each point is wholly dependent upon the lithology at a preceding observation point. This statement implies that even if the data is sparsely distributed, lithology at a specific point will be dependent upon the nature of the depositional interface at a proceeding point (above or below within the z direction) than the lithology at a point further down (or up) the stratigraphic column. In this context Markov chains are considered useful for geology as they can identify subtle geologic relationships apparent in sedimentary deposits between two or more facies that would not otherwise have been observed (Miall, 1973). This applicability of Markov chains to account for geologic tendencies is, according to Carle (1999), apparent as they are a highly effective means to account for all spatial cross correlation in data. Carle (1999) also states that it is this capability that explains why Markov chains should be considered ideal for stochastic modelling of geologic categorical variables.

Although Carle (1999) recognises that implementing Markov chains is not an automatic process as geologic data does not exactly conform to mathematic and probability theory. The author states that Markov chains can facilitate the application of geostatistics by the following:

- Simplifying the application of co regionalisation models.
- Allowing the integration of geologic data.
- Ensuring that spatial variability models adhere to probability law.

In application when applied to one-dimensional categorical data, a Markov chain model can be described as:

$$T(h_{\emptyset}) = \exp(R_{\emptyset}\, h_{\emptyset})$$

Equation 2

Where $h_{\emptyset}$ denotes lag in direction ø and ø, and $R_{\emptyset}$ represents a transition rate matrix,(Krumbein, 1969)

$$R_{\emptyset} = \begin{bmatrix} r_{11,\emptyset} & \cdots & r_{1k,\emptyset} \\ \vdots & \ddots & \vdots \\ r_{k1,\emptyset} & \cdots & r_{kk,\emptyset} \end{bmatrix}$$

Equation 3

Within the transition rate matrix the entries $r_{jk\emptyset}$ represent the rate of change from category j to category k (conditional to the presence of j) (Jones, Walker and Carle, 2005).

Then, to achieve a fit between the Markov chain model and the observed transition probability model, the transition rates can be adjusted (Jones, Walker and Carle, 2005). With the development of the 1D vertical Markov chain from downhole borehole data, the spatial variability models can be developed for x and y by interpolating the Rø specified for each direction (Jones, Walker and Carle 2005), (Weissmann and Fogg, 1999). However the geologic data in x and y direction are typically not adequately closely spaced enough for discrete lag Markov chain modelling (Carle and Fogg, 1997).

To account for this low data density, TPROGS can incorporate Markov chains rate matrices developed from observed geological phenomena. The phenomena used by TPROGS to link vertical and horizontal transitions is the Walthers Law of sedimentary facies succession. Incorporating Walthers Law with the proportions determined in the vertical Markov chain model ensures that the inclusion of mean lengths and juxta positional tendencies are geologically plausible in the lateral directions (Jones, Walker and Carle, 2005).

From Lopez (2015) "Walther's Law states that any vertical progression of facies is the result of a succession of depositional environments that are laterally juxtaposed to each other". Lopez (2015) describes how Walthers Law simply implies that facies in the vertical and lateral directions are similar, that is, as depositional environments shift laterally sediments tend to stack vertically. The author describes how this facies shift in space and time results in related sedimentary environments becoming laterally superimposed thus creating vertical successions. This relationship confirms that vertical sedimentary sequences can be a record of sedimentary sequences that were deposited laterally. It is essentially this application of Walthers Law in the context of TPROGS that enables the transition rates in the horizontal direction to be derived from transition rates developed in the vertical direction (GMS, 2016).

There are different methods for fitting the Markov chains into the measured transition probability curves within the TPROGS utility. Some of these methods from GMS (2016) are discussed below.

Edit transition rates – This option allows the transition rates and means proportions to be edited. The proportion and rates for background material do not need to be defined. The proportion and transition rates for the background hydrofacies are adjusted so that the proportions sum to 1.0.

Edit embedded transition probabilities – For this option the conditional probabilities of geologic units that occur adjacently next to other geologic material in a specified direction is analysed by embedded Markov chains (Carle, 1999). The borehole data and the embedded transition probabilities are displayed as a matrix. The transition rates can be determined from the transition probabilities within this matrix.

Edit maximum entropy factors - With this option the on diagonal matrix are determined by the means lens length utilising the below relationship:

$$\boldsymbol{r_{kk,\emptyset}} = -\frac{\mathbf{1}}{\boldsymbol{L_{k\emptyset}}} \qquad \textbf{Equation 4}$$

In this equation, L is the mean lens length with the off diagonal term represented by the ratio of the transition rate to the transition rate for maximum entropy. Carle and Fogg (1997) state that in this equation the mean length of a category in the specified direction is the total length occupied by that category divided by the number of embedded occurrences of it, that is, the mean length in the vertical direction can otherwise be referred to as the mean thickness of the category. It should be noted this method is the default for editing the Markov chains in GMS.

If this is equal to 1 the probability that a given material is adjacent to another material is consistent with a random distribution of the material. This methodology represents the juxta positioning tendencies in the borehole data moving in the z up direction. This methodology allows the editing of transition rates and can allow the implementation of fining upwards tendencies into the TPROGS model (GMS, 2016).

Once the relevant method has been utilised to develop the vertical Markov chain model the Markov chain for the strike and dip (x, y) directions needs to be developed. To implement this process in TPROGS the respective 1D vertical and lateral Markov chains are then converted to a 3D Markov chain model using the MCMOD utility (Carle, 1999). The 3D Markov chain file generated by the MCMOD program is then utilised to inform the spatial variability model for the conditional simulation utility (TISM).

2.7.5 Simulation

Setting up a grid is the final phase of implementing a transition probability analysis utilising TPROGS. To create a number of realisations the TSIM utility is launched and the 3D Markov chains are used to formulate the indicator co-kriging and objective functions. The output from TSIM is a set of arrays of indicator values (figure 6) specifying the material ID for the corresponding grid (Carle, 1999). The author describes how the TSIM utility generates simulations of the transition probability through a two stage process as follows:

1) An initial configuration is generated using a co-krieging version of the sequential indicator simulation (SIS) algorithm of Deutsch and Journal (1992).
2) Improve the conditional simulation via iterative runs so as to match the simulated and modelled transition probabilities via a quenching (annealing) algorithm.

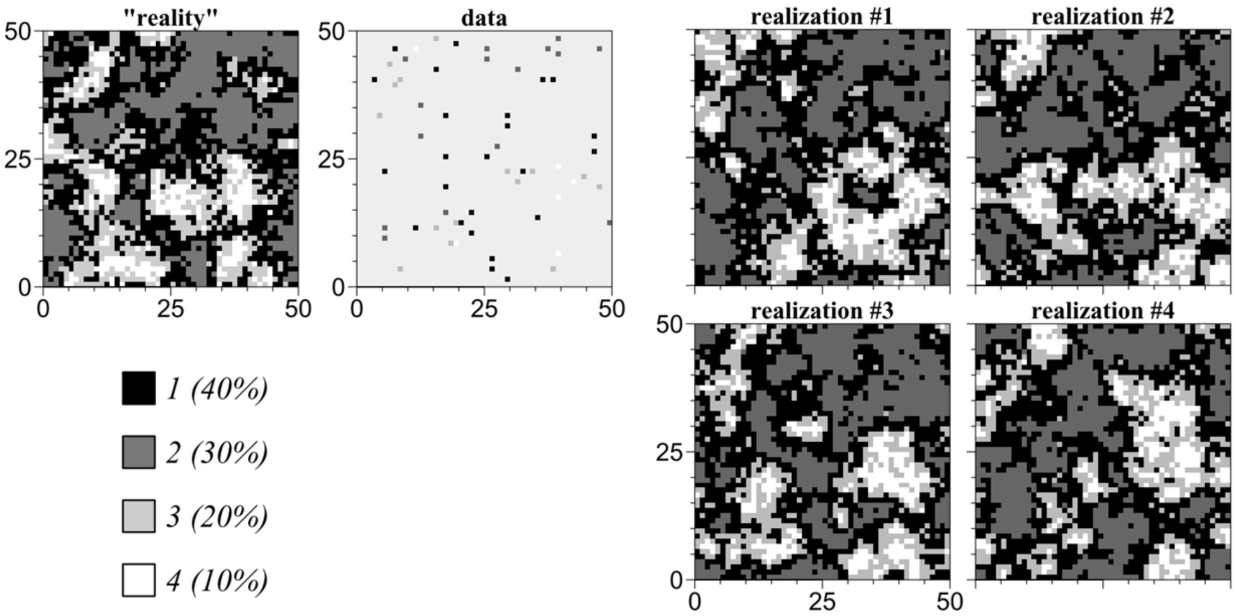


Figure 6 TPROGS simulation process

Carle (1999) states that this interdependent two step process is necessary as the first step (SIS simulation) will not produce stochastic realisations that adhere to a spatial variability model of the dataset, and the quenching algorithm not being effective without the initial rudimentary simulation being generated. The author describes how both of these steps can utilise the same Markov chain model and therefore can run in sequence.

3. METHODOLOGY

3.1 Beenyup study site

3.1.1 Site Description

This project on sand body connectivity within the Wanneroo member (Leederville Aquifer) is located at the site of Water Corporation's groundwater recharge facility within the waste water treatment plant in Craigie northern Perth suburbs, (figure 7). A highly detailed site characterisation study was conducted in 2009 by the Water Corporation with the drilling of a recharge bore (BNYP 03/07) and the construction of a nested series (n=22) of monitoring bores. Further work was conducted at the site in September 2014 to enable the recharge site to produce up to 14 GL/annum of purified water for recharge into the Leederville aquifer. This work included the drilling of a further two recharge bores (BNYP 2/15, BNYP 3/15) and monitoring bores (BNYP 02/12, BNYP 01/14, BNYP 01/15). Down hole geology data from the bores drilled in these studies were

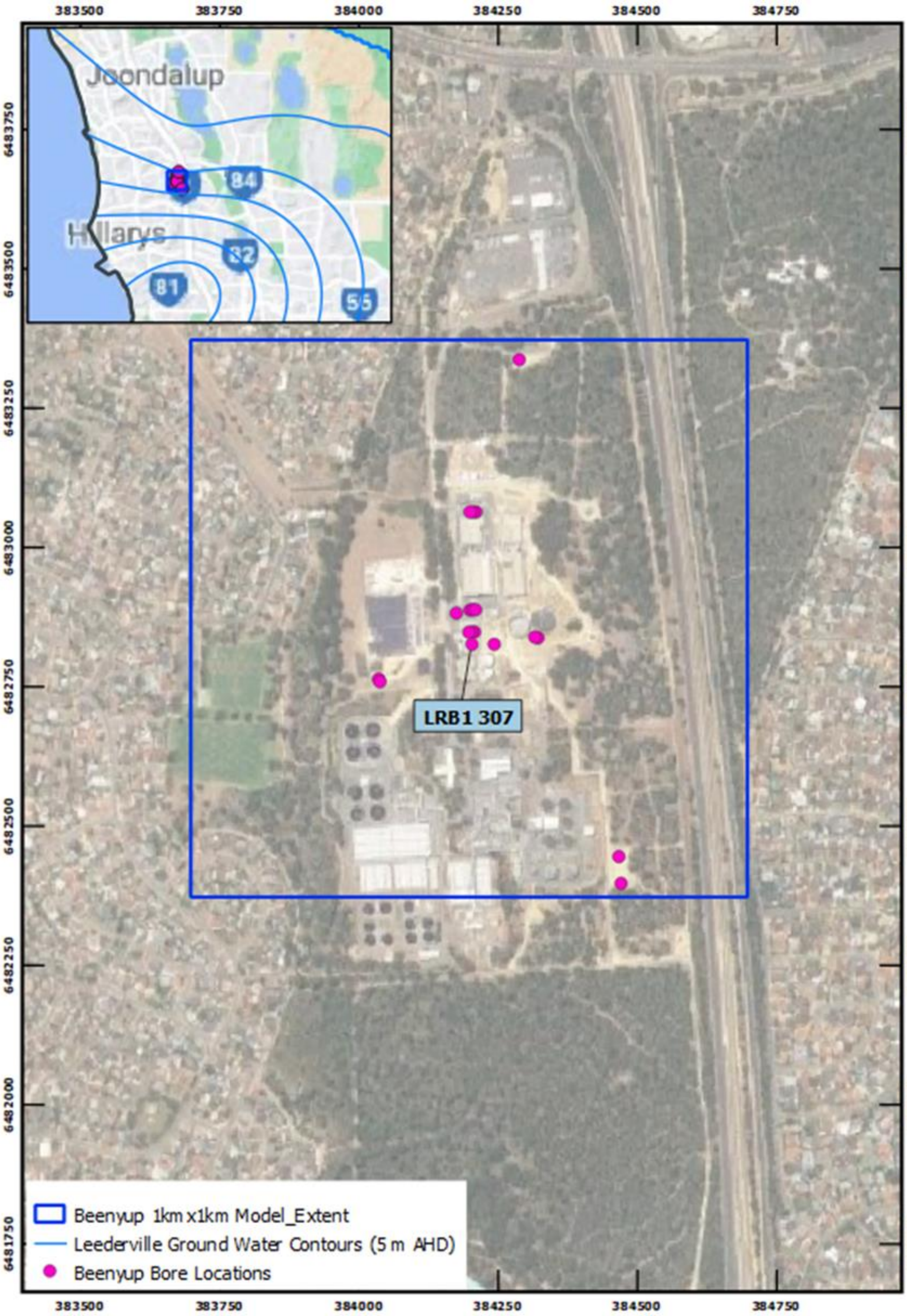


Figure 7 Location of the Beenyup site in the Northern Perth suburbs, and the extent of the model domain.

