University of Southern Queensland

Faculty of Health, Engineering and Science

Analysis of Steady State Vs Dynamic Modelling of Groundwater Mounding in Development Areas in WA

A dissertation submitted by

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In fulfilment of the requirements of

ENG4111 and ENG4112 Research Project

towards the degree of

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Abstract

In Western Australia, a key design requirement in the land development industry is to ensure that finished lot levels have sufficient separation to groundwater levels. This is to ensure the practical and economic construction of dwellings, as well as to protect the amenity of the dwellings and provide recreational areas and gardens that are not water logged and fit for use. To achieve this there are two standard methodologies used within the industry being, the filling of lots to gain separation and/or the provision of adequate subsoil drainage to lower and control groundwater. The cost of importing fill to development sites is becoming increasingly high as existing sand supplies are becoming exhausted. There is also a considerable environmental cost to extracting and transporting sand fill. Hence, the accuracy of the design techniques used to asses fill requirements and drainage systems is paramount in providing efficient, economically viable designs. There are various models and methodologies used throughout the industry in the design of drainage systems and earthwork levels, these include steady state models such as the Hooghoudt equation, as well as dynamic software models like MODFLOW. This report investigates a selection of these models and the variance between them as well as the different techniques and methods for disposal of stormwater.

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Limitations of Use

Certification

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

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Luke Rusconi

07/10/2016

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Acknowledgements

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I would also like to acknowledge the assistance of Water and Environment Engineer of Calibre Consulting (Aust), Bishwa Mishra. Bishwa provided assistance in helping me learn the basics of the MODFLOW software package and was also willing to listen and debate the various theories that I was developing throughout my work on this project.

Finally, and most importantly I would like to thank my wife Kristy for her support and understanding for the last 6 years. It was Kristy who inspired me to undertake these studies and without her unwavering support the completion of this degree would not have been possible.

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1.0 Introduction

In Western Australia, the design principles employed in the land development industry are significantly influenced by the practices of the Building and Construction Industry, specifically, the market value of development lots due to site classification, construction techniques and costs. Residential property builders have for a long time required residential development lots to have a geotechnical classification of ‘A’ or ‘S’ class. This is the highest classification and requires that the lots will experience minimal settlement. For this classification minimal footings and slabs are require for building construction and as a result are the most cost effective option from a building point of view. Because this style of building has become the “norm” in Western Australia, if lots of a lower classification are produced they are subject to significantly increased construction costs for larger footings and slabs and as a result are difficult to sell in the market. Because of this market driven requirement, land developers are required to import large quantities of fill material to site to fill proposed lots and achieve the required site classification.

This construction technique has an unwanted effect on clay sites. The effect of placing clean sand fill on clayey impermeable layers is the creation of a perched groundwater level within the clean sand profile. Engineers are required to design adequate drainage systems and earthwork levels to control and provide separation to these groundwater levels.

Another common scenario facing the land development industry in Western Australia is high, naturally occurring water table. Sandy pervious sites with high groundwater levels at or close to natural surface are common. On these sites, imported sand fill is placed in combination with subsoil drainage, not to achieve site classification, but to achieve a required separation to groundwater. This separation is required to allow the construction of footings and pads for buildings, protect houses from rising damp, and to ensure the general amenity of recreational areas.

In Western Australia the common method of disposing of stormwater on lots is to connect roofs and hardstand areas to soak wells. Stormwater is recharged to the sand profile as concentrated flow contributing to the mounding of groundwater levels. Rainfall also soaks through turf and garden areas as a more uniform infiltration to the sand profile. This recharge of stormwater within the sand layer can cause considerable groundwater mounding. If there is insufficient separation to the groundwater table, building foundations can be affected and the efficiency of stormwater drainage systems can be reduced. Prolonged surface inundation can degrade recreation areas and in extreme cases can affect the integrity of road pavements. Engineers are required to carry out calculations to assess the degree of groundwater mounding so that drainage systems and earthwork levels can be designed to ensure that relevant specifications for clearance to groundwater are met.

The cost of importing fill to construction sites is significant, both economically and environmentally. Economically, it is generally the single most expensive construction element in land development. The availability of sand is limited so contractors are forced to pay elevated rates for the product and are quite often required to haul the material long distances from available pits to the site. The environmental approvals required to create sand pits for the extraction of fill are significant and there are few sites suitable for extraction as they require extensive clearing and damage to native habitat. There is also an environmental cost associated with the transportation element in carting material long distances from these sand pits to construction sites.

Given these economic and environmental costs there is a strong focus on minimising the amount of fill required on development sites. It is critical that engineers use the most relevant and accurate methods for the calculation of groundwater mounding and ultimately the determination of the required fill level. This project will review a selection of the methods available to engineers for calculation of the mounding and will compare and make comment on the variances and relevance of each method.

1.1 Aims and Objectives

The aims of this project are to conduct an analysis on a typical test case or test cases using a selection of groundwater mounding calculations and to review and comment on the results and the factors that affect the calculations. The main objectives of this research are:

- To apply a selection of equations/methodologies for the calculation of groundwater to a typical test case scenario.
- To compare and analyse the variance in the results.
- To conduct a cost comparison to find the most cost effective option in achieving the required groundwater separation.

2.0 Literature Review

This literature review provides information that gives an overview of groundwater mounding and the relevant components and equations that affect groundwater mounding. An overview of Western Australian drainage design principles and relevant guidelines is included also.

2.1 Study Area

For the purpose of the proposed analysis a theoretical model will be prepared based on the site characteristics experienced in Dunsborough, Western Australia. The theoretical model will be based on a standard back to back lot configuration commonly seen in urban development and will represent a perched groundwater situation.

2.2 Location

The theoretical site will be assumed to be relatively flat which is characteristic of the Dunsborough/Quindalup region and the majority of the Swan coastal plain.

The existing soil profiles in the area consist of thin layers of sandy topsoil over clayey sand and silty sand. These soil types typically have very low permeability values and are subject to shrink swell characteristics between the drier and wetter months. A typical bore log taken in the Dunsborough Lakes Estate is shown below.

Excavation					Sampling			Field Material Description					
METHOD	EXCAVATION RESISTANCE	WATER	DEPTH (metres)	DEPTH RL	SAMPLE OR FIELD TEST	ACID SULPHATE SAMPLE	RECOVERED	GRAPHIC LOG	USCS SYMBOL	SOIL/ROCK MATERIAL DESCRIPTION	MOISTURE CONDITION	CONSISTENCY DENSITY	STRUCTURE AND ADDITIONAL OBSERVATIONS
E	F		0.0 – 1.0						SP	SAND: fine to medium grained, brown becoming grey, trace organic fines and rootlets in top 0.2 m, with some non-plastic fines	W / M	MD	Perched water encountered at surface
			1.0 – 2.5						SC	Clayey SAND: fine to coarse grained, mottled grey and orange, 20-30% medium to high plasticity fines, with some fine to coarse grained iron cemented gravel	M	F	
			2.5 – 4.0							Hole terminated at 2.50 m Target depth Groundwater not encountered			

Sketch & Other Observations

Comments:	See Explanatory Notes and Method of Soil Description sheets for details of abbreviations and basis of descriptions

Figure 1 – Typical soil Characteristics (Calibre Consulting (AUST) Pty Ltd)

Dunsborough has a typically Mediterranean climate, with the majority of annual rainfall occurring in winter. The wettest month according to the Bureau of Meteorology website is June with a mean monthly rainfall of 162.9mm. The annual average rainfall for Dunsborough is 805mm. The IFD chart for Dunsborough is shown below.