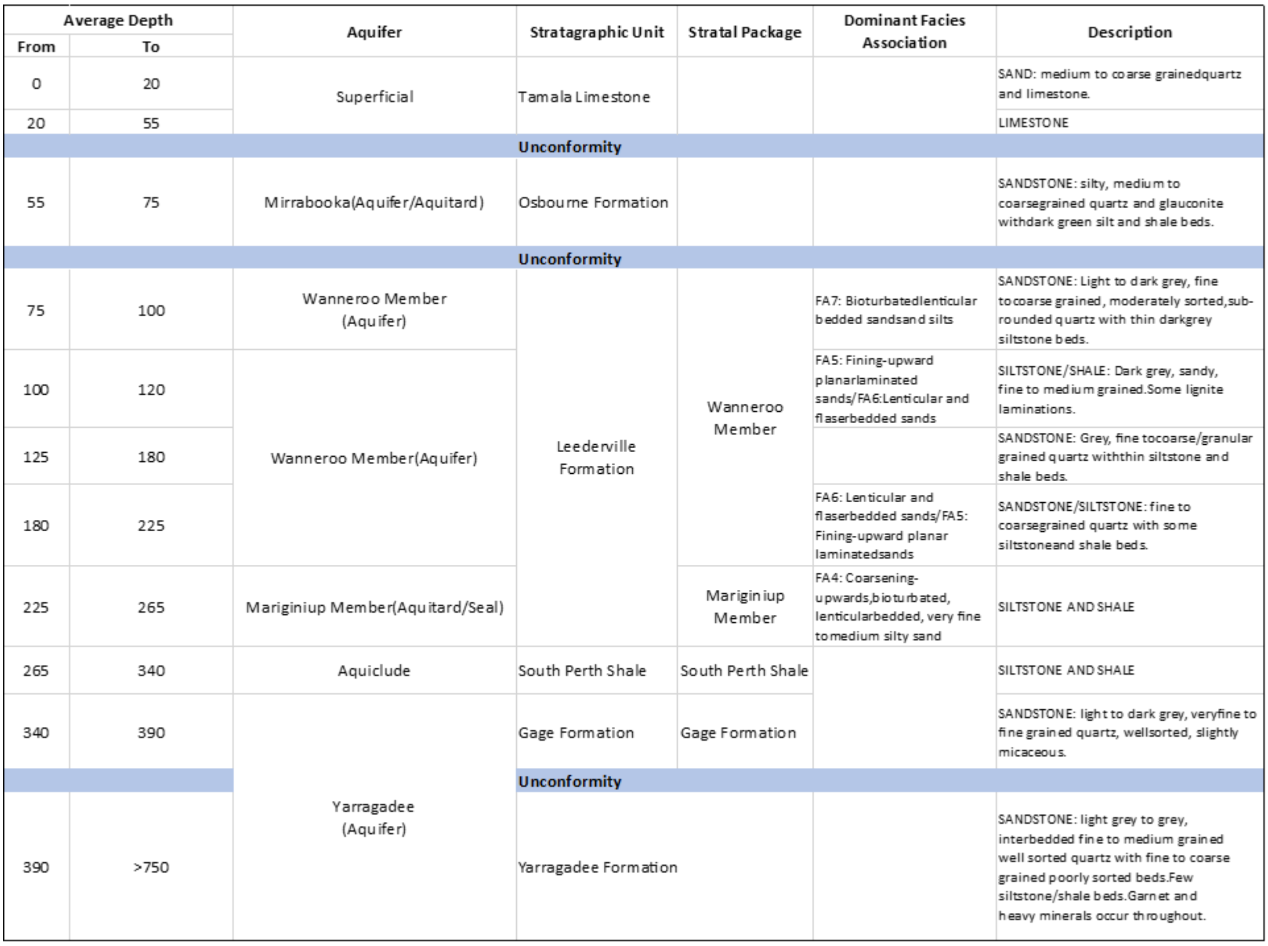
utilised in building the facies models developed in this project. There is a general NE to SW gradient regionally in the potentiometric head of the Leederville aquifer. Abstraction at the Gwelup bore field to the south and the coastal borefields to the north have resulted in a localised groundwater divide at the Beenyup test site. Within the extent of the northern portion of the Leederville aquifer (Gnangara mound) the Leederville aquifer is typically unconfined and is hydraulically connected (variably) to the superficial aquifer. Although at the site of the Beenyup member low permeability facies of the Pinjar Member/Shale rich upper Wanneroo act as a localised hydraulic impediment (Department of water, 2014).

Injection bores for the stage 1 Beenyup groundwater recharge trial is screened through the entire thickness of the high sand content FA5 facies association of the Wanneroo Member. At this location test pumping has confirmed that transmissivities are very high in a localised radius around the recharge bore BNYP 03/07. The Wanneroo member although considered to be a highly productive unit within the Leederville aquifer does exhibit some degree of internal heterogeneity with grain size variability observed in the down hole geology logging as well as the geophysics. This apparent geologic structure is also evident in the larger scale pump tests conducted at the site with barrier effects noted to the north and south of the recharge site.

3.1.2 Site Scale Stratigraphy

The Beenyup study area is situated in the western portion of the Wanneroo Member (Leyland, 2011). The Wanneroo at this location is comprised of three facies associations as identified in core and gamma ray response (figure 8). These facies associations represent a lower tidally influenced delta plain dominated by heterolithic tidal flats (FA6, FA7) and intercalated sand dominant channel fill deposits (FA5) (Leyland, 2011). Leyland (2012) states that this western portion of the Wanneroo Member has the highest sand proportions, with the distribution channel fills (FA5) having the highest porosity. The FA6 and FA7 heterolithic tidal facies typically have a silty sand composition and are overall considered to be of a lower porosity.

The thickness of the channel fill (FA5) sequences are described by Leyland (2012) as in the range of 10 to 30m depth for individual fill complexes through to 30 to 50m thick for more complex stacked sequences, (figure 9). The 30 to 50m thick stacked sequences can be laterally correlated over distances of 5 to 10 km but the 10 to 30m channel sands are not laterally correlated and are only expected to maintain widths of 10 to 300m. The heterolithic tidal flat facies FA6 and FA7 intercalate with the sand rich facies and are typically between 10 to 40m in thickness.



Average Depth		Aquifer	Stratagraphic Unit	Stratal Package	Dominant Facies Association	Description
From	To					
0	20	Superficial	Tamala Limestone			SAND: medium to coarse grainedquartz and limestone.
20	55					LIMESTONE
			Unconformity			
55	75	Mirrabooka(Aquifer/Aquitard)	Osbourne Formation			SANDSTONE: silty, medium to coarsegrained quartz and glauconite withdark green silt and shale beds.
			Unconformity			
75	100	Wanneroo Member (Aquifer)	Leederville Formation	Wanneroo Member	FA7: Bioturbatedlenticular bedded sandsand silts	SANDSTONE: Light to dark grey, fine tocoarse grained, moderately sorted,sub-rounded quartz with thin darkgrey siltstone beds.
100	120	Wanneroo Member(Aquifer)			FA5: Fining-upward planarlaminated sands/FA6:Lenticular and flaserbedded sands	SILTSTONE/SHALE: Dark grey, sandy, fine to medium grained.Some lignite laminations.
125	180					SANDSTONE: Grey, fine tocoarse/granular grained quartz withthin siltstone and shale beds.
180	225				FA6: Lenticular and flaserbedded sands/FA5: Fining-upward planar laminatedsands	SANDSTONE/SILTSTONE: fine to coarsegrained quartz with some siltstoneand shale beds.
225	265	Mariginiup Member(Aquitard/Seal)		Mariginiup Member	FA4: Coarsening-upwards,bioturbated, lenticularbedded, very fine tomedium silty sand	SILTSTONE AND SHALE
265	340	Aquiclude	South Perth Shale	South Perth Shale		SILTSTONE AND SHALE
340	390	Yarragadee (Aquifer)	Gage Formation	Gage Formation		SANDSTONE: light to dark grey, veryfine to fine grained quartz, wellsorted, slightly micaceous.
			Unconformity			
390	>750		Yarragadee Formation			SANDSTONE: light grey to grey, interbedded fine to medium grained well sorted quartz with fine to coarse grained poorly sorted beds.Few siltstone/shale beds.Garnet and heavy minerals occur throughout.

Figure 8 Beenyuyp site specific stratigraphy of the Leederville aquifer (Water Corporation, 2016).

The channel fill FA5 facies association developed where a fall in sea levels resulted in the incision of 3 to 50m deep distributary valleys into the heterolithic delta plain. These distributary valleys were then infilled with channel fill sediment creating laterally extensive sand bodies of 5 to 10km. These channel fill facies are typically represented by 3 to 8m fining upward sequences of planar laminated sand. Typically these sand bodies feature a coarse laminated base with some silt drapes and small scale cross bedding and flaser bedded silty sands present. This facies association is interpreted by Leyland (2011) to represent a strong tidal influence within a low to moderate energy environment of deposition. The FA6 Facies association is dominated by lenticular sand to flaser bedded fine to medium grained silty sands. There are local coarse beds of sand present and rare bioturbation. There are also minor 1 to 4m thick laminated medium bedded sands and minor 1 to 2m intervals of laminated very fine interbeds of sands and silts. These thin laminated sequences are considered to indicate fluctuating energy conditions typical of a strong tidal influence. The FA7 facies is described as a bioturbated heterolithic facies consisting of fine to medium silty sand and sandy silt. The lenticular bedding present in the FA7 facies associations indicates that the energy of the depositional system was variable and likely a tidal flat system.

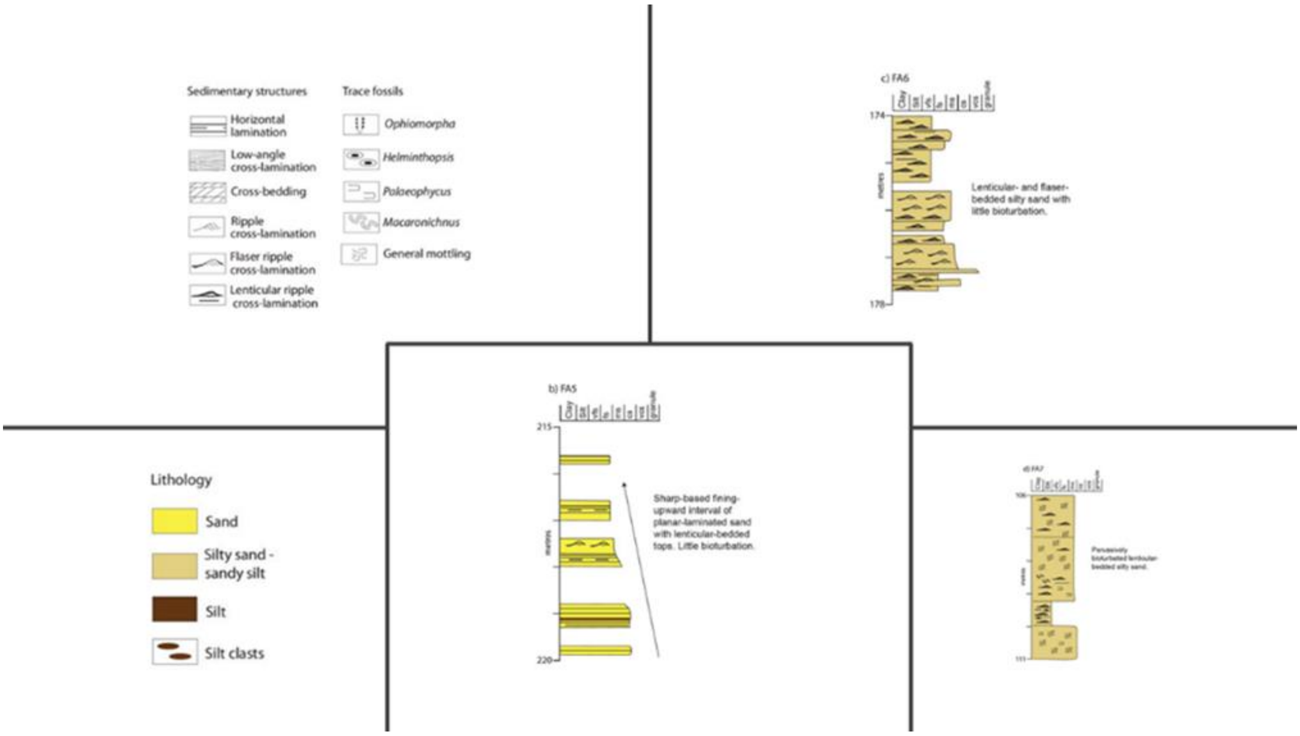


Figure 9 Representative facies associations present within the modelled extent (Leyland, 2011).

Interpretation of high resolution three-dimensional seismic conducted over the immediate extent of the Beenyup recharge site has identified that the sandstone dominated units within the Wanneroo member are not overly continuous and do not present as competent reflectors (Water Corp, 2009). From the study, high permeability but thin and likely discontinuous sand beds have been identified in the downhole geophysics that likely form ribbon like structures within the higher silt content mixed facies, (Water Corp, 2009). Overall the authors have interpreted the Wanneroo member at the Beenyup recharge site as representing a discontinuous heterogeneous depositional setting with isolated strand/lenticular-like sandstones**.**

As recognised by Leyland (2011) and Backhouse (1998), deposition of the Leederville aquifer represents a transition from fluvial to tidal environments, with fluvial deposition dominant to the east of the Beenyup recharge site. To the west of the Beenyup recharge site, Leyland (2011) recognised that near shore tidal conditions start becoming more prominent. The nearshore tidal conditions are typified by prograding tidal bars, (FA4) to tidally influenced channel fills and tidal flats (FA5 – FA7). This increasing marine influence and change in deposition environment from prograding tidal bars to tidally influenced flats and channel fills indicates that deposition of the Wanneroo Member at the Beenyup recharge likely occurred as a prograding tidal delta (Storms et al., 2005; Legler et al., 2013; Abdel-Fattah, 2016).

In this sequence stratagraphic work undertaken on the Leederville aquifer by Leyland (2011) the high silt clay facies that is currently interpreted as the Pinjar Member is re interpreted as being associated with the heterolithic delta plain and tidal flat deposits of the upper Wanneroo Member, (FA7 facies association).

However there are caveats with this interpretation from Leyland (2011) at the Beenyup recharge site, In personal communications with Water Corporation and DWER (2021) it is suggested that as the FA7 interpretation is not present in other work such as Davidson 1995 and without a more broadly applied re classification that is consistent with the Leyland 2011 work. This conceptualisation is not a view widely supported by either Water Corporation or DWER. Although it is considered that with the next iteration of the regional re conceptualization of the PRAMS model, this conceptualization could be more closely examined.

Through out the remainder of this work the conceptualization of the Leederville aquifer at the Beenyup recharge site is consistent with Leyland (2011). This is to ensure continuity with the facies association interpretation undertaken by Leyland (2011) which forms the basis of the geostatistical facies modeling utilised here.

3.1.3 Hydraulic Conductivities

The initial conceptualisation of the study by Water Corp (2009) of the Beenyup study site has placed the hydraulic conductivities for sand bodies at 10 m/d and the silts at approximately 10^{-6} m/d. The mixed sand/silt facies dependent upon the level of connectivity can be as low as 10^{-6} but as high as 5 m/d where the siltstones and shales are laterally extensive (Water Corp*,* 2009). It is noted that although hydraulic conductivities taken from sandstone cores ranged from 13 m/d to 18 m/d, these rates are likely to be at the lower end of the actual conductivity range for sand bodies at the site. The bias is likely due to the poor sampling of the loosely consolidated coarser grained sand fraction (Water Corp, 2009). Although there is some evidence of low Kh/Kv anisotropy in the sand rich units, the vertical hydraulic conductivities for mixed facies and silts taken from BNYP 1/07 typically range in the order of four to five orders of magnitude (Department of Water, 2017).

3.1.4 Sand Body Connectivity Trends in The Leederville Aquifer

From the work undertaken by Ainsworth (2005) in marginal marine deposition environments, a relationship between the depositional setting and connectivity is established. The author identified that there is greater connectivity in wave dominated comparted to fluvial dominated depositional environments. In these marginal marine environments the three primary controls on sand body connectivity as identified by Ainsworth (2005) include the sand to silt ratio, sand body dimensions and their geometry.

This fluvial to wave depositional environment shift in sand body connectivity is observed in the Leederville aquifer by Leyland (2011) in logged core and downhole geophysics. Distinct zonation due sand content in the Wanneroo member was observed with continually increasing sand content from the fluvial dominant eastern section to the tidally influenced mid zone then increasingly becoming more sand dominant in the wave dominant setting to the west. This zonation occurs as fluvial floodplains (FA6) with minor channel fills (FA1) give way to tidal flats (FA6, FA7) in the middle zone then to tidal flats (FA6, FA7) and stacked valley fills (FA5) to the western edge.

The work undertaken by Leyland (2011) established that the valley fill deposits within the Wanneroo are the primary high porosity unit. These units are typically 30 to 50m in thickness and are interpreted to extend 5 to 10km laterally. Along with the valley fill deposits the distributary channel fill sand bodies are also considered highly permeable and are expected be 10 to 300m wide. However, as of yet, the lateral correlation of these sand rich units has not been possible.

3.1.5 Barrier effects

Pump testing completed at the Beenyup recharge site at bores 1/07 and WTP97 in proximity to the Joondalup Fault has identified a barrier effect that may be impacting south westerly groundwater flow (Silva, Yesertener and Wallace-bell, 2013). However, as noted by the Department of Water (2017) in the recently completed PRCAC study, no direct evidence from drilling, groundwater age, salinity or major ion chemistry data for a barrier effect due to faulting has been observed. To resolve this issue the PRCAC study highlights the need to incorporate data from DWER and the Water Corporation such as the Beenyup Stage 1 reinjection volume data, groundwater level data from Leederville and Yarragadee monitoring bores and data collected as part of Beenyup Stage 2 groundwater investigations, including drilling and potential seismic surveys (Department of Water, 2017).

Leyland (2011) has noted that the bioturbation of the FA7 unit (Pinjar) and the apparent increase in sand content of the FA7 (Pinjar) facies to the south of the Beenyup site is likely to reduce its effectiveness as a hydraulic barrier, resulting in an increased chance of the recharge water leaking into the overlying aquifer under increased pressure**.**

The east west draw down trend observed in the pumping tests (figure 10), conducted at LRB3 and LRB2 is interpreted by Rock Water (2016) as a consequence of the higher conductivity east west orientated FA5 facies at this location. The boundaries of these valley fill sands are interpreted to extend south of LRB3 approximately 300m and approximately 1000m north of LRB2. This work undertaken by Rock Water (2016) has highlighted risks where the high conductivity units are not present in the Beenyup recharge site. If the sands are not extensive and not well-connected, textural contrasts at lithofacies boundaries could occur which may act to impede the flow field.

Originally it was thought that the Kings Park formation approximately 4km to the south west of the Beenyup recharge site was responsible for the barrier effects observed in the pumping tests. However the recent work undertaken by Rock Water (2016) has indicated that the barrier is actually located a lot closer to the recharge site and that more than one boundary likely exists.

The Beenyup site conceptualisation studies state that the presence of these hydraulic barriers is likely to result in higher recharge pressures to the north and south The studies concluded that the north south hydraulic impediment is likely due to reduced flow rates at textural juxtapositions within or at the margins of the FA5 facies association. It should be noted that the textural barriers are considered to predominantly reflect hydraulic conductivity contrasts and do not represent actual low flow barriers.

Pumping Rate	Bore	Distance from Pumping Well (m)	Draw down After 48 Hrs pumping (m)	Transmissivity Cooper-Jacob Method 2 (m /day)		Storativity Cooper-Jacob Method	Average Transmissivity Theis Method 2(m/day)	Average Storativity Theis Method
				Line 1 -	Line 2			
175 L/s	BNYP LRB2	0	17	1820	700	-	2030	4.00E-04
	LMB2	62	6.1	1600	785	1.90E-03		
	LMB1	462	3.76	1670	870	4.70E-04		
	LMB3	958	2.75	1900	845	3.40E-04		
	AM27A	1250	3.1	2540	NA	2.30E-04		
180L/s	BNYP LRB3	0	15.5	1530	680	-		
	LMB3	48	5.04	1690	735	1.50E-02	1910	4.80E-04
	LMB1	518	3.97	1940	770	4.00E-04		
	LMB2	960	2.75	1900	845	3.40E-04		
	AM27A	1250	3.1	2540	730	2.30E-04		

Figure 10 Hydrogeologic data from pump testing conducted by Water Corporation (2016).

The conceptualisation study also states that it is likely the very high transmissivity observed in the Wanneroo member at the Beenyup site will not extend outside the extent of the incised channel sands (FA5**).**

3.1.6 Recharge into the Wanneroo Member

The initial modelling for the Beenyup stage 1 recharge site (Water Corp, 2009) indicated that an injection rate of 5 ml/d over three years would result in a horizontal flow of 440m of the injectant with an assumed porosity of 0.1. If the measured porosity of 0.3 is utilised the injectant only flows 250m.

The vertical flow assumptions were based on a 60m recharge head within the 15m thickness of the FA7. In this modelling there was no indication of seal failure and that influence of injected water from the vertical hydraulic gradient will be restricted to the injection zone immediately around the injection site.

The modelling suggests that the injection plume is confined to the lithology as intersected by the well screen and that that flow is biased to the horizontal direction (Water Corp, 2009).

The numerical model suggests that vertical flow will stay within the Leederville aquifer and there will not be significant groundwater ingress into the overlying siltstone layer. In this conceptual study the MODPATH particle tracking used to estimate travel time to the Leederville production bores shows that at a 165 GL per annum abstraction regime it is estimated to take 60 years for the injectant to reach production bore WT45.

3.2 Geologic controls on sand body connectivity

An aquifer is heterogeneous when the contained permeability and associated hydraulic conductivity are not uniformly distributed and is anisotropic when groundwater flow through the aquifer material has a dominant orientation (Galloway and Hobday 1996). In aquifers, anisotropy and heterogeneity can be interrelated, where heterogeneity in sedimentary structure such as bedding planes results in a preferential orientation of permeability and, therefore, groundwater flow. In most sedimentary systems Galloway and Hobday (1996) transmissivity is highly anisotropic and is controlled by the depositional trend of the high permeability sand bodies, transmissivity can have both horizontal and vertical flow gradients as well as abrupt terminations where high conductivity sand bodies are truncated by lower permeability units.

In figure 11, two schematics of depositional environments (fluvial channel and barrier sand) with equivalent sediment permeabilities and thickness both exhibiting anisotropic flow but with greatly different transmissivities. Of the two environments the channel sands have the highest transmissivity due to the channel sand body being orientated in the direction of regional ground water flow resulting in less resistance due to permeability contrasts from textural juxtaposition. Although consisting of the same thickness and sediment permeability the barrier sands are much less transmissive as the stratigraphy is orientated perpendicular to the regional gradient and truncates flow due to the increased incidence of sand body juxtaposition lower permeability sediments (Galloway and Hobday 1996).

This preferential orientation of transmissivity (anisotropy) is observed in tidally influenced depositional systems. In these environments sand bodies such as those contained within delta distributary channels can be highly heterogeneous and when modified due to tidal reworking this sediment heterogeneity can result in an abundance of localised permeability barriers where low permeability sediment is juxtaposed against high conductivity sand bodies orientated parallel to the primary direction of sand deposition. These permeability barriers can take the form of variably inclined sand and mud alterations (heterolithic laminae) that extend from the channel slope into the tidal flat zones (Galloway, 1996; Choi *et al.,* 2004). The vertical stratigraphy of deltas can exhibit unique characteristics in tidally dominant depositional settings. In these environments cross bedding including bidirectional structures and extensive bioturbation can be extensive (Slatt, 2013).

Image removed due to copyright restriction.

Figure 11 Preferential groundwater flow orientation due to depositional trends in sedimentary aquifers (Galloway and Hobday, 1996).

In narrow embayment's, tidal energy can extend far landward and result in high energy environment in an otherwise low energy setting. In these environments (figure 12), sand is typically confined to tidal channel networks parallel to the dominant direction of tidal flow. Typically, in sedimentary aquifers the principal direction of flow will conform to the primary orientation of the higher conductivity facies fluid flow pattern in tidal-influenced deltas is highly dependent upon depositional processes. This depositional control on preferential flow is observed where the sand bodies are elongate in the depositional dip direction but laterally discontinuous in the depositional strike direction (Slatt, 2013).

Image removed due to copyright restriction.

Figure 12 Conceptual schematic of interdistributary flat in tidally influenced delta environment (Slatt, 2013).

In a review of the current literature undertaken by Gibbling (1996), distributary channels that have incised into heterolithic strata in coastal marine settings are recognised as being typically 3 to 20m thick with width to thickness ratios less than 50. The author observed that distributary channels can be deeply incised into basal sediments, have a low sinuosity and may bifurcate. The distributary fill sequence is noted to be dominated by vertical accretion with some soft sediment deformation and slumping present. The accretion surfaces that are present indicate that distributary channels in delta settings do shift laterally to some extent.

3.3 Geology Textural Classification

The first step in developing the Beenyup hydrofacies models in TPROGS involved the amalgamation of the bore hole geology into seven distinct textural classes (table 1). These textural classes were derived from the sand to silt ratio for each interval as described in the geology description of the downhole log. No attempt was made to discriminate between grain sizes within the sand bodies as the sand grain size assessment by the logging geologist had been kept to a visual qualitative textural description. Although the descriptors of fine, medium and coarse grained were used, and often in the same logging interval, this qualitative logging did not provide the necessary resolution for subdivision of the sand bodies within the Beenyup model domain.

Table 1 Textural class and hydrofacies scheme development.

Example Geologic Descriptions	Textural Class	4 Class Hydrofacies Scheme	Hydraulic Conductivity
Grey to transparent, silty, medium to coarse grained, well sorted, sub - rounded quartz sand; 10% silty clay with pyrite aggregate	Sand	**Sand -** Greater than 90% sand content	20 (m/d)
Pale grey, fine to coarse grained, moderately to poorly sorted, sub-angular to sub-rounded quartz sand; 40% grey silty clay; trace fine to medium grained pyrite aggregate.	Silty Sand	**Heterolithic Sand Dominant** - From less than 90% to greater 50% sand content	1 (m/d)
Green clay; 50% medium to coarse grained, moderately sorted, sub-rounded quartz and glauconite grains.	Clayey Sand		
Silt; 40% sand, transparent to light brown, coarse to very course grained moderately to poorly sorted sub angular quartz.	Sandy Silt	**Heterolithic Fines Dominant** - From less than 50% to greater than 30% sand content	0.1 (m/d)
Green clay; 40% medium to coarse grained, sub-rounded quartz and glauconite grains.	Sandy Clay		
Grey silty clay; 30% sand, grey, medium to coarse grained, moderately to poorly sorted, sub-angular quartz; 5% lignite; trace fine grained pyrite aggregate.	Silt	**Fines** - Greater than 70% fines content	0.00001 (m/d)
Dark Grey muddy Clay < 5% fine to coarse grained poorly sorted sub angular quartz sand.	Clay		

As typically the TRPOGS software works best with five or less distinct hydrofacies units, the hydrofacies schemes developed consisted of four hydrofacies. In both of these schemes, the Sand and Fines schemes were left unchanged. In the textural classification scheme, sands with a fines content of less than or equal to 10%, regardless of the described sand grain size, were kept as sands. Then for sand intervals with greater than 10% and less than 50% fines content, the classifications silty sands and clayey sands were assigned. Sand intervals with greater than and equal to 50% fines content and less than 70% fines were classified as Sandy Silt and Sandy Clay respectively.

Finally intervals with greater than or equal to 70% fines content were classified as silts or clays. This classification scheme is considered to be hydrologically representative as it can be reasonably assumed (with some caveats) that the higher the fines content of an interval the lower its associated hydraulic conductivity will likely be. The fines unit as the lowest conductivity hydrofacies was derived from the amalgamation of the Clay and Silt textural classes. The heterolithic hydrofacies as the intermediate hydraulic conductivity unit is an amalgamation of all other textural units between the sand and fines end members. Although this textural classification allowed the breakdown of the study site geology into four distinct hydrofacies, it is still problematic due to the inherently subjective nature of onsite geologic logging.

It is entirely possible that what one geologist will log as 30% fines could easily be logged 10% above or below (or even more) by another geologist logging the same interval. It is for this reason that the mixed sand silt facies (variable sand/silt ratio) have been kept to the heterolithic hydrofacies classifications. This is a broad range which represents intervals that contain greater than 10% through to less than 70% fines content. These broad intermediate groupings allow for some degree of uncertainty in the logging schemas used.

As the respective sand and fines end members units are typically able to be more consistently logged as either clean sands or clay silt by geologists on different programs over time this heterolithic classification can be considered to contain the higher levels of uncertainty compared to either the sand or fines hydrofacies classification. This textural classification scheme differs from the observations made previously in core that had intersected the Wanneroo Member at the Beenyup study site. Leyland (2011) had identified textural classes based on sand silt ratios, within the core from Beenyup 1/07 as well as from calculations derived from downhole Gamma ray logs. These descriptions are as follows: Sand (100-80% sand), Silty sand (80-50% sand), sandy silt (50-20% sand) and fines (20-0% sand).

3.4 TPROGS Model Development

The domain for the TPROGS model is 1km x 1km in x and y dimensions and a total of 165m deep, (appendix 2). The discretisation is 10m x 10x 1m and It is a cell centred grid. The development of the down hole conditioning data in the GAMEAS utility was conducted in Groundwater Modelling System’s (GMS) inbuilt TPROGS module due to its simplicity and intuitive graphical user interface and interactive 3D capacity. The MCMOD and TSIM TPROGS modules were run externally of the GMS TPROGS utility which allowed the hydrofacies realisations (*.bgr) generated by TSIM the utility to be used externally in the stochastic FloPy, (USGS, 2020) simulations with MODFLOW 6, (USGS, 2020). A total of 19 holes were utilised as conditioning data for the TPROGS model. The anisotropy (depositional dip) was set to 90 degrees (east to west) and the map grid (deposition strike) was set to North – South. This orientation broadly conforms to the known orientation of the sediment supply during the deposition of the Wanneroo in the Cretaceous. In the extensive review of sand body geometry by Giblling (2006) it is noted that distributary channel fill sequences have a high incidence of WT (width to thickness) ratio of between 5-10. From these broad observations the lens lengths of the Hydrofacies in the Beenyup model were set to the following dimensions (table 2).