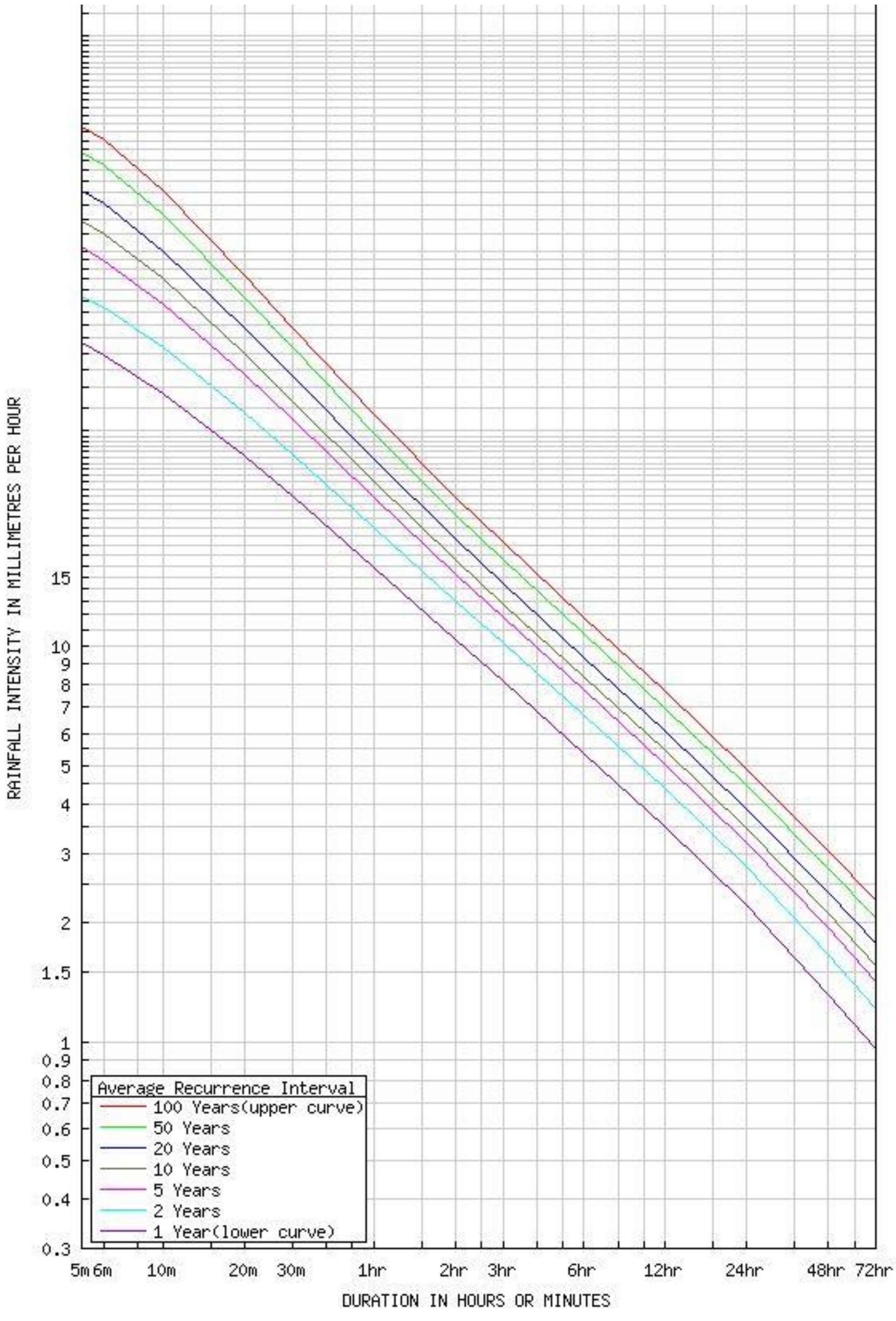

Figure 2 – Dunsborough Rainfall Intensities (Bureau of Meteorology)

2.3 Groundwater Characteristics

Groundwater exists where pores within a soil profile are completely saturated with water. Rainfall seeps into the soil and moves downward until it reaches a state of saturation or an impermeable layer.

In the perched water table conditions to be analysed in the theoretical model, two zones exist within the soil profile that are described in terms of their moisture content, these being the unsaturated zone and the saturated or phreatic zone. In the unsaturated zone, the pore spaces in the soil profile are only partly filled with water. The saturated zone exists where the pore spaces in the soil profile are completely filled with water. Capillary action can cause further rise of the groundwater surface above the phreatic surface and is shown in the figure below as the capillary fringe.

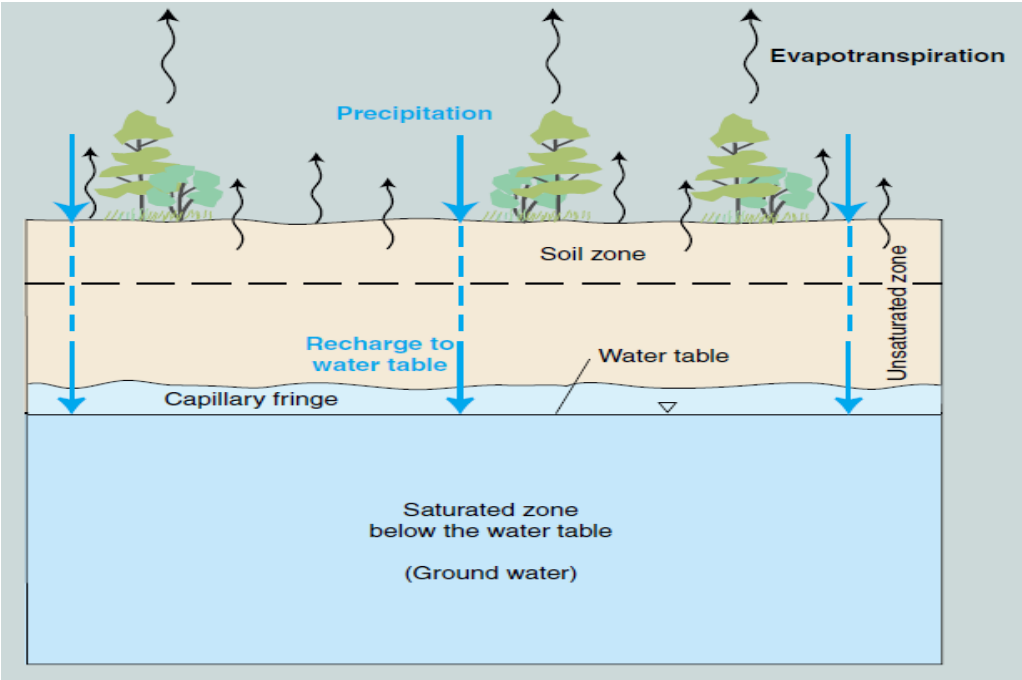

Figure 3 – Groundwater definitions Source: USGS Sustainability of Ground Water Resources 1999 (Alley, MA, Reilly, TE, Franke, OL 1999 p6)

Capillary rise occurs as moisture adheres to the surface of sand grains. The rate of capillary rise is generally a lot slower than fluctuations of the phreatic surface due to stormwater recharge. After a storm event the time required to see a fluctuation in the water surface due to capillary rise is a lot longer than the time required for the phreatic surface to rise and then begin to return to prior levels, as such the relevance of capillary rise to groundwater mounding is minimal.

2.4 Unsaturated Flow

The region above the phreatic surface is where unsaturated flow occurs. In the case being used for this theoretical model this flow will be due to rainfall infiltration and stormwater recharge from soak wells. This rate of movement of water in the unsaturated zone is described by the unsaturated hydraulic conductivity which (Ritzema 1994) suggests is the single most important parameter affecting water movement in the unsaturated zone.

2.5 Saturated Flow

Saturated flow occurs below the phreatic surface where the pore space is completely filled with water. In the example being analysed the horizontal flow of water above the clay layer toward the subsoil drains is an example of saturated flow. The rate of flow is a function of the hydraulic head and is affected by the saturated hydraulic conductivity of the soil.

2.6 Hydraulic Conductivity

Hydraulic conductivity or permeability of a soil is the most significant soil parameter influencing subsurface drainage design. (Hillman and Cocks 2007), advise that the hydraulic conductivity of sand in the Perth area varies as a result of fines content, which is defined as the percentage fines less than 0.075 mm particle size. Values vary from less than 1 m/d to 10 m/d. Figure 4 shows a typical PSD for imported fill sand used in the Dunsborough region.

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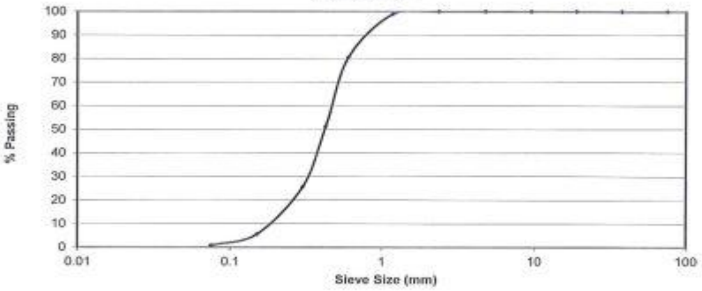
TEST REPORT

Sheet No. 1 of 1

CLIENT: Busselton Civil & Plant Hire	SAMPLE NO: CT 50984
PROJECT: Kaloorup Pit	JOB NO: 96-1-40
LOCATION: Submitted Sample	FIELD DESCRIPTION: Sand
	DATE PSD TESTED: 11-Feb-15
PROPOSED USE: -	DATE PI/LS TESTED: -
CLIENT REF: -	DEPTH: -

PARTICLE SIZE DISTRIBUTION

AS 1289.3.6.1



PARTICLE SIZE DISTRIBUTION AS 1289 .3.6.1			
Sieve Size	% Passing	Sieve Size	% Passing
75.0 mm	100	1.18 mm	99
37.5 mm	100	0.600 mm	80
19.0 mm	100	0.425 mm	51
9.5 mm	100	0.300 mm	26
4.75 mm	100	0.150 mm	6
2.36 mm	100	0.075 mm	1

PLASICITY INDEX & LINEAR SHRINKAGE	
Liquid Limit % AS 1289.3.1.1	n/a
Plastic Limit % AS 1289.3.2.1	n/a
Plasticity Index % AS 1289.3.3.1	n/a
Linear Shrinkage % AS 1289.3.4.1	n/a
Length of Mould mm	n/a
Sample history	n/a
Sample Preparation Method	n/a
Nature of Shrink	n/a

Notes:

Sampled by Client

Approved Signatory: H.Yama

Date: 13-Feb-15

Report Number: CT 50984 / 1

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Figure 4 – Typical Particle Size Distribution for Fill Sand in the Dunsborough Region. (Calibre Consulting (Aust) Pty Ltd)

A hydraulic conductivity of 5m/day for fill sands imported to sites and compacted is considered to be sufficient for design purposes. The table below gives indicative saturated hydraulic conductivity values for various soil mediums.