Table 2 TPROGS hydrofacies proportions and average lens lengths.

Material	Proportion (%)	Vertical (m)	Strike (m)	Dip (m)
Sand	0.40	7.59	40	200
Het_Sand	0.23	4.91	50	70
Het_Fines	0.20	5.58	50	60
Fines	0.18	5.20	30	40

3.5 Stochastic Hydraulic Conductivity Modelling in FloPy.

A simple transient flow model with a 1m gradient over the 1000m domain length was developed in FloPy utilising MODFLOW 6 with the model run through x, y and z directions of the (n=30) realisations for the TPROGS model variants. The flow in three dimensions was imposed by simulating variations in the hydraulic boundaries. For the x direction, a hydraulic gradient was imposed in the x-direction by setting the cells in the first and last columns as constant. A similar approach was applied to the y direction, using boundaries in the first and last rows, and in the z direction using the first and last columns. The flow through the model domain (Q) was recorded as the water added by the constant head boundary for the up-steam cells in the domain. From this modelling the effective conductivity in each of the principal model directions was calculated. The effective conductivity for each principle direction was derived from the equation 5 (Renard and Allard, 2011)**.**

$$\boldsymbol{K_{eff} = \frac{QL}{A(h_1 - h_2)}}$$

Equation 5

Q is total flow rate in and out of the domain (m/d) h1 and h2 are the two constant heads applied to the down and upstream boundaries respectively, L is the length of the domain parallel to the direction of flow and A is the cross-sectional area of flow perpendicular to the flow direction. In the FloPy modelling the effective conductivity for x and y was determined with equation 6 and 7 respectively and effective conductivity for z with equation 8. In these equations Q is still discharge, Lx and Ly are the domain lengths in depositional strike and dip directions, d is domain depth, and h1 and h2 are hydraulic head.

$$\boldsymbol{Kx = Q * Lx/(Ly * d * (h2 - h1))}$$ **Equation 6**

$$\boldsymbol{Ky = Q * Ly/(Lx * d * (h2 - h1))}$$ **Equation 7**

$$\boldsymbol{Kz = Q * d/(Lx * Ly * (h2 - h1))}$$ **Equation 8**

The effective conductivity (Keff) is a measure of the preferential flux within an aquifer (Knudby and Carrera, 2005). As such the presence of flow channelling or preferential flow can be determined by what extent a small portion of the aquifer material (e.g facies, depositional structure) can disproportionally contribute to a large portion of the flow. From this observation the authors state that effective conductivity should be considered a metric that can act as a proxy or indicator off geologic structure within an aquifer.

4. RESULTS

4.1 Hydrofacies modelling

4.1.1 Hydrofacies proportions and conditioning data.

The proportion of the seven different textural classes (table 1) were calculated for the entire Wanneroo member within the Beenyup study area. It is clear that the sand textural class makes up the largest proportional volume (table 3), and silty sands and sandy silts are also proportionally high. Of note is the higher silt content within the model domain compared to the clays. As a comparison the model domain was further broken down to the facies associations as identified by Leyland (2011). The sand and silt proportions within the facies association subdivision broadly conform to conceptually what is considered the dominant textural class for each. This can be observed where FA5 is sand dominant, FA6 has proportionally higher heterolithic classes and FA7 has the higher silt/fines content.

Table 3 Texture class proportions within the Study area

Texture Class	**Proportion %**			
	Wanneroo	**FA7**	**FA5**	**FA6**
Sand	44.54	40.04	51.04	36.69
Silty Sand	17.25	14.07	15.34	26.15
Clayey Sand	5.6	3.85	5.62	8.38
Sandy Silt	12.76	14.07	15.34	8.6
Sandy Clay	3.32	2.5	3.07	5.14
Silt	15.58	24.22	9.08	13.69
Clay	0.96	1.25	0.51	1.37

Proportionally the sand hydrofacies is the dominant material within the study area (table 4). This is followed closely by the heterolithic classes. Although the fines category is much less than both, it still comprises just over 16% of the total proportional volume from the bore hole conditioning data.

Table 4 Hydrofacies proportions within the downhole lithology conditioning data.

Hydrofacies %	FA7	FA5	FA6	Wanneroo Total
Sand	40.04	51.04	36.69	44.54
Het_Sand	17.93	20.96	34.52	22.85
Het_Fines	16.57	18.41	13.73	16.07
Fines	25.47	9.60	15.05	16.54

Within the breakdown of the seven textural classes into the four hydrofacies classes (table 4) as per the scheme outlined in table 1, it is clear that the FA5 facies association has the largest sand hydrofacies proportions with the FA6 facies association predominantly heterolithic. Compared to FA6 the sand proportion in FA7 is larger, but the heterolithic proportions are lower, FA7 has the largest fines proportion of all the facies associations. This distribution of hydrofacies between facies associations conforms as with the textural class breakdown to the likely proportional volumes expected from the conceptual understanding of the Wanneroo member.

The location of the bore holes used as conditioning data in this study are listed in appendix 1. These bore holes can be observed in the TPROGS model, extending along the north south axis (figure 13). The bores are not evenly distributed with a large portion concentrated in the central zone of the model domain around the Beenyup recharge site (BNYP 3/07). It should be noted that not all of the bores penetrated the full depth of the Wanneroo member. Of the 19 bores only 13 fully penetrated to the base of the model domain. As such the lower 48m of the model is considered to have a higher uncertainty than the upper 112m, which had full coverage of the conditioning data set.

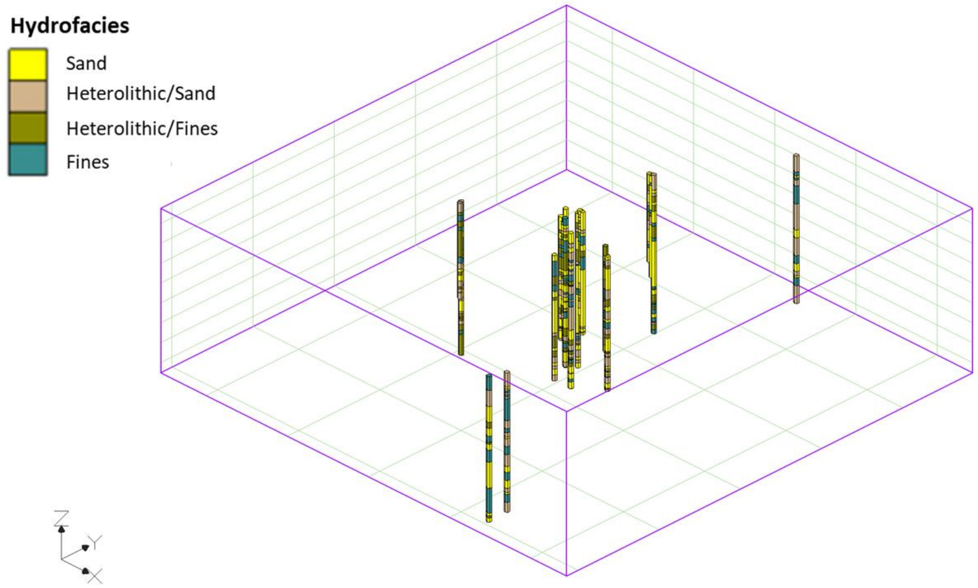


Figure 13 Distribution of borehole conditioning data within 1km x 1km model domain, 2 x vertical exaggeration.

4.1.2 Transition Probability and Hydrofacies Models

From the transition probabilities generated in the TPROGS GAMEAS utility from the downhole lithology data a general fining upwards trend can be observed within the transition probabilities in the top row as Sand transitioning from Het_Sand - Het_Fines to Fines, (Table 5). The Het_Sand to Het_Fines transition probability is less than the Het_Sand to Fines transition, suggesting that the silt within the model domain will intercalate within the dominantly heterolithic textured intermediate hydrofacies. This confirms that there is a high level of heterogeneity and disorder within the system aside from the broad general fining up trend observed.

Table 5 TPROGS Transition probabilities for the downhole conditioning data

Material	Sand	Het_Sand	Het_Fines	Fines
Sand	7.588	0.500	0.263	0.237
Het_Sand	0.527	4.908	0.162	0.311
Het_Fines	0.471	0.306	5.581	0.224
Fines	0.333	0.261	0.406	5.200

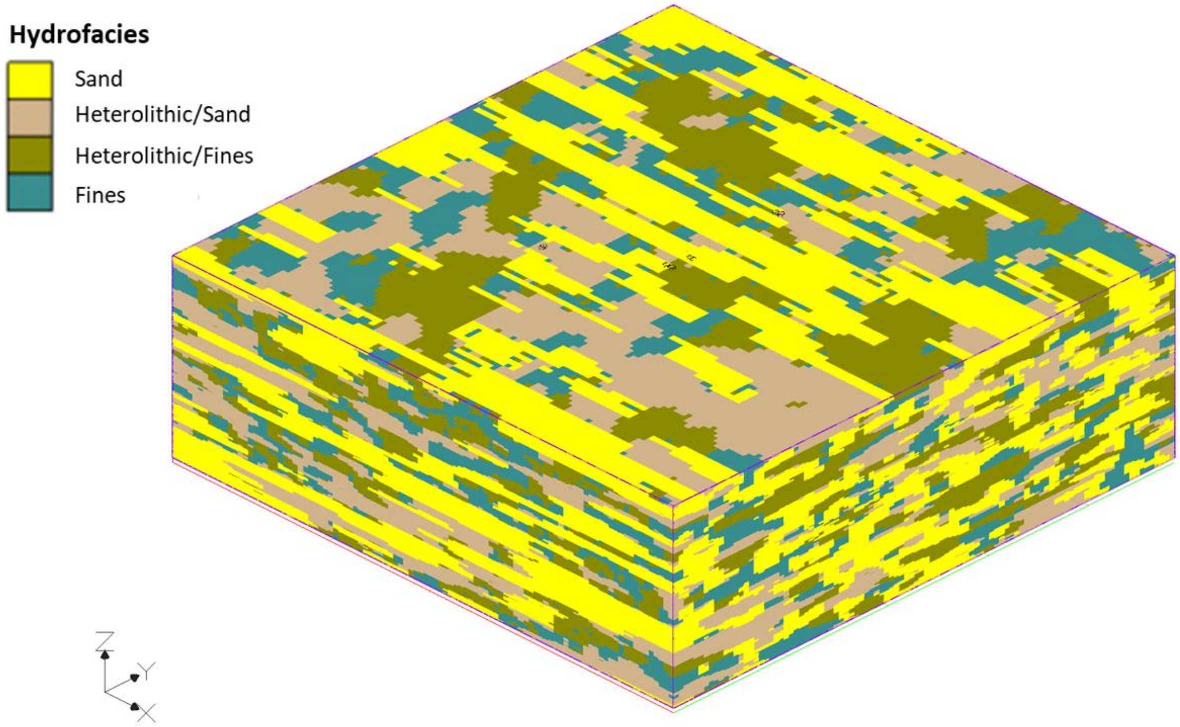


Figure 14 Example TPROGS Hydrofacies model of the Beenyup study site, 2 x vertical exaggeration.

The block TPROGS model (figure 14) does show the preferential trend imposed upon the sand bodies in the modelling process. Cross sections cut through the model domain on a north – south, east – west axis demonstrate that a clear change in the organisation of the hydrofacies can be observed between the units.

In the depositional strike direction (figure 16) the model does show a very discontinuous network of sand bodies intercalating with the heterolithic and fines hydrofacies classes. The depositional dip direction (figure 17) is distincly different with continous sands that connect across almost the entire width of the east west domain of the model.

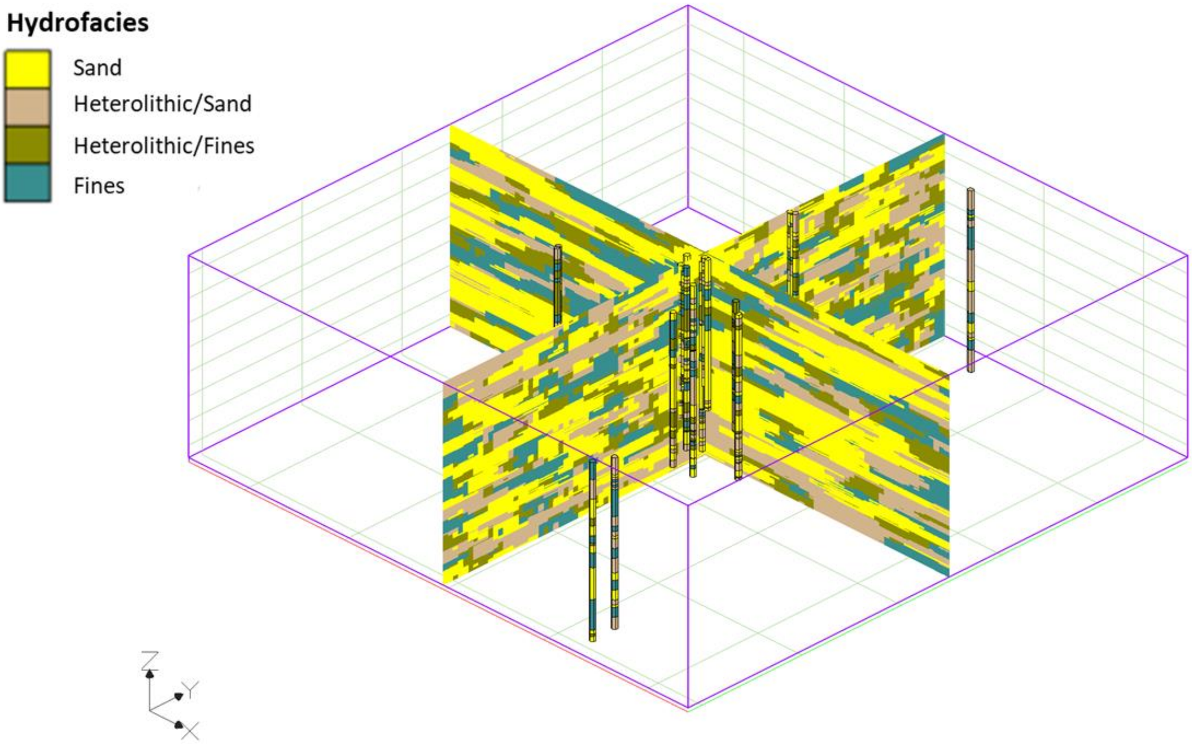


Figure 15 Cross sections cut through an example TPROGS realisation, 2 x vertical exaggeration.