Soil Texture Class	K_{sat} (mm/hr)	K_{sat} class
Coarse Sand	360	Very Rapid
Sand	208	Rapid
Loamy Sand	61	Rapid
Loam Fine Sandy	36	Moderately Rapid
Sandy Loam	26	Moderately Rapid
Fine Sandy Loam	19	Moderately Rapid
Loam	13	Moderate
Silt Loam	7	Moderate
Silt	7	Moderate
Sandy Clay Loam	4	Moderately Slow
Clay Loam	2	Moderately Slow
Silty Clay Loam	1.5	Moderately Slow
Sandy Clay	1.2	Slow
Silty Clay	0.9	Slow
Clay	0.6	Very Slow

Table 1 – Indicative saturated hydraulic conductivity values for various soil mediums (UNSW 2007)

2.7 Specific Yield

Specific yield is another soil property that is significant when considering subsurface flow. Hillman Cocks 2007 define this as the "amount of water released as the sand is drained, measured as a proportion by volume, or conversely the amount required to fully saturate the soil". When the soil profile is free draining, a percentage of water is held due to capillary forces which means that the specific yield is less than the porosity as the pore space is partially filled with water. A figure of greater than 0.2 but less than 0.25 is indicative imported fill sands (Davidson, 1995).

2.8 Steady State Flow

(Leach and Volker 2005) summarise steady state flow as, a flow that occurs when, the magnitude and direction of the flow at any point in an area of analysis are constant with time. Steady State flow produces a curved surface as shown in the diagram below. The maximum mounding generally occurs at the midpoint between subsoil drains except when concentrated recharge occurs that may cause localised mounding.

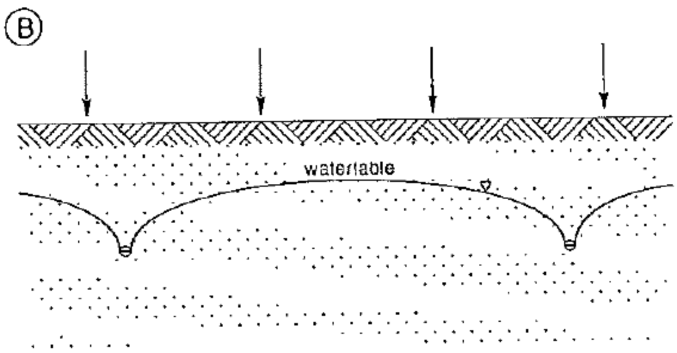


Figure 5 – Typical mounding under steady state conditions: Drainage Principles and Applications (Ritzema HP 1994)

(Ritzema 1994), summarised that in calculating steady state flow situations, flow is considered two dimensional, recharge is uniform and the soil profile is homogenous and

Isotropic and as such there would be no variance in hydraulic conductivity throughout the soil profile.

2.9 Unsteady or Transient Flow

Transient flow occurs when recharge rates, or infiltration varies with time. Transient flow is common and equations representing this type of flow are regularly used in software packages to calculate subsurface flow for use in engineering situations, infiltration problems and pump tests (Leach and Volker 2005).

2.10 Swan Coastal Plain Groundwater Environment

Barber 2005, reported that aquifers exist within the Aeolian sands and coastal limestone that exist on the Swan Coastal Plain. These aquifers are recharged by infiltration from rainfall. There are extensive swamps and wetlands that exist along the Swan Coastal Plain that rely on groundwater systems. Ephemeral streams exist on the eastern extremity of the plain into which groundwater also discharges as well as significant river systems like the Swan and Moore Rivers.

Mounding of the groundwater occurs across the plain due to recharge from rainfall infiltration, with the highest point of the mounding occurring centrally, then tapering off to the discharge points in the east and west. The phreatic surface breaks to the surface in some locations due to the undulating shape of the natural surface. These are the locations at which swamps, wetlands and damp lands have formed, with the size and depth of these features fluctuating with groundwater rise and fall. In areas of urban development and horticultural land uses many of these waterbodies have become eutrophic. Management strategies including artificial recharge, groundwater use limitations, groundwater monitoring and modelling have all been employed with varying degrees of success, however they have not prevented a decline in groundwater levels at a steady rate since the 1950s. In extreme cases some wetlands no longer exist (Barber 2005).

2.11 Dwellings, Buildings, Development Issues

2.11.1 An Overview of Western Australian Drainage Design Principles

In Western Australia, drainage design principles are generally developed and enforced by the various local governments and the Department of Water. In general, small 1 year 1hr events are captured and soaked in bio-retention systems located at source within road reserves. These are designed in accordance with "Water Sensitive Urban Design" principles and are enforced and controlled by the Department of Water. 1 in 5-year storm events are captured and directed to street drainage where stormwater pit and pipe systems are sized for the 1 in 5-year event. The design of these systems are based on the rational method as detailed in Australian Rainfall and Runoff. These pit and pipe systems discharge to detention or soakage basins which are sized to reduce the peak "post development" storm discharge to a rate equalling the "pre development" peak storm discharge. Slotted subsoil drains as shown in Figure 6 are constructed to protect road pavements, building slabs and public amenities from rising groundwater levels.

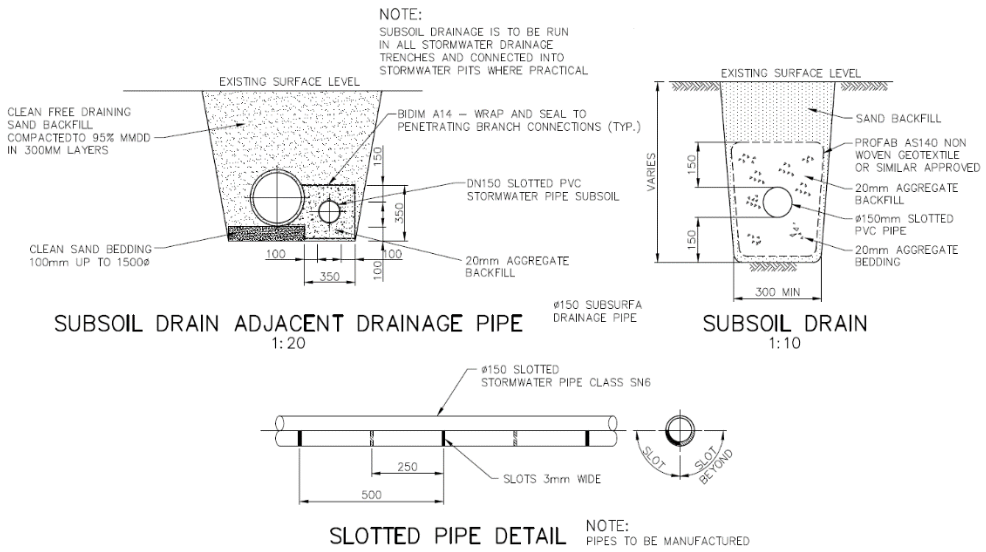


Figure 6 – Typical Subsoil Details (Calibre Consulting (Aust) 2016)

For residential developments there is generally two alternatives for the onsite treatment of stormwater for individual lots. Generalised figures showing these are shown below.

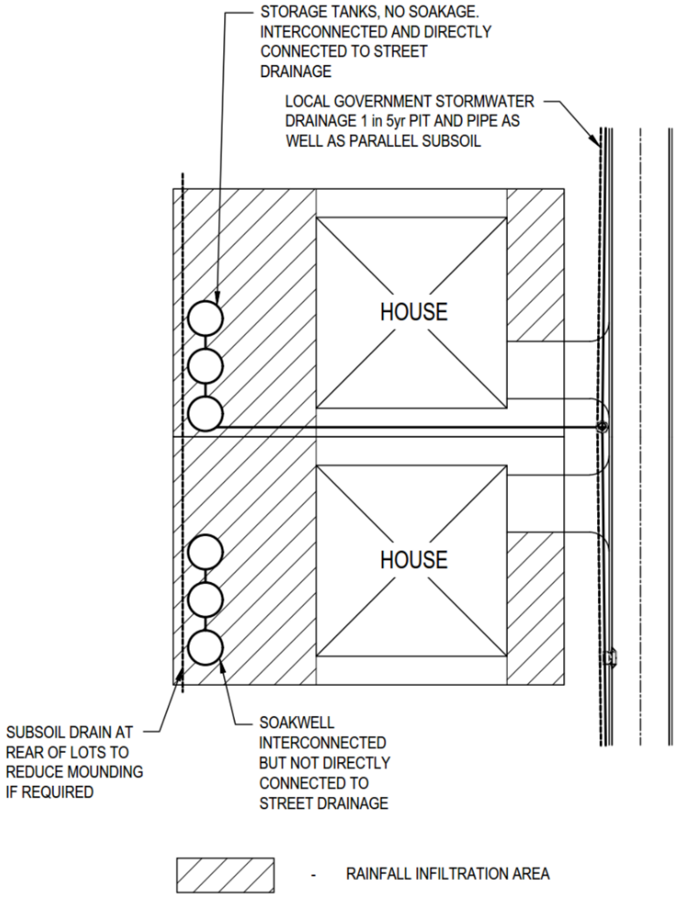


Figure 7 – Typical Residential Onsite Drainage Systems

The first option is by way of traditional soak well pits. Roof drainage from buildings and stormwater runoff from hardstand areas is directed to soak wells where it is detained and soaked into the soil recharging the groundwater profile. The number, or volume of the soak wells per lot is determined by the overall drainage design but in general they are normally sized to cater for a portion of the 1 in 5-year event with the remainder of the storm event accounted for in the street drainage design. There are pros and cons to this method of onsite stormwater disposal.

Pros: Stormwater is recharged to the groundwater profile at or close to the source of the rainfall. It is a tried and true drainage system that requires little to no maintenance and its design is very simplistic and does not require professional expertise for maintenance or construction. It is also a standalone system that has no interconnection to the local government street drainage.

Cons: Soak well disposal of stormwater results in a high level of water recharge to the soil profile. This causes increased groundwater mounding and as a result increased levels of fill to achieve the required separation distances. Subsoil drainage is also required to reduce the effect of mounding. Subsoil is generally placed in the street running parallel to street drainage but in some instances may also be required in the rear of properties as the shorter the separation between subsoil drains the less the mounding.

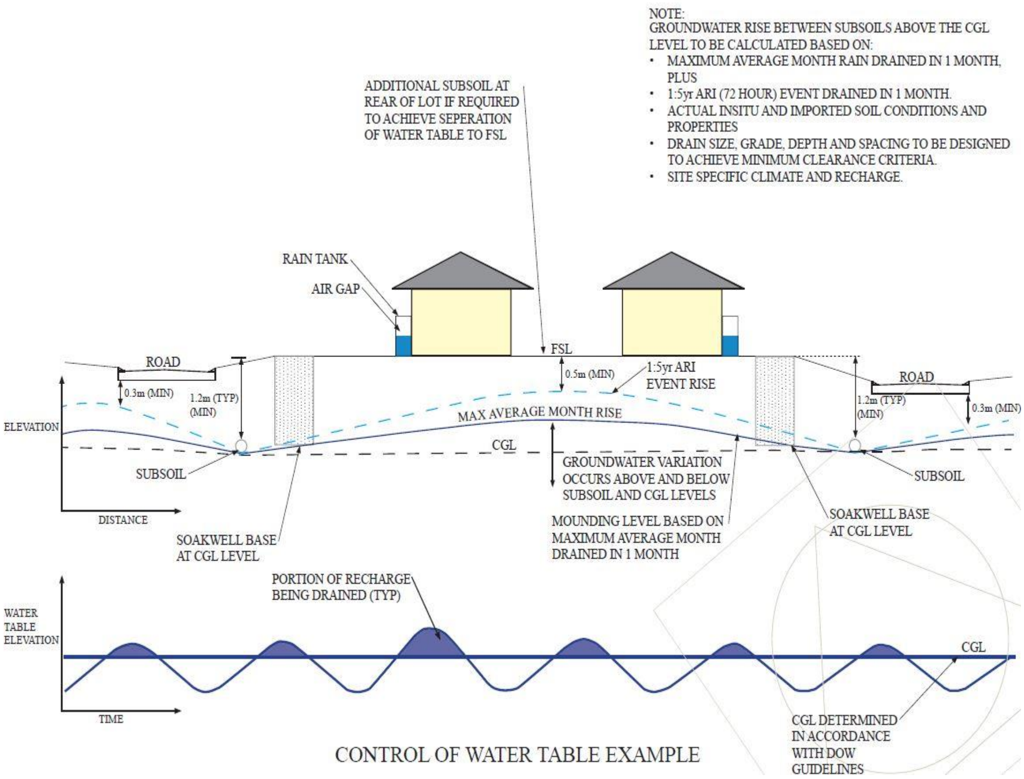


Figure 8 – Groundwater mounding requirement (Calibre Consulting (Aust) Pty Ltd)

The second option available for onsite treatment of stormwater is to install solid walled sub surface tanks (not perforated) that connect to the local government street drainage. These tanks do not allow soakage with their sole purpose being to store and detain flow. A throttled outlet is installed from the tanks to a connection point in the street drainage, this outlet is sized so that the tanks fill up during the peak storm event but do not over flow. There are also pros and cons to this method of stormwater disposal.

Pros: The amount of water recharged to the soil profile beneath residential slabs and footings is minimal and as a result reduced groundwater mounding is experienced. The amount of fill required on the development site is drastically reduced providing an obvious economic benefit as well as an environmental benefit in the reduction of carting and extraction of sand fill.

Cons: It could be argued that transporting the stormwater away from the source via piped stormwater systems and disposing or soaking it at an end point location is interrupting the local cycle and movement of groundwater. There is also a direct interaction between the onsite disposal system and the local government street system which can cause complications with maintenance responsibilities.

2.11.2 Relevant Legislation and Guidelines in Western Australia

The land development industry in Western Australia has developed a series of accepted groundwater separation distances and guidelines through individual's experience and general industry discussion. The "IPWEA Draft Specification for Separation distances for groundwater controlled urban development" was developed to formulate these guidelines and provide a guide to engineers working within the industry. The following is a summary of this guideline with detail removed that is not seen as relevant to this project.

The objective of the groundwater separation distance guidelines, as described in the document, "is to provide criteria (specifications) for groundwater separations appropriate to acceptable levels of risk and amenity for critical elements of built form and infrastructure and provide guidance regarding appropriate methodology (design) for assessment and approval of groundwater levels and separations" (IPWEA 2016).

When designing subsurface infrastructure, modelling is required to ensure that drainage systems will be sufficient for their purpose. Generally, when assessing subdivisions and their subsurface drainage requirements, analysis will be conducted on several typical locations within the development. This would include a section through a typical back to back lot configuration and potentially any recreational areas where drainage and groundwater mounding may be an issue.

The design of groundwater systems is integral to the performance of:

- Roads and service infrastructure.
- Earthworks design.
- Landscape elements including public open space and water quality treatment systems.

The Better Urban Water Management (WAPC 2008) document requires urban water management plans to be prepared at each stage of the development process. The IPWEA document summarises the requirements for groundwater design at each stage in the table below.

Planning stage	Requirement
District water management strategy	Modelling of groundwater mounding is not required. . The DWMS should identify if groundwater management may be necessary based on a review of available regional bore data available from the Department of Water's Water Information Network and consider key defining factors including key receiving environments; complexity and connectivity of groundwater resources/aquifers; and groundwater dependent ecosystems.
Local water management strategy	Define appropriate controlled groundwater level and describe the implications for any identified groundwater dependent ecosystems. Include ground-truthed desktop investigations with sufficient detail to provide a conceptual understanding of the site conditions. This includes establishing if the site is part of the regional system or a local aquitard. Preliminary modelling to consider fill implications for the potential drainage system layout (spacing of road reserves) is required and should provide 'proof of concept' for the proposed design. Design parameters (eg for imported fill) may be specified generically.
Urban water management plan	Modelling to develop and test the subsoil drainage system is required and should incorporate the following level of detail: • Designed urban form; • Investigated and/or designed geotechnical conditions; • Measured and/or specified parameterisation; and • Designed drainage system. Detailed geotechnical investigations with sufficient coverage to provide a detailed understanding of the site conditions are required. Design parameters (eg for imported fill) applied in modelling should be identified as a part of construction specifications. In-situ testing for key parameters may be required during construction as part of quality control and/or following construction prior to practical completion.

Table 2 – Summary of groundwater modelling requirements – Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p4)

2.11.2.1 Models

The IPWEA document gives guidance on model selection for various tasks.

A selection of modelling methodologies are currently used by the industry. The various model types which the document considers appropriate are:

• Steady state calculations which are typically spreadsheet based.

• Dynamic models which can be spreadsheet based or developed within software packages.

2.11.2.2 Boundary/Initial Conditions

The IPWEA guideline summarises the use of boundary conditions and what is deemed appropriate for design.