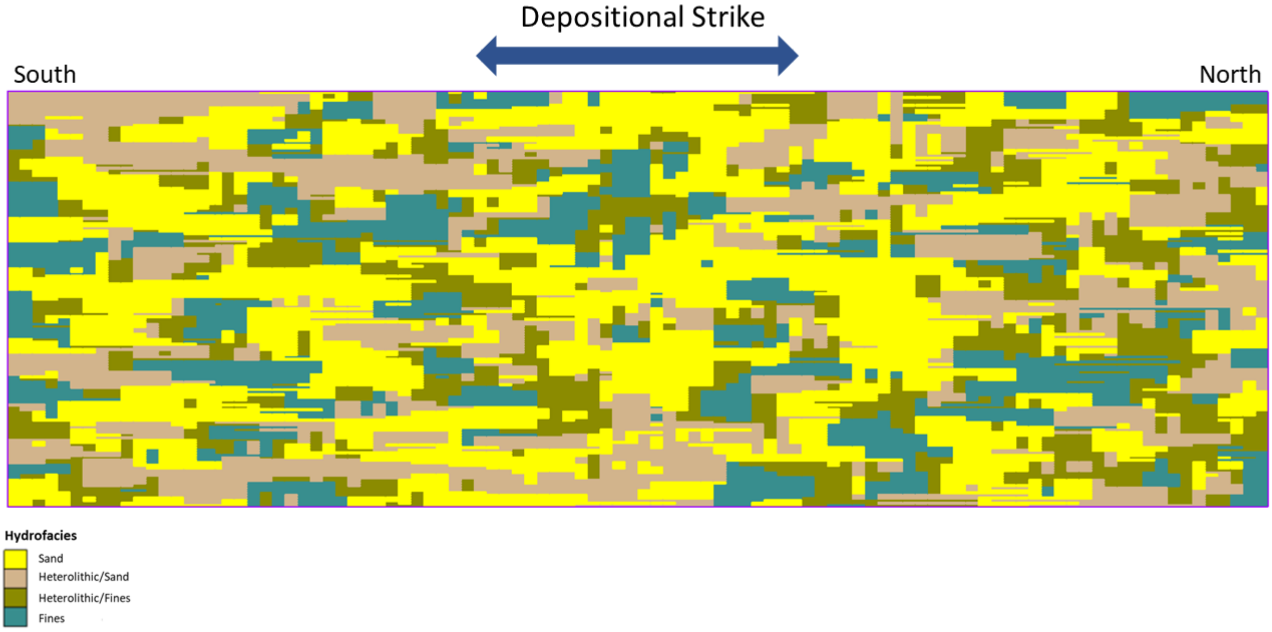


Figure 16 North to south cross section through TPROGS realisation (Depositional Strike), 2 x vertical exaggeration.

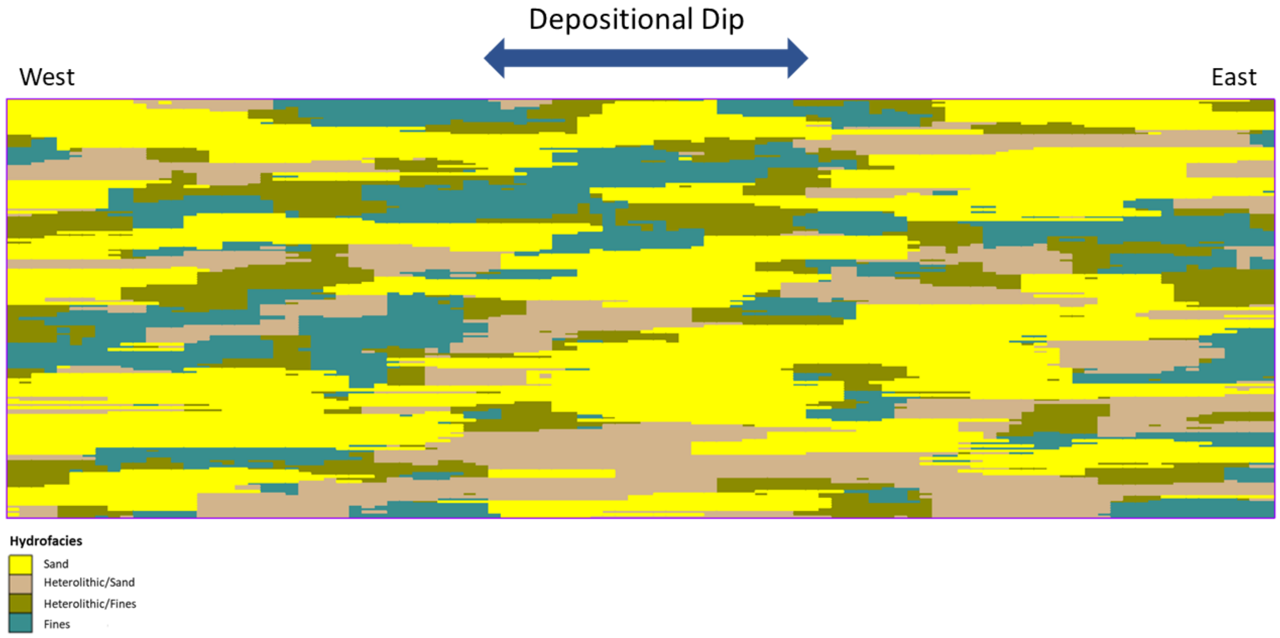


Figure 17 East to west cross section through TPROGS realisation (Depositional Dip), 2 x vertical exaggeration.

4.2 Stochastic Hydraulic Conductivity Modelling in FloPy.

4.2.1 Effective Conductivities

Looping the TPROGS material sets (n=30) through the MODFLOW 6 FloPy model resulted in effective conductivity values for the X, Y and Z directions (table 6). Between the depositional dip and strike direction there is an apparent anisotropy ratio of almost 2 and an Kh/Kv anisotropy ratio of 0.06 in Ky and 0.12 in Kx orientations.

Table 6 Summary statistics for base case anisotropic model

Sum Stats	Dip	Strike	Kv
Average	6.63	3.36	0.41
Std	0.06	0.10	0.03
Min	6.43	3.16	0.35
25th	6.64	3.31	0.42
50th	6.65	3.26	0.43
75th	6.66	3.41	0.44
Max	6.72	3.57	0.47

It should be noted that no anisotropy was imposed on the vertical flow via adjusted conductivity values for the hydrofacies. Whereas typically a Kh/Kv ratio of 1:10 is utilised in groundwater modelling scenarios, in this case the Kh/Kv ratio is 1:1. Keeping a 1:1 Kh/Kv ratio ensured that variances in effective conductivity between Kh and Kv can be attributed to the hydrofacies connectivity and not the actual anisotropy of the hydraulic conductivity internally within the facies. Although this will certainly be having an impact on the actual vertical flow within the Wanneroo at the study site, the primary aim of this study is to investigate the impact that facies connectivity has on groundwater. Consequently the observed Kh/Kv here can be attributed to the actual orientation of the facies themselves.

4.2.2 Sensitivity tests

From the initial anisotropic model, hydraulic conductivities have been altered for the different hydrofacies. This enabled a sequence of sensitivity test model runs to try and determine what hydrofacies class exerted the greatest control over the effective conductivity values in dip strike and vertical orientations for the conceptual model. The results of these sensitivity tests are presented in appendix 3 as histograms of the effective conductivity (Keff).

Table 7 Summary statistics for 200 m/d model

Sum Stats	Dip	Strike	Kv
Average	60.39	23.16	1.77
Std	0.76	1.17	0.15
Min	58.98	20.73	1.54
25th	59.83	22.42	1.62
50th	60.33	23.16	1.75
75th	60.88	23.92	1.88
Max	62.03	25.77	2.09

For the first sensitivity test the hydraulic conductivity of the sand hydrofacies class was increased to 200 m/d, with all other values remaining the same as the base anisotropic model. With the sands hydrofacies class now assigned a hydraulic conductivity of 200 m/d there is almost a 10-fold increase (table 7) in effective conductivity in the dip orientation. The anisotropic Ky/Kx ratio is almost 3 and the Kh/Kv ratio is 34 in the dip orientation and 13 in the strike orientation. Again, as in the anisotropic base case scenario, the strike orientation exhibits the greater standard deviation in effective conductivity.

For the second sensitivity test the hydraulic conductivity of the fines hydro facies class was decreased two orders of magnitude from 10^{-5} to 10^{-7} m/d**.** The results show that there was little variation in effective conductivity of the three orientations compared to the original model (table 8). The Ky/Kx anisotropy ratio is similar to the base case at 2 with the Ky/Kv and Kx/Kv ratios at 16 and 8 respectively. The vertical anisotropy ratios are greater for the reduces conductivity fines when compared to the anisotropic base case.

Table 8 Summary statistics for the 10^{-7} fines model

Sum Stats	Dip	Strike	Kv
Average	6.72	3.37	0.41
Std	0.05	0.09	0.03
Min	6.62	3.16	0.35
25th	6.68	3.31	0.39
50th	6.72	3.37	0.42
75th	6.75	3.42	0.44
Max	6.82	3.57	0.47

Finally a binary model was run stochastically through the MODFLOW 6 FloPy loop**.** In the binary model all the hydraulic conductivities were converted to 10^{-7} m/d, except for the sand hydrofacies which retained the 20 m/d hydraulic conductivities of the base case scenario. The results of this binary model run (table 9), clearly show that horizontal Ky/Kx anisotropic ratios do not differ greatly from the base case model. However the Ky/Kv and Kx/Kv anisotropy ratios are significantly larger than the base case and the 200 m/d sand scenario.

Table 9 Summary statistics for Binary model

Sum Stats	Dip	Strike	Kv
Average	5.68	1.95	0.111
Std	0.11	0.13	0.016
Min	5.41	1.71	0.073
25th	5.63	1.85	0.100
50th	5.67	1.94	0.107
75th	5.74	2.03	0.122
Max	5.91	2.25	0.145

5. DISCUSSION

The intent of this study was to test how heterogeneity within the Wanneroo Member of the Leederville Aquifer can influence the anisotropy of groundwater flow at site scale (1km x 1km). It was not possible in this study to delineate the larger lateral permeability boundaries that act to impede horizontal flow regionally, as had been identified in the site conceptual studies. These boundaries if they exist (likely FA5 channel fill sand in contact with FA6 heterolithic tidal flat facies) will be outside the 1km x 1km domain of this model.

To test the impact of site scale heterogeneity on groundwater flow, geostatistical hydrofacies models of the site with a dip and strike orientation that conformed to the conceptual understanding of the Wanneroo member at this location were developed. The conceptual site scale hydrofacies model were then used as hydraulic conductivity fields in stochastic MODFLOW groundwater flow simulations. In these simulations the effective conductivity for the depositional dip, strike and vertical directions were calculated in each direction for an ensemble of realisations (n = 30).

From the results of this stochastic flow modelling the following observations can be made.

In the base case model hydraulic conductivity in the dip direction is greater than in the strike direction by a factor of 2, confirming that permeability contrasts due to juxtaposition of hydrofacies in the strike direction will impede flow resulting in an anisotropic flow field within the conceptual hydrofacies model of the site.

Sensitivity tests were then conducted which involved varying the hydraulic conductivity for the hydrofacies in the FloPy simulations included a high conductivity sand simulation, a low conductivity fines simulation and a binary simulation where all but the sand unit were closed out by all facies but sand assigned a hydraulic conductivity of 10^{-7} m/d . These sensitivity tests clearly show that it is the sand bodies themselves and their apparent connectivity or lack off, that control groundwater flow within the conceptual model of the study site.

This can be observed whereby decreasing the hydraulic conductivities of the fines hydrofacies class by two orders of magnitude there was very little change in overall effective conductivity in dip, strike or vertical orientations. Whereas increasing the sand hydraulic conductivity by a single order of magnitude will increase effective conductivity in all directions by almost a factor of 10 with dip to strike anisotropy almost 3. This demonstrates the overwhelming control that sand body connectivity has on preferential flow within the conceptual hydrofacies model.

The results from the binary model run show that the contrast in effective conductivity between depositional dip, strike and vertical orientations is maintained with an anisotropy ratio of 3 for the horizontal plane. However the anisotropy ratios between the horizontal and vertical orientations range 51 to 19 for the binary model compared to 17 to 8.5 in dip and strike for the base case. This large increase in Kh/Kv ratio between base case and the binary model may suggest that conceptually the lower anisotropy applied to the heterolithic and fines hydrofacies in the depositional dip and strike orientations has resulted in greater connectivity between these units in the vertical orientation compared to the highly anisotropic sands. This observation has possible ramifications for the assumptions regarding the localised hydraulic sealing effect of the higher fines content FA7 facies association above the Beenyup recharge site.

Although there may be limited vertical connection of the anisotropic sand channel hydrofacies, the heterolithic and fines hydrofacies could be exhibiting a greater degree of connectivity vertically due to their more isotropic distribution. Consequently it can not be assumed that a lower sand volume (or higher fines content) equates to a reduction in vertical movement of groundwater. The depositional fabric within also plays a role in vertical anisotropy, but inversely to the manner in which it impacts flow in the horizontal planes.

The observations made in this site scale hydrofacies modelling study are in line with the work undertaken by Fogg *et al.* (2000), who state that effective permeability is very sensitive to textural juxtaposition due to geologic heterogeneity imposed by depositional processes within an aquifer. The authors state that where the effective hydraulic conductivity occurs parallel to connected channel networks it is just the arithmetic mean of the conductivity in the dip direction. However in the strike and vertical orientations the groundwater flow is controlled by complex hydraulics imposed by the increased textural juxtaposition present when flow moves perpendicular to the depositional dip direction of the sedimentary body.

This direction control on effective conductivity is also confirmed by Zinn and Harvey (2003) in stating that the upper and lower bounds of the effective conductivity of system can be set with the upper bound represented by the arithmetic mean and the lower bound represented by the harmonic mean. The authors confirm that these bounds can be conceptualised as flow through a perfectly layered system in dip and strike orientations.

6. CONCLUSION

The primary aim of this study was to determine the extent of any hydraulic barriers at the Beenyup recharge site and determine what the implications are for management of the resource. It can be stated that lithologic controls within the Leederville aquifer at the Beenyup study site can impose anisotropy on groundwater flow at a site scale. The results of the stochastic FloPy modelling conducted on the conceptual hydrofacies models confirms that if there is a preferential orientation of the sand bodies, there will be greater connectivity in the direction of deposition compared to the strike direction (perpendicular to deposition). This anisotropy is likely the result of the abundant juxtaposition of heterolithic and fines hydrofacies classes truncating the higher conductivity sand domain in the strike orientation.

If flow gradients are not parallel to the principle westerly orientation of the high conductivity sand facies and are driven perpendicular to this orientation by induced gradients from recharge operations or from abstraction by nearby production bores, there is increased likelihood that textural juxtaposition between facies boundaries will result in permeability contrasts that impede flow in the strike orientation. As these site scale textural contrasts due to depositional processes are not likely observable in other methods such a surface geophysics. Higher resolution investigations of the aquifer geology should be conducted during the conceptual stages. Future aquifer storage and recovery projects when implemented within the high conductivity zones, the Leederville aquifer will almost certainly encounter this anisotropic flow due to site scale intra facies heterogeneity.

7. FUTURE WORK

Clearly the sands are exerting a dominant control of the hydraulic conductivity at the site. However there are caveats associated with this assumption, for example, a clean sand that is well sorted will typically have a higher hydraulic conductivity than a silt dominant unit with minor sand component of the same grain (or larger grain size). A pure sand unit that is well sorted but dominantly of a finer grain size could have an overall lower horizontal hydraulic conductivity than that of the mixed sand and fines unit. In this context it is the mixed but coarser sand interval that could likely be having the greater impact (assuming connectivity) on hydraulic flow.

The description of the logged geology throughout the Beenyup study site indicates that grain sizes typically range from fine through to medium coarse to very coarse for most intervals. As such the sand, heterolithic classes and fines hydrofacies units can all have a highly varied sand grain size distribution in any logged interval. With the only discriminator between these being the relative fines content comparted to the sand content, the sand to fines ratio. To fully utilise the textural variation that is apparent within the available downhole data there would be a need to conduct a particle size distribution analysis on the downhole geology. The result would be that the units which contain an objectively larger proportion of coarser sized grains to be modelled as an individual hydrofacies.

The recent logging by the Water Corporation on production bores WT5 and WT25 as well as the site investigation studies conducted for the groundwater recharge trial (GWRT) stage 2 site situated further to the north of the Beenyup study site in 2019 involved this type of breakdown of the particle size distribution between sand – silt and clay sized particles.

It is highly likely that this accurate and detailed logging of the particle size distribution would have greatly facilitated the identification of the dominant flow pathway within the study site. Identification of the coarser sized fraction would have greatly improved the understanding of how juxtaposition of sediment textures due to depositional fabric impacts preferential groundwater flow in the conceptually homogeneous sand bodies such as the FA5 Facies association, which on a local scale will be the dominant pathway for groundwater flow in the Wanneroo member.

To account for the uncertainty inherent in the geological logging withing the Leederville aquifer other means of determining the sand to silt ratio can be implemented. As downhole gamma logs were collected for the vast majority of holes within the study site it is feasible that this data can be used to account for the inherent uncertainty that may be present in down hole geology logging and allow a more consistent identification of hydrofacies based on sand to silt ratios.

As undertaken by Leyland (2011) down gamma can be utilised to determine down hole sand/silt ratios with a synthetic log of sand percentage produced.

$$Sand\ \% = 100 - 33(\ 2^{2V_{sh}} - 1) \qquad V_{sh} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$ Equation 9

Once confirmed against the available high quality geology logging, the down hole gamma silt/sand ratio could be categorised and utilised in TPROGS simulations, instead of or alongside the down hole geology.

Although the stochastic modelling process as undertaken in this study does show that depositional architecture if present at the site will have an impact on the groundwater flow, the underlying assumptions used in this model are still conceptual. In order to determine if the realisations generated in the TPROGS modelling process are in any way realistic other site data collected in the various conceptual studies could be utilised. One option is the use of flow logs to calibrate the realisations against. During the initial conceptualisation phase of the Beenyup ground water recharge trial flow logs were collected for bores that had undergone pump testing. A simulated pump test could be conducted and looped through each realisation with an artificial flow log generated for each that can be compared to the original site flow log for the pumped hole.

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APPENDICES

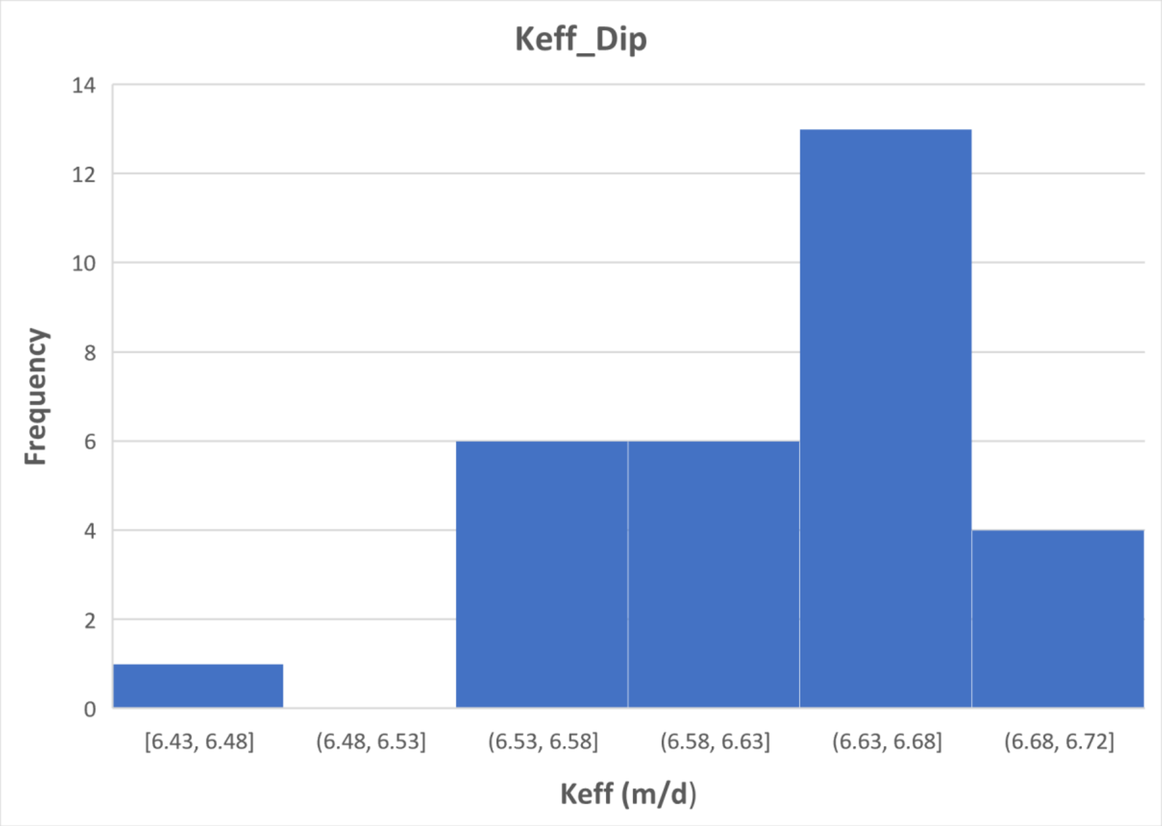
Appendix 1 - Id and location for the 19 holes used as conditioning data in the TPROGS Model.

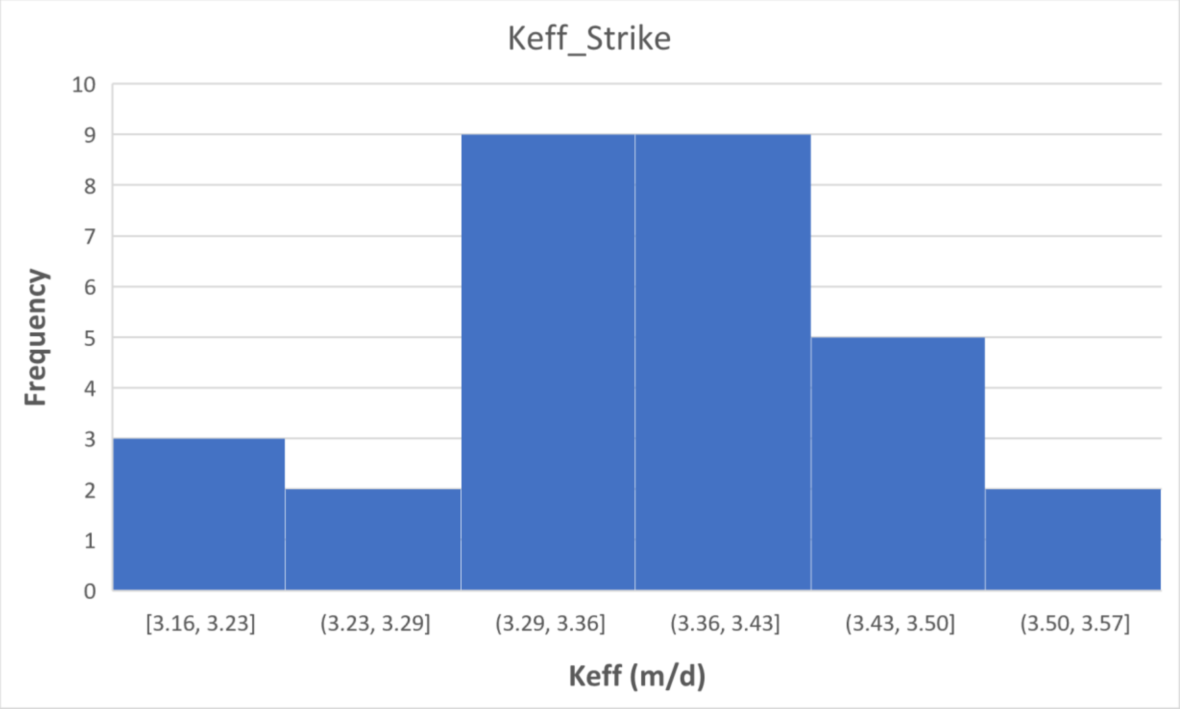
BHID	Easting	Northing
BNYP 107	384244	6482826
BNYP 2 12	384176	6482882
BNYP1/08_120E_209m	384322.9	6482838
BNYP12/08_60N_203m	384200.3	6482888
BNYP13/08_60N_167m	384205.5	6482888
BNYP14/08_60N_187m	384210.5	6482888
BNYP17/08_240N_201m	384211.4	6483064
BNYP18/08_240N_162m	384205.7	6483064
BNYP19/08_240N_151m	384200.6	6483064
BNYP2/08_120E_171m	384317	6482839
BNYP20/08_180W_200m	384036.6	6482764
BNYP21/08_180W_159m	384038.7	6482759
BNYP6/08_20N_202m	384208.7	6482848
BNYP7/08_20N_165	384203.7	6482848
BNYP8/08_20N_187m	384198.6	6482848
LMB3 1 15	384472	6482397
LRB1 3 07	384204	6482826
LRB2 2 15	384289	6483337
LRB3 3 15	384468	6482445

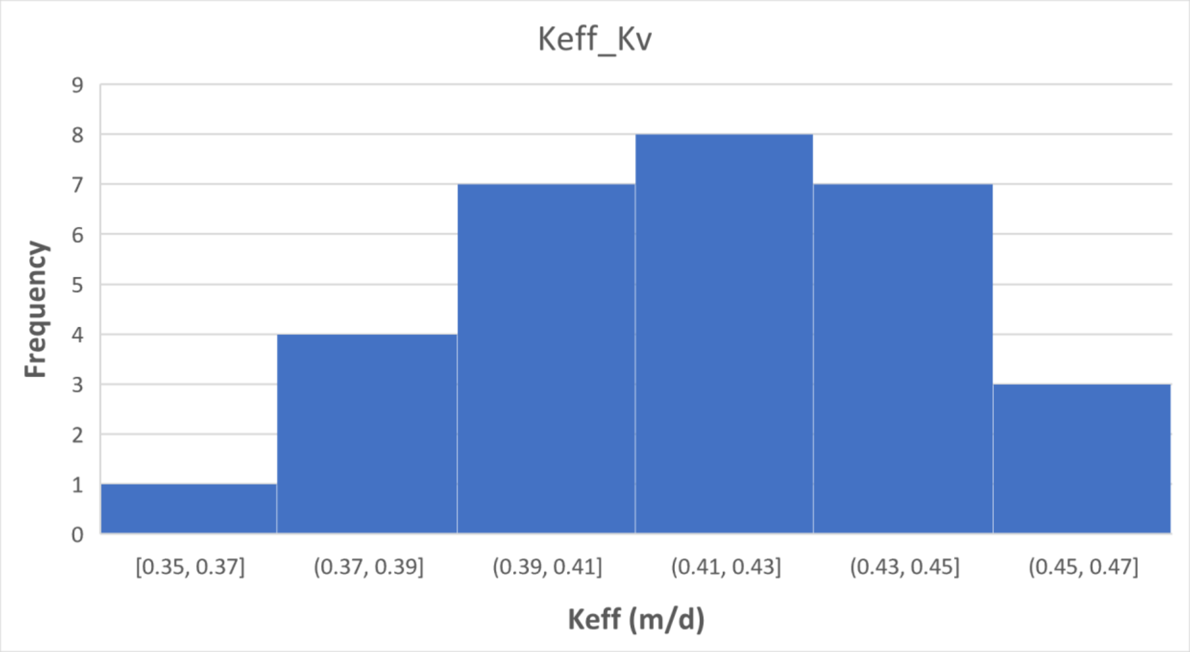
Appendix 2 – TPROGS Model domain extents