For simplified 1-dimensional models invert levels can be set at either the invert level of the pipe or at the half full level of the subsoil drain. Drains should be assumed to be free flowing so that the hydraulic conductivity of the sand is the factor affecting flow and not the drain discharge capacity. In areas where no subsoil drainage exists it is suggested that a worst case groundwater level at the boundary may need to be considered.

For two dimensional or three dimensional models fixed or variable boundary conditions should be established using regional or district scale modelling and or, if available, groundwater monitoring data meeting the requirements of the Australian groundwater modelling guidelines (Sinclair Knight Merz).

2.11.2.3 Geotechnical and Hydrological Parameters

(IPWEA 2016) defines the following parameters to be applied when undertaking design calculations:

- Specific yield for imported fill = 0.2
- Hydraulic conductivity for imported fill = 5 m/day

The guideline also proposes recommended net recharge ranges for different scales of groundwater investigation. See Table 3 below.

Land use	Net recharge range
Lot scale 1D modelling:	
Roof/hardstand (with soakage)	80-90%
Roof/hardstand (with pipe connections)	0-10%
Vegetation	10-20%
Turf	40-50%
Street scale 1D or small scale 2D/3D modelling:	
Lots (R10-30 with soakage)	50-60%
Lots (R10-30 without soakage)	10-20%
Lots (30 and above with soakage)	70-90%
Lots (R30 and above without soakage)	10-15%
Road reserves (with soakage)	80-90%
Road reserves (without soakage)	0-20%
Public open space	10-50%
District/regional scale 2D/3D modelling:	
Urban residential (soakage areas)	60-90%
Urban residential (non-soakage areas)	10-20%

Table 3 – IPWEA recommended groundwater recharge rates - Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p7)

A typical back to back lot cross section is assumed for the ranges shown in table 3, these are made up of portioned recharges from different surfaces as detailed below:

- Hardstand = 0% recharge
- Street soakage = 90% recharge
- Turf = 50% recharge
- Mixed turf/vegetation = 30% recharge
- Concentrated Lot soakage through soak wells =100% recharge

These recharge rates are combined to give a proportioned rate to be used for uniform recharge. The recommended values are

- Small backyards with soak wells = 80% recharge based on a ratio of 100% for roof/hardstand and 50% for turf.
- Large backyards with soak wells = 60% recharge based on a ratio of 100% for roof/hardstand and 50% for turf and gardens.

It was noted that there was no specific detail given in the guideline for what constitutes a "small backyard" or a "large backyard" assumptions would have to be made by the reader to categorise various sites.

2.11.2.4 Separation Distances

The following tables detail "deemed to comply" separation distances for various land uses as outlined in the IPWEA guide. These will be used for further analysis in this project.

Type of drainage infrastructure	Specification
Underground infiltration systems	0mm from the 50% AEP phreatic surface
Surface infiltration systems (vegetated)	300mm from the 50% AEP phreatic surface
Surface infiltration systems (duel function turf)	Default to Recreation POS standards

Table 4 – Drainage infrastructure separation distance - Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p10)

Type of drainage infrastructure	Specification
Residential lots > 800 m2	No criteria. It is expected that design of lots will include site specific consideration of appropriate levels of amenity.
Residential lots 400 m2 to 800 m2	300mm of coarse sand applied to anticipated garden areas in the rear of lots above the 50% AEP phreatic surface
Residential lots <400 m2	150mm of coarse sand applied to anticipated garden areas in the rear of lots above the 50% AEP phreatic surface

Table 5 – Residential lots separation distance - Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p10)

Soil type	Separation distance
Gravel:	
Coarse	150 mm
Medium	150 mm
Fine	200 mm
Sand	
Coarse	300 mm
Medium	450 mm
Fine	650 mm

* Classification of soils types is based on Table A1 of AS 1726-1993 Geotechnical site investigations.

Table 6 – Turfed Public open space separation distance based on typical soil types - Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p11)

The guideline's generalised approach to subsurface drainage design is to select an appropriate model, calculate the phreatic surface and then add the deemed to comply separation distance to achieve a finished earthwork level. It's worth noting from the figure below that the capillary fringe is not included in the separation distance. This is likely due to the time that capillary effects take place being a lot longer than the time a groundwater mound returns to a normal state after a storm event.

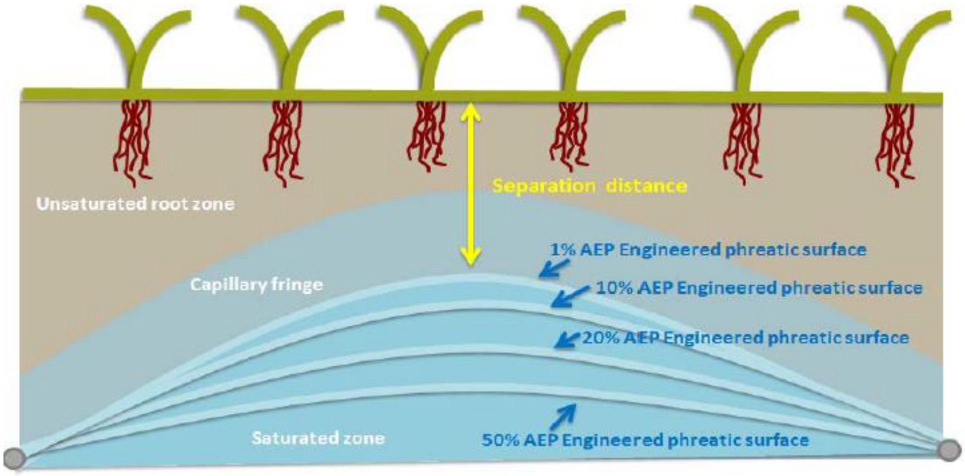


Figure 9 – Correlation between phreatic surface and deemed to comply separation - Draft Specification distances for groundwater-controlled urban development (IPWEA 2016 p12)

3.0 Steady State Equations

3.1 Darcy's Law

In 1856 a French engineer named Henry Darcy published a report that described his study of the flow of water through a sand medium (Leach & Volker 2005). Darcy performed an experiment that measured the head and rate of flow. He observed that that the rate of water flowing through a sand profile per unit of time had a relationship to the difference in head of the water levels from one end of the sample to the other and to the length that the water had to flow.

The result of these findings is known as Darcy's Law and is described in the equation below:

$$Q = -KA\frac{\Delta h}{\Delta l}$$

Where:

Q = Discharge measure in units of volume per time (m^3/s);

K = hydraulic conductivity distance per time (m/s);

$\frac{\Delta h}{\Delta l}$= hydraulic gradient;

A = cross sectional area, units of area (m^2).

Darcy's Law assumes slow laminar groundwater flow, which is the case in the majority of situations. Ritzema 1994, defines laminar flow in terms of Reynolds number and indicates that a value equal to or less than 1 will allow the use of the Darcy equation.

The equation for Reynolds number:

$$Re = \frac{\mathrm{v \ x \ d50 \ x \ \rho}}{\eta}$$

Where:

v = Apparent velocity or discharge per unit area (m/s)

d50 = mean diameter of soil grain (m);

p = mass density (kg/m^3); and

n = dynamic viscosity (kg/ms).

In general, Darcy's Law can be used for saturated flow, steady state flow, unsteady or transient flow. It can be used in homogeneous materials and heterogeneous materials, isotropic and anisotropic situations (Leach & Volker 2005).

3.2 Dupuit Theory

Ritzema 1994 summarizes that Dupuit's method was developed to simplify calculations associated with groundwater movement given the complexities of a curved water surface. The key assumptions in this method are that the flow is steady state, Darcy's law is applicable, and at any vertical section along a groundwater mound all velocities are in the horizontal direction. This horizontal velocity equation is:

$v = -K(\frac{dy}{dx})$T

The equation for the hydraulic gradient between two points is:

S = $(\frac{dy}{dx})$

These assumptions can under estimate the water surface in the vicinity of subsoil drains given the steep slope of the surface water in these locations (Ritzema 1994).

3.3 Darcy's Law Hillman and Cocks Application

M.O. Hillman and G.C. Cocks are two engineers that were employed by Coffey Geotechnics Pty Ltd. They prepared a paper titled "Subsoil Drainage Design – Perth Residential and Road Developments" that was published in Australian Geomechanics Vol 42 No 120 on the 3rd of September 2007. The method of subsoil drainage design detailed in this paper is based on Darcy's Law and the Hooghoudt equation. The following is a summary of the Hillman Cocks paper.

(Hillman and Cocks 2007) summarised that the important aspects to subsoil drain design in Perth sand environments are:

1. Thickness of sand layer overlying an impermeable layer and
2. The degree of groundwater mounding above the impermeable layer.