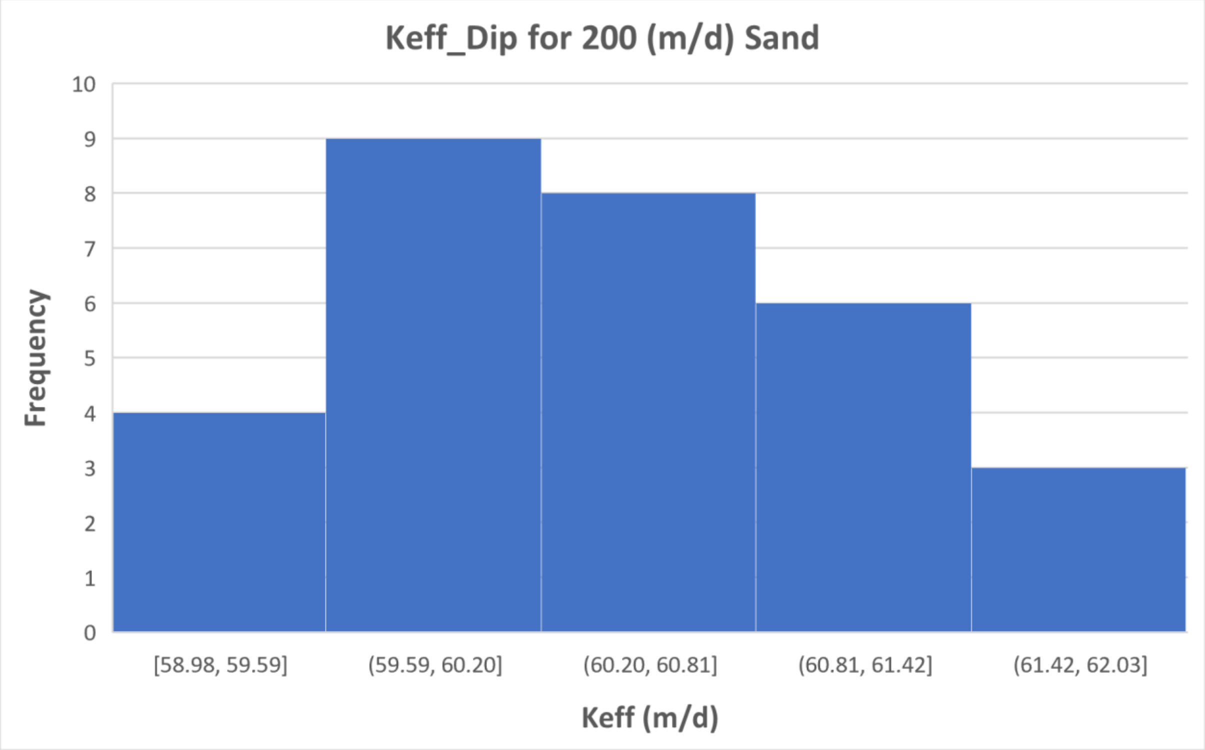
TPROGS Model Domain	
Grid type	Cell Centred
X origin	383856.9
Y origin	6482338.5
Z origin	-210
Length in X	1000 m
Length in Y	1000 m
Length in Z	165 m
Cell X	10m
Cell Y	10m
Cell Z	1m

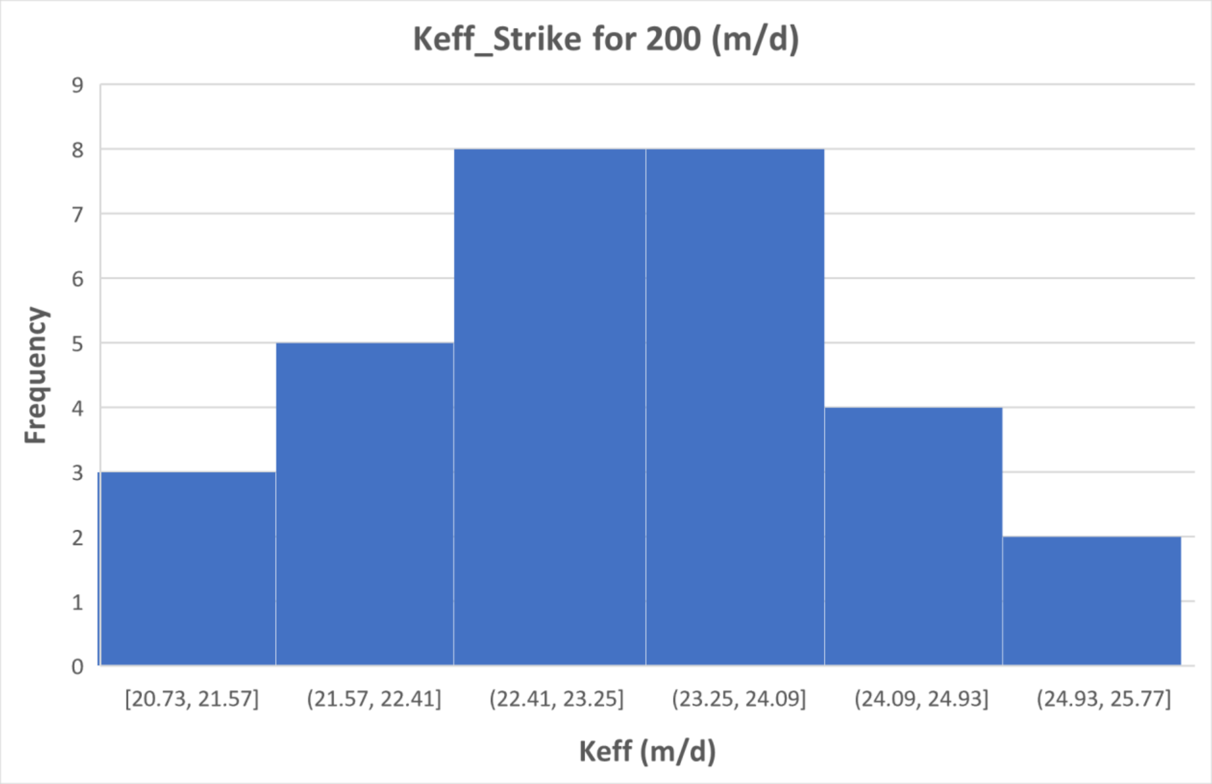
Appendix 3 – Effective conductivity histograms for Dip, Strike and vertical orientation s of the various FloPy stochastic simulations.

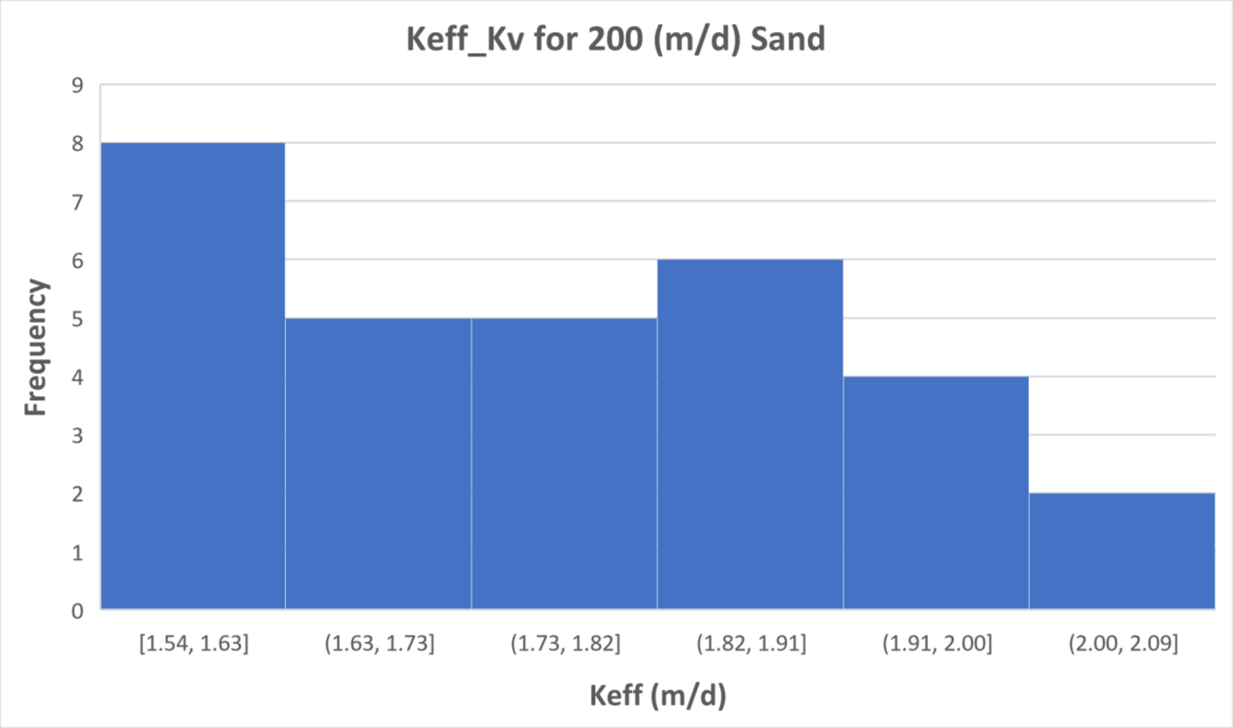


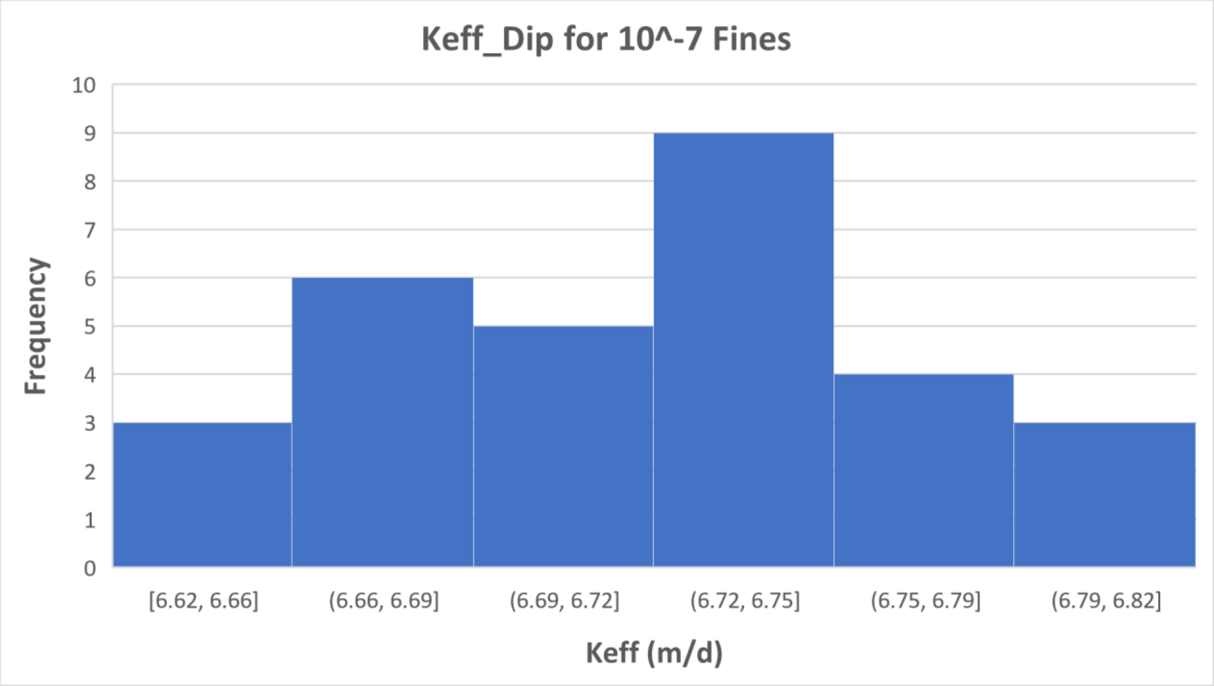


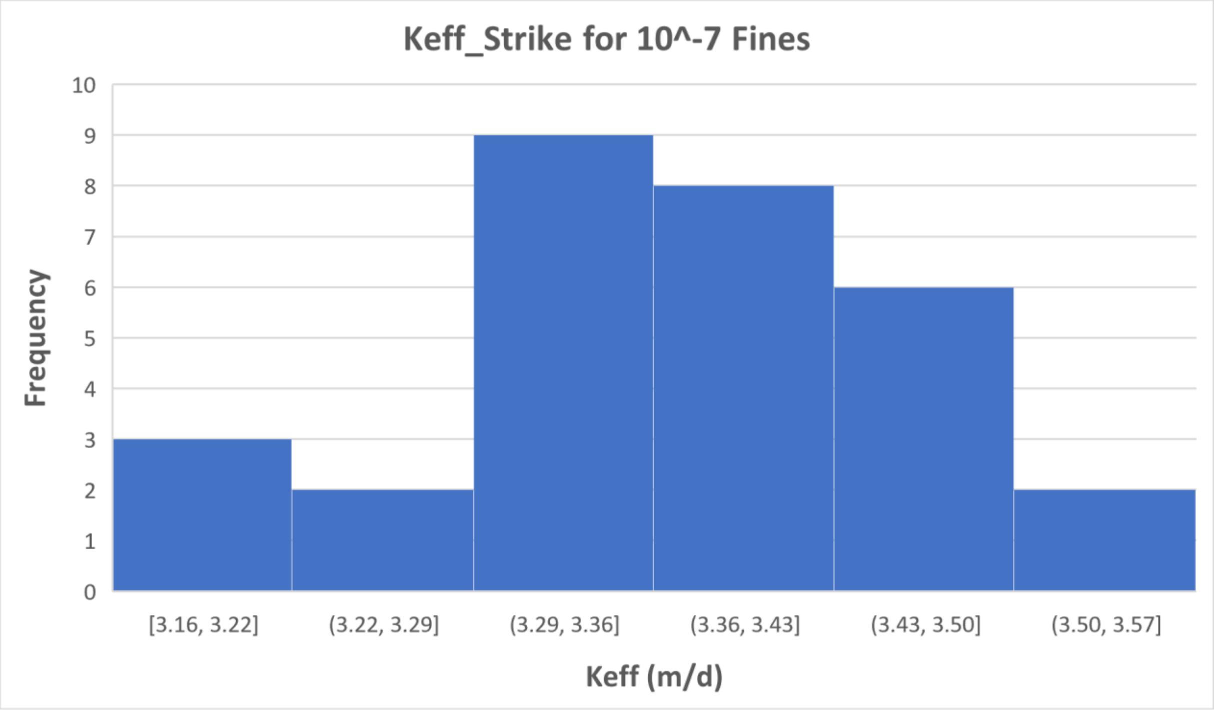

Keff_Kv
Frequency
0
1
2
3
4
5
6
7
8
9
[0.35, 0.37]
(0.37, 0.39]
(0.39, 0.41]
(0.41, 0.43]
(0.43, 0.45]
(0.45, 0.47]
Keff (m/d)

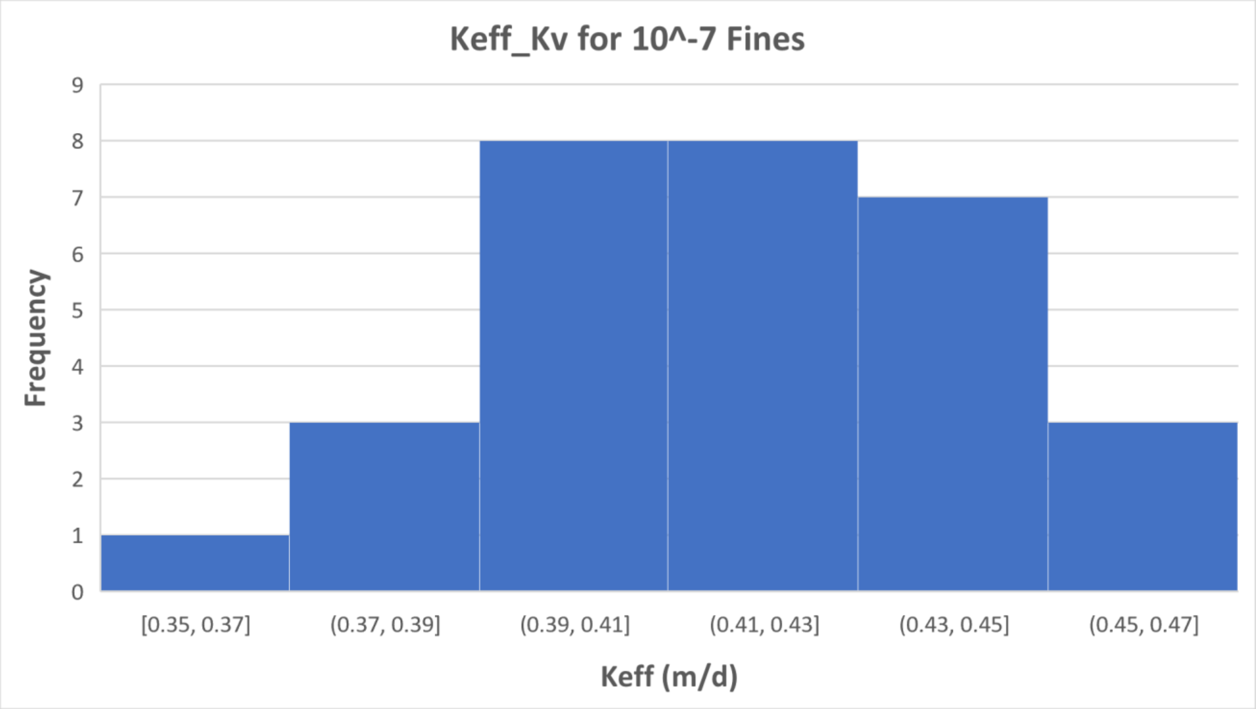

Keff_Dip for 200 (m/d) Sand
Frequency
0
1
2
3
4
5
6
7
8
9
10
[58.98, 59.59]
(59.59, 60.20]
(60.20, 60.81]
(60.81, 61.42]
(61.42, 62.03]
Keff (m/d)

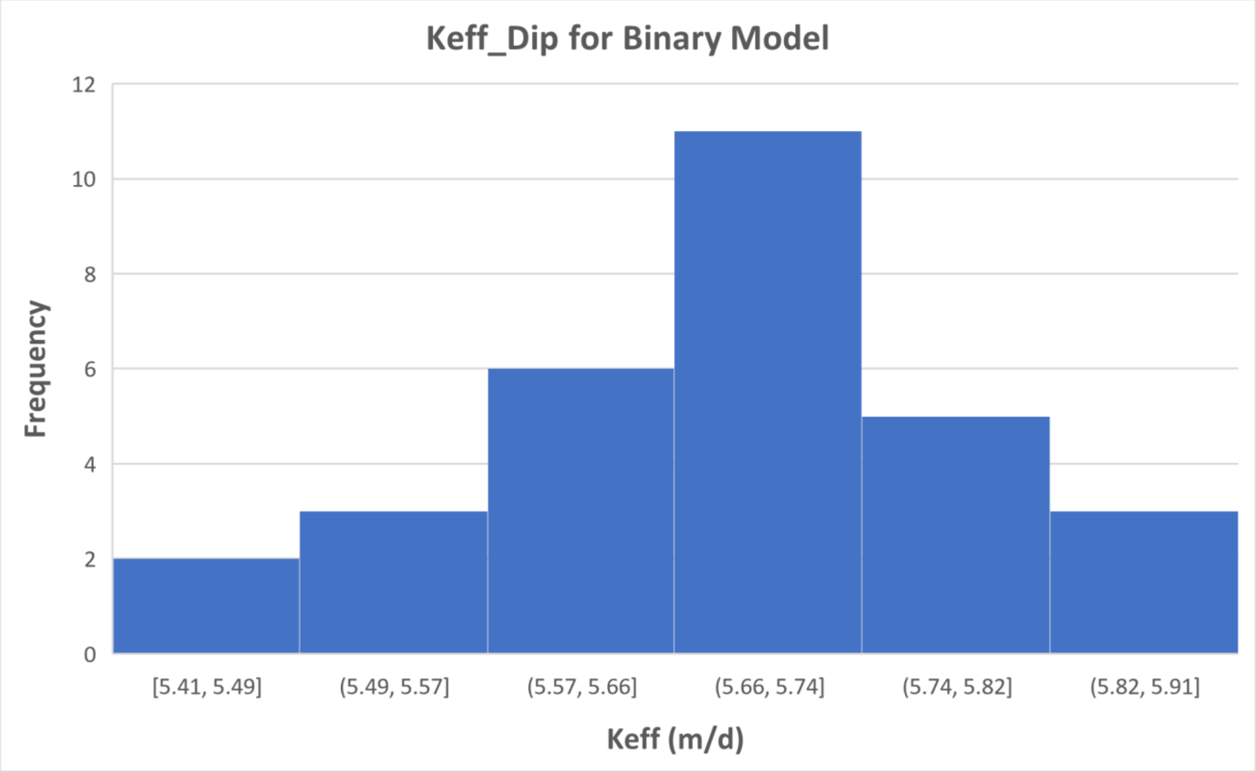

Keff_Strike for 200 (m/d)
Frequency
0
1
2
3
4
5
6
7
8
9
[20.73, 21.57]
(21.57, 22.41]
(22.41, 23.25]
(23.25, 24.09]
(24.09, 24.93]
(24.93, 25.77]
Keff (m/d)

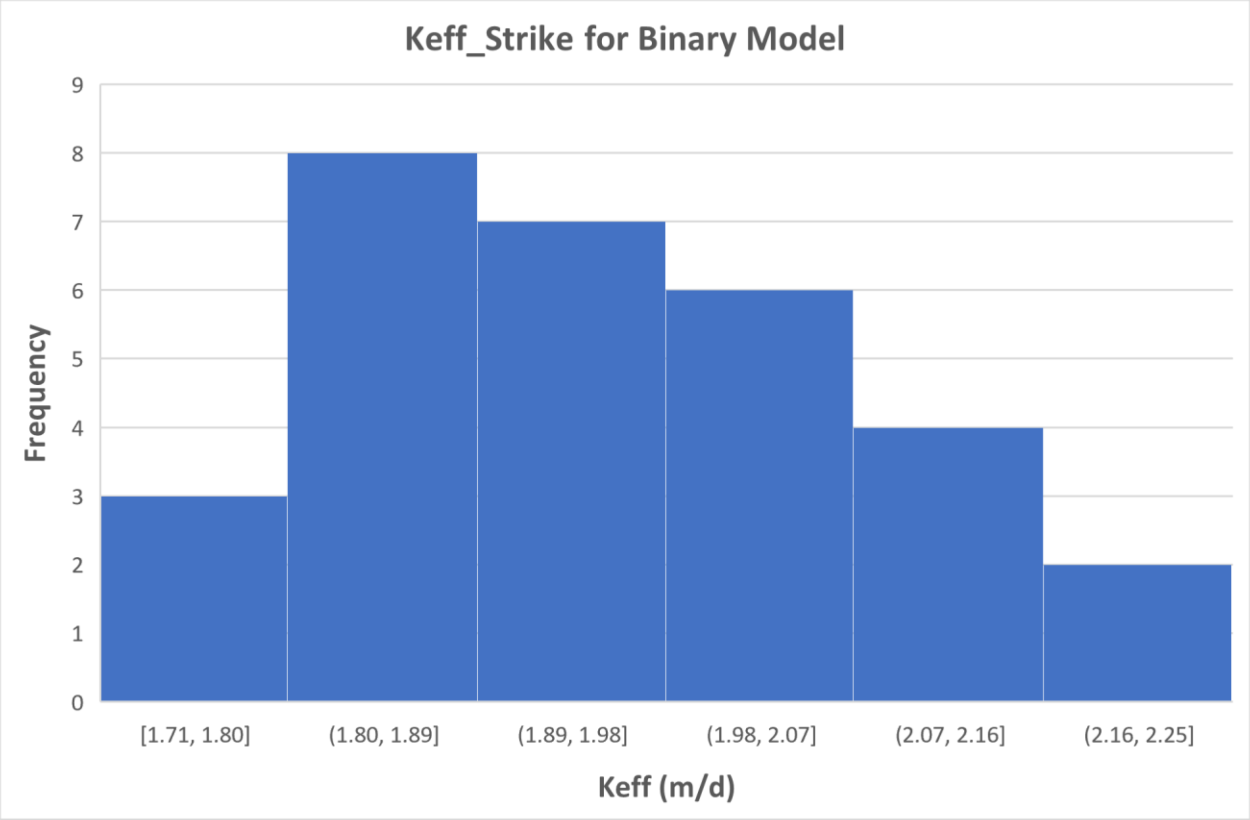

Keff_Kv for 200 (m/d) Sand
Frequency
0
1
2
3
4
5
6
7
8
9
[1.54, 1.63]
(1.63, 1.73]
(1.73, 1.82]
(1.82, 1.91]
(1.91, 2.00]
(2.00, 2.09]
Keff (m/d)

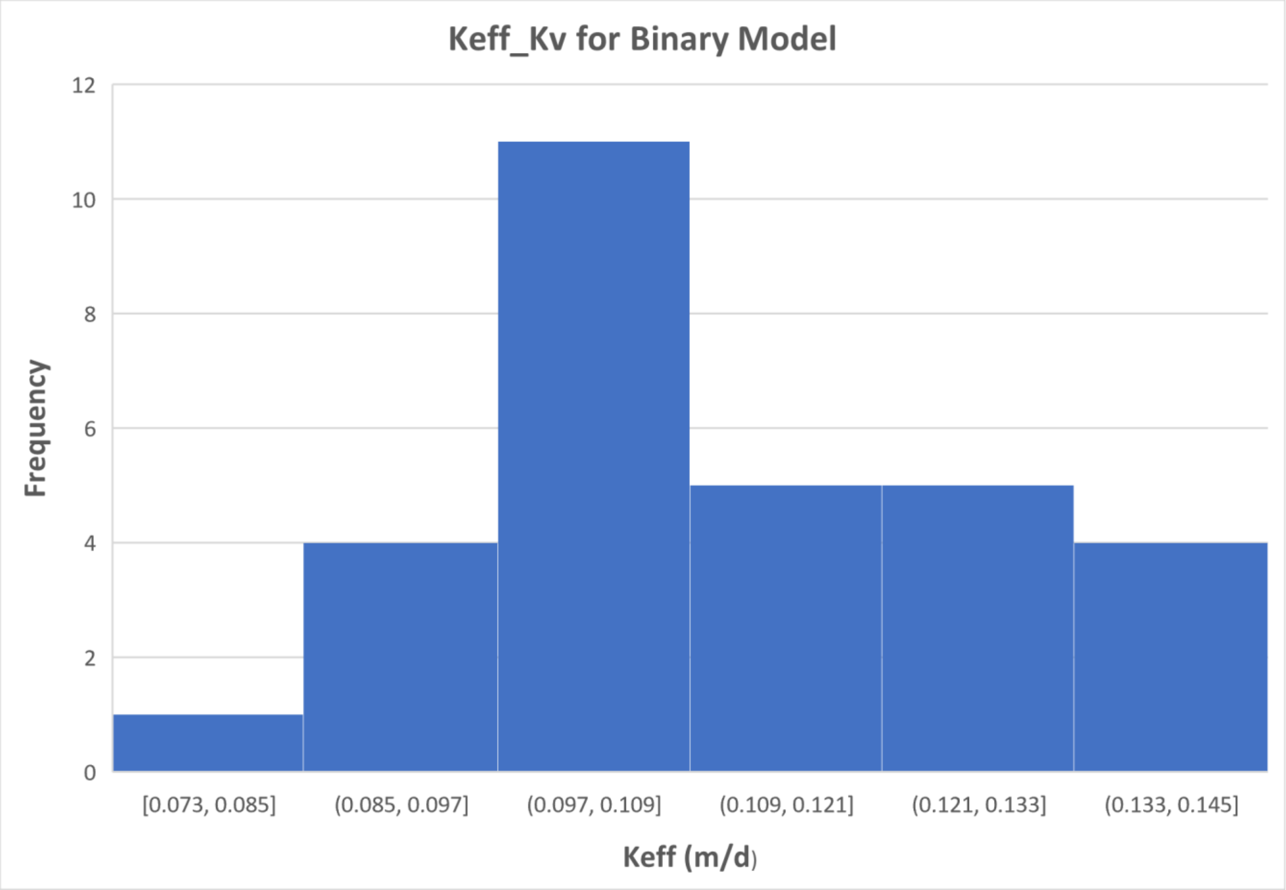

Keff_Dip for 10^-7 Fines
Frequency
10
9
8
7
6
5
4
3
2
1
0
[6.62, 6.66]
(6.66, 6.69]
(6.69, 6.72]
(6.72, 6.75]
(6.75, 6.79]
(6.79, 6.82]
Keff (m/d)


Keff_Strike for 10^-7 Fines
Frequency
10
9
8
7
6
5
4
3
2
1
0
[3.16, 3.22]
(3.22, 3.29]
(3.29, 3.36]
(3.36, 3.43]
(3.43, 3.50]
(3.50, 3.57]
Keff (m/d)


Keff_Kv for 10^-7 Fines
Frequency
0
1
2
3
4
5
6
7
8
9
[0.35, 0.37]
(0.37, 0.39]
(0.39, 0.41]
(0.41, 0.43]
(0.43, 0.45]
(0.45, 0.47]
Keff (m/d)


Keff_Dip for Binary Model
Frequency
0
2
4
6
8
10
12
[5.41, 5.49]
(5.49, 5.57]
(5.57, 5.66]
(5.66, 5.74]
(5.74, 5.82]
(5.82, 5.91]
Keff (m/d)


Keff_Strike for Binary Model
Frequency
9
8
7
6
5
4
3
2
1
0
[1.71, 1.80]
(1.80, 1.89]
(1.89, 1.98]
(1.98, 2.07]
(2.07, 2.16]
(2.16, 2.25]
Keff (m/d)


Keff_Kv for Binary Model
Frequency
12
10
8
6
4
2
0
[0.073, 0.085]
(0.085, 0.097]
(0.097, 0.109]
(0.109, 0.121]
(0.121, 0.133]
(0.133, 0.145]
Keff (m/d)