(Hillman and Cocks 2007) suggested that the time frame required to see a rise in water table due to capillary action is weeks and potentially longer. When a soil profile is subject to recharge from rainfall infiltration or stormwater recharge the phreatic surface will rise as water moves through the sand to subsoil drains, capillary rise associated with this new level could take a lot longer to achieve a significant rise than it will take the subsoil drains to drain the recharged water and reduce the water table to the previous level.

Thus it is the reader's interpretation that capillary rise can be neglected in the calculation of mounding within sand fill layers. This supports the IPWEA paper where the capillary fringe is neglected in the separation requirements.

The typical scenario discussed in the paper and as detailed in previous sections of this report involves parallel drains that intercept groundwater and control the level of the phreatic surface between the drains. Groundwater fluctuates due to rainfall infiltration from the surface and stormwater discharge from concentrated sources such as soak wells. The model assumes steady state conditions and a soil profile consisting of sand over an underlying impermeable layer.

As detailed in figure 10 the height (Hm) of the mound is a function of the distance between the subsoil drain and the midpoint of the mound which is defined as (Sp). Other inputs required are the hydraulic conductivity of the sand layer, and recharge to the water table that occurs within section being analysed (Hillman & Cocks 2007).

Hm = Height of the mound at the midpoint between drains. (m)

Sp = The distance from a drain to the midpoint. (m)

Hb = the level of subsoil drainage above the impermeable layer (m)

K = Hydraulic Conductivity (m/day)

Q = Recharge (kL/day)

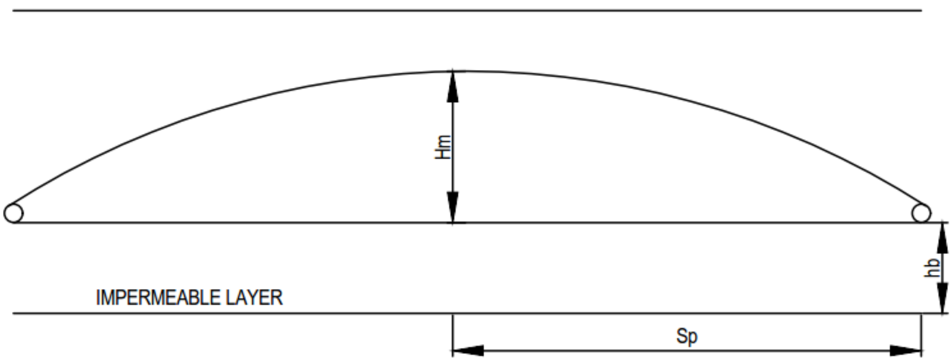


Figure 10 – Hillman Cocks Method

(Hillman and Cocks 2007) reported that Darcy's Law can be used to calculate the height (Hm) under assumed conditions, and listed the assumptions as:

- The hydraulic gradient varies from crest of mound to drain invert.
- Distributed infiltration from rainfall will start flowing toward the drain locations at a flow rate increasing from 0 at the mound to its maximum at the drain.

The method described the integration of the Darcy equation for ΔHm / ΔSp, resulting in two sets of equations as listed below:

Uniformly Distributed Rainfall

$H_m / S_p = ((h_b/S_p)^2 + (Q/(S_p \times k))^{0.5} - (h_b/S_p)$

Concentrated Infiltration (at crest of mound)

$H_m / S_p = ((h_b/S_p)^2 + (2 \times Q/(S_p \times k))^{0.5} - (h_b/S_p)$

These equations were then used to develop the figures below.

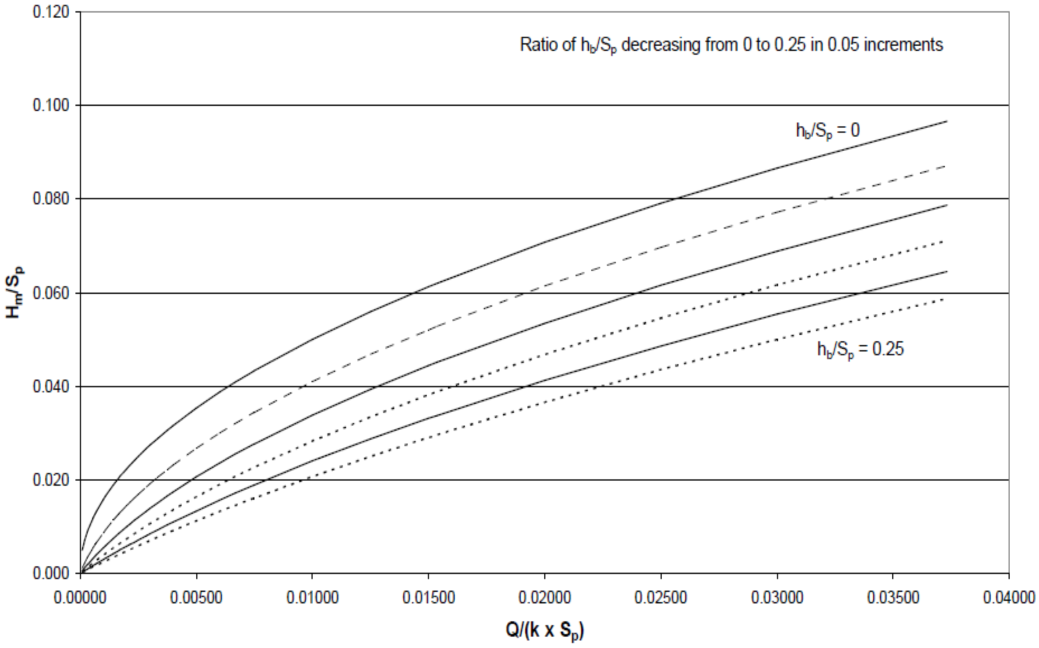


Figure 11 – Uniformly Distributed Infiltration (Hillman & Cocks 2007)

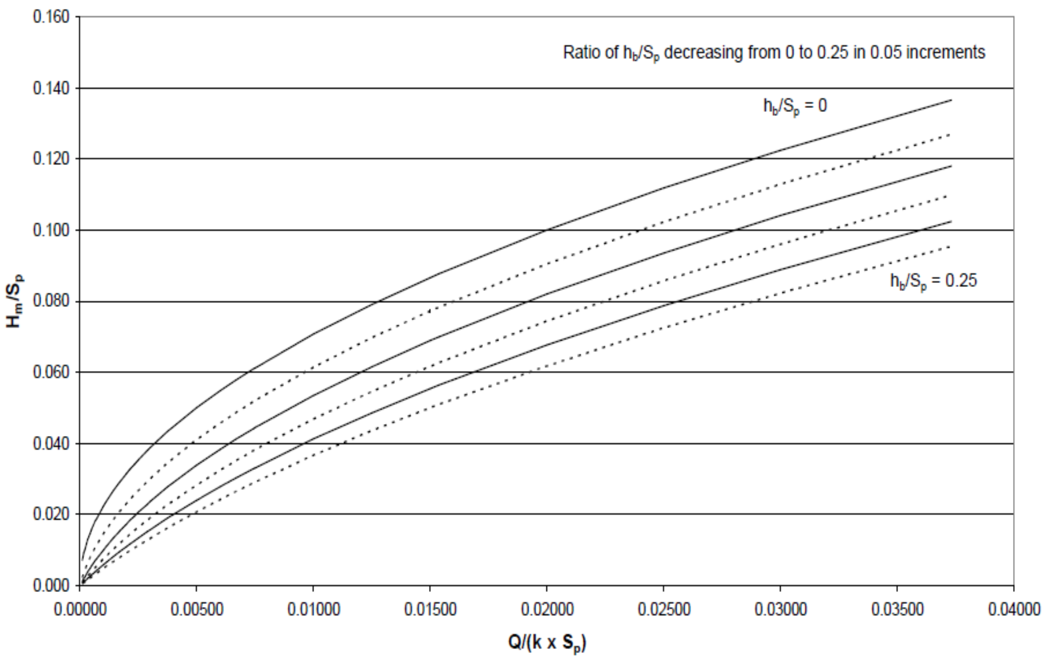


Figure 12 – Concentrated infiltration at crest of mound (Hillman & Cocks 2007)

A combination of the two conditions represented in the figures would commonly occur in land development where soak wells are regularly used for onsite stormwater disposal. Hillman and Cocks suggest that judgement needs to be made about the type of distribution of rainfall within the section being analysed. The two charts can be used to assess a range or limits of the mound height based on a given recharge to the section being analysed. When using the charts engineering judgement needs to be used to assess the degree of uniform and concentrated flow for the site.

An approximate estimate of the height of the phreatic surface at any point between the drain and the mound is given by:

A = 0.175 ln B + 1 (3) for the uniformly distributed case.

A = 0.4 + 0.6 B (4) for concentrated infiltration.

A = ratio of height at point of interest, to total mound height.

B = ratio of distance from drain at point of interest to distance to crest of mound.

When applying the above method to residential lots the (Hillman & Cocks 2007) summarised method is given below.

- A rainfall should be selected that represents an event most suitable for design.
- The rainfall intensity selected should be factored to give the actual recharge or infiltration rate;
- Refer to the design charts to assess upper and lower values of the height of mounding.

3.4 Hooghoudt Equation

The Hooghoudt equation was developed using Darcy's Law, the continuity principle and the Dupuit-Forchheimer theory. The equation is used for groundwater analysis and can be used to determine flow rates to drains and phreatic surface heights.

The Dupuit-Forchheimer theory is based on the principle that Darcy's formula can be used to calculate flow through a vertical plane at a selected distance from subsoil drainage. Considering this plane at the subsoil drain location the continuity principle is true when the water that enters the soil profile in the area between the plane and the midpoint of the subsoil drains passes through the vertical plane to enter the drain (Ritzema 1994).

The Hooghoudt Equation shown below was developed based on these principles.

$$q=\frac{8Kdh+4\ Kh^2}{L^2}$$

Where:

q = drain discharge (m/d)

K = hydraulic conductivity (m/d);

d = equivalent depth (m)

L = spacing between drains (m)

h = height of mounding above the drain (m).

Hooghoudt developed the concept of an imaginary impervious layer that relates to an equivalent depth. When drains are positioned above the impervious layer, extra head loss is required to achieve the same flow rate in the drains. The equivalent depth accounts for this head loss.

The equivalent depth d was further developed by (Van der Molin and Wesseling 1991) (As cited in Ritzema 1994) who developed formula for the exact calculation of d.

$$d = \frac{\frac{\pi L}{8}}{\ln \frac{L}{\pi r_o} + F(x)}$$

Where:

$$x = \frac{2\pi D}{L}$$

$$F(x) = \sum_{n=1}^{\infty} \frac{4e^{-2nx}}{n(1-e^{-2nx})} (n = 1,3,5,\ldots) \qquad x > 0.5$$

$$F(x) = \frac{\pi^2}{4x} + \ln \frac{x}{2\pi} \qquad x \le 0.5$$

Two important assumption of the Hooghoudt equation are that:

- Flow is to a height of half the subsoil drains
- Subsoil drains have no entrance resistance.

4.0 Dynamic Model - Unsteady state

4.1 MODFLOW GMS (Aquaveo)

(Harbaugh, Banta, Hill and McDonald 2000), describe MODFLOW as a computer program that simulates three-dimensional groundwater flow through a porous medium by using a finite difference method. It uses a modular structure which groups programs of similar function together, options in the model are constructed so that they are independent of each other. MODFLOW can be used to compute two or three dimensional models.

The below partial-differential equation describing the movement of groundwater is used in MODFLOW.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

Where:

Kxx, Kyy, and Kzz represent hydraulic conductivity in the x, y, and z coordinates, which the model assumes are parallel to hydraulic conductivity major axes (L/T).

h = potentiometric head (L)

W = represents volumetric flux per unit volume from recharge sources i.e. rainfall infiltration, wells etc. (W<0.0 represents out flow and w>0.0 flow into system (T^{-1})

Ss = the porous materials specific storage (L^{-1})

t = time (T).

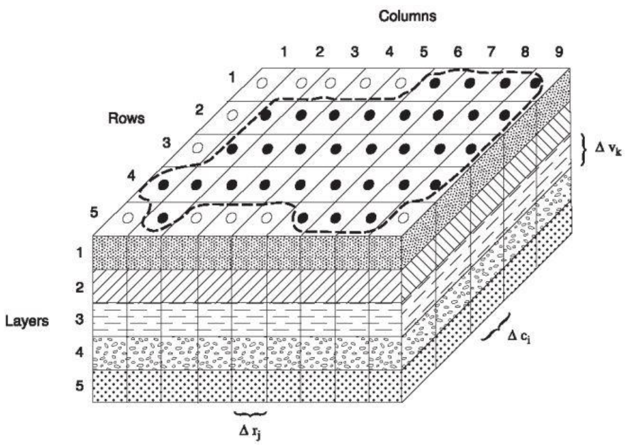


Figure 13 - MODFLOW cells (U.S. Geological Survey)

The above equation is what is used to describe transient, three-dimensional groundwater flow once combined with initial and boundary conditions, and assumes a heterogeneous and anisotropic profile.

The equation above is solved using the finite element method. The software divides the groundwater flow system into a series of cells, as per Figure 13, and assigns each cell a node for which the head is calculated.

The equation used to solve for each cell is:

$$
\begin{aligned}
& CR_{i,j-\frac{1}{2},k}\left(h^{m}_{i,j-1,k}-h^{m}_{i,j,k}\right) \quad + \quad CR_{i,j+\frac{1}{2},k}\left(h^{m}_{i,j+1,k}-h^{m}_{i,j,k}\right) \\
+ \quad & CC_{i-\frac{1}{2},j,k}\left(h^{m}_{i-1,j,k}-h^{m}_{i,j,k}\right) \quad + \quad CC_{i+\frac{1}{2},j,k}\left(h^{m}_{i+1,j,k}-h^{m}_{i,j,k}\right) \\
+ \quad & CV_{i,j,k-\frac{1}{2}}\left(h^{m}_{i,j,k-1}-h^{m}_{i,j,k}\right) \quad + \quad CV_{i,j,k+\frac{1}{2}}\left(h^{m}_{i,j,k+1}-h^{m}_{i,j,k}\right) \\
+ \quad & P_{i,j,k}\,h^{m}_{i,j,k} \quad + \quad Q_{i,j,k} \quad = \quad SS_{i,j,k}\left(DELR_j \times DELC_i \times THICK_{i,j,k}\right)\frac{h^{m}_{i,j,k}-h^{m-1}_{i,j,k}}{t^{m}-t^{m-1}}
\end{aligned}
$$

Where:

h = the head at each individual cell reference for a time step (m).

CV, CR, CC = Hydraulic conductance’s between adjacent nodes.

P = the sum of coefficients of head for recharge terms for each cell reference.

Q = the constants from recharge terms summed for each individual cell. Q is negative for outflow from the system and positive for inflow.

SS = the specific storage for each cell. This is only relevant to transient simulations.

DELR = the width of cells in the specific column.

DELC = the width of cells in the specific row.

THICK = vertical thickness at each individual cell reference.

T^m = the time at time step m.

5.0 Methodology

As already discussed the theoretical analysis will be based on soil conditions, climate conditions and hydrogeological characteristics representative of Dunsborough in Western Australia. The drainage condition to be analysed will consist of a 2 layered soil profile made up of permeable sand fill over impermeable natural clays creating a perched water table. This design scenario is typical of that experienced in the Dunsborough region. The main objective is to compare the methodology and results associated with the calculation of the peak mounding of the phreatic surface within the permeable sand layer.

An analysis will be conducted using steady state models, which will be compared for variations and accuracy in calculating the degree of mounding. Transient models will then be used to analyse the site to provide a further comparison. Various stormwater disposal methods will also be analysed to assess which method provides the most efficient design in minimising the phreatic surface mounding.

The steady state models to be used in the analysis are:

- Darcy/Dupuit Equation
- Hillman and Cocks method
- Hooghoudt Equation
- MODFLOW

The Dynamic Model to be used in the analysis is:

- MODFLOW

5.1 Collation of Site Specific Data

Below is a table that summarises the required inputs as listed in the literature and the values that will be used in the selected test case analysis. These values will be constant across all the analysis cases.

	Value as suggested in Guidelines	**Value selected for Test case**	**Remarks**
Hydraulic Conductivity (m/day)	1 – 10	**5**	This is industry accepted value for typical imported fill sand compacted to 95% MMDD.
Separation Distance (mm)	300	**300**	As required by the IPWEA Guideline.
Subsoil Drain spacing	30-40 when subsoil located at rear of lots. 60 – 90 road reserve to road reserve	**35, 60 and 90**	The intention is test all cases.
Rainfall recharge rates (%) uniformly distributed - soak wells	60% -80%	**60%**	This is based on the area of the lot and proportion of hardstand and vegetated surfaces.

Rainfall recharge rates (%) Uniformly distributed - No soakage, connected to street drainage.	10% -20%	**20%**	This is based on the area of the lot and proportion of hardstand and vegetated surfaces.
Rainfall recharge rates for detailed lot analysis (%)	Turf Areas 50% Hardstand Areas 90%	**50%** **90%**	
Rainfall Event	1 in 2 yr 72hr event	**1 in 2 yr 72hr event**	
Rainfall Intensity (mm/hr)	-	**1.21**	As provided by the Bureau of Meteorology

Table 7 – Standard IPWEA Requirements relevant to the Analysis.

5.2 Model Development

5.2.1 Hooghoudt Equation

A spreadsheet was prepared that calculates the maximum mounding based on the Hooghoudt equation using the required inputs. A graph displaying the distribution of mounding between the subsoil drain and the maximum mounding height was included.

Hooghoudt Equation	$q=\frac{8Kdh+4Kh^2}{L^2}$				
Project:				**x (m)**	**h (m)**
			0	45	0.05
Input Data			5	40	0.89
			10	35	1.25
Insitu Soil Permeability (m/day)	**K**	**5**	15	30	1.53
1:2yr 72 hr event (mm/hr)		**1.21**	20	25	1.77
Recharge (%)		**60**	25	20	1.98
Depth to impermeable layer below subsoils (m)	**d**	**0**	30	15	2.17
Drain Spacing (m)	**L**	**90**	35	10	2.34
			40	5	2.50
1:2yr 72 hr event total rain (mm)		87.12	45	0	2.66
Total design recharge rate (m/d)	**q**	0.0174			
a= 4K=		20			
b= 8KD=		0			
c= $-QL^2$		-141.13			
maximum rise between subsoils (m)	**h**	2.66			

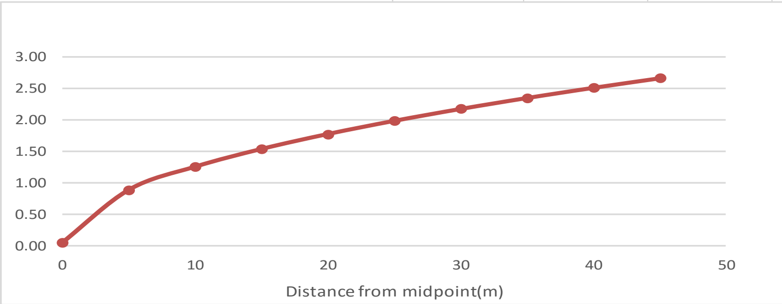


Figure 14 – Steady State Flow Spreadsheet Hooghoudt Equation

5.2.2 Hillman Cocks Method

A spreadsheet was prepared based on the calculations required for the Hillman Cocks method. The two cases for concentrated flow and uniformly distributed flow are calculated separately and then a ratio is applied to achieve the final calculated mounding height. The ratio applied in this theoretical model is based on the proportion of hardstand area to lawns and gardens as the hardstand area is assumed to be directed to soak wells, which is concentrated flow, and lawns/gardens uniformly distributed flow. The hardstand to lawn/garden ratio is calculated for each test case based on the lot size and assuming a constant house area for all test cases. A graph showing the distribution of the mound over the distance between the subsoil drain and the midpoint has been included. This is calculated using the Hillman Cocks recommended method. It should be noted that in this method the discharge q = the recharge rate and this is represented in (m^3/day).

Hillman Cox

Sp (m)	45	Distance from drain to midpoint	
hb (m)	0	Distance of drain above impervious	
Q (m3/d)	0.783	0.0174	
K(m/d)	5		
Uniform Hm (m)	2.654619	Max HM	3.149429
Concentracted Hm (m)	3.754198		

x(m)	B	A	Hm (Uniform)	A	Hm (Concentrated)	Hm (factored)
0						0.05
5	0.111111	0.615486	1.633879795	0.4666667	1.751958904	1.687015394
10	0.222222	0.736786	1.955887041	0.5333333	2.002238747	1.976745309
15	0.333333	0.807743	2.144249206	0.6	2.25251859	2.192970429
20	0.444444	0.858087	2.277894288	0.6666667	2.502798434	2.379101154
25	0.555556	0.897137	2.381557468	0.7333333	2.753078277	2.548741832
30	0.666667	0.929044	2.466256452	0.8	3.003358121	2.707952203
35	0.777778	0.95602	2.537868424	0.8666667	3.253637964	2.859964717
40	0.888889	0.979388	2.599901535	0.9333333	3.503917807	3.006708857
45	1	1	2.654618617	1	3.754197651	3.149429182

Uniformly Distributed Rainfall

$H_m / S_p = ((h_b/S_p)^2 + (Q/(S_p \times k))^{0.5} - (h_b/S_p)$

Concentrated Infiltration (at crest of mound)

$H_m / S_p = ((h_b/S_p)^2 + (2 \times Q/(S_p \times k))^{0.5} - (h_b/S_p)$

Equations (3) (uniformly distributed rainfall case) and (4) (point inflow at crest of mound) respectively:

$A = 0.175 \ln B + 1$ (3)

$A = 0.4 + 0.6 B$ (4)

Where A = ratio of height at point of interest, to total mound height
and B = ratio of distance from drain at point of interest to distance to crest of mound.
(Note: in both cases, the height can not be assessed within 1 m of the drain)

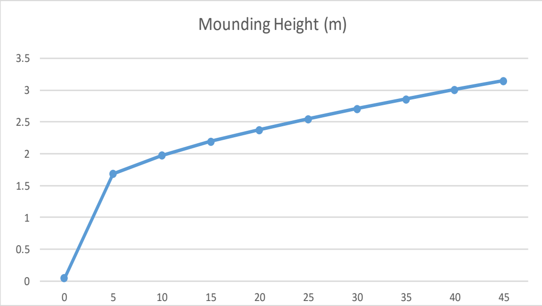


Figure 15 – Steady State Flow Spreadsheet Hillman Cocks Method

5.2.3 Darcy/Dupuit Equation

(Fetter 2001) detailed that a combination of the Darcy Equation, Q = $-KA\frac{\Delta h}{\Delta l}$, and the Dupuit Equation q' = $\frac{1}{2}K(\frac{h1^2-h2^2}{L})$, can be derived to produce the equation below:

$$h = \sqrt{h1^2 - \frac{(h1^2 - h2^2)x}{L} + \frac{w}{k}(L-x)x}$$

Where:

h = the head at a distance x (m).

x = the distance from the subsoil drain (m).

h1 = the head at the origin point (m). In this instance h1 is at the subsoil drain. The drain is assumed to be a diameter of 150mm and flowing half full, so h1 has a value equal to 0.075m.

h2 = the head at L (m). When calculating the maximum mound at the midpoint this value is also 0.075m as it represents the second subsoil pipe and L represents the spacing between the two pipes.

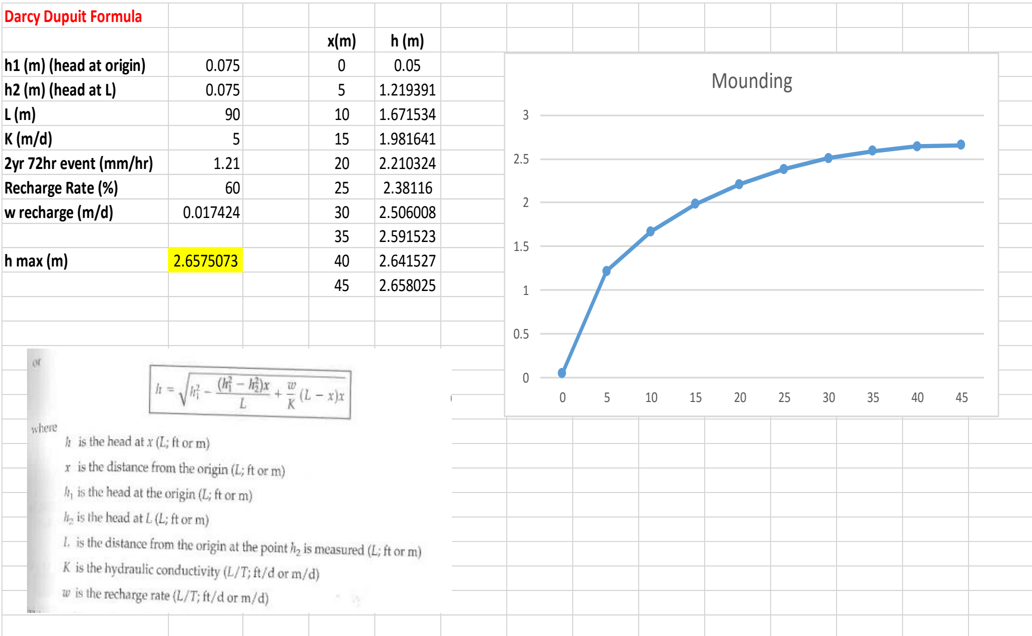
K = the hydraulic conductivity of the soil (m/d)

w = the recharge rate (m/d).

This equation is valid for steady state flow and is based on the principle that any change of flow is equal to a change in the water table. In this instance the change is a gain and is due to stormwater infiltration. This infiltration is represented by w (recharge rate).

The equation calculates the elevation h of any point between h1 and h2 allowing for a recharge between h1 and h2.

A spreadsheet was developed using this formula to calculate the maximum (h) given the required inputs. This equation was also used to develop a graph showing the variance in the mound between the subsoil drainage and the crest of the mound.



Darcy Dupuit Formula		x(m)	h (m)
h1 (m) (head at origin)	0.075	0	0.05
h2 (m) (head at L)	0.075	5	1.219391
L (m)	90	10	1.671534
K (m/d)	5	15	1.981641
2yr 72hr event (mm/hr)	1.21	20	2.210324
Recharge Rate (%)	60	25	2.38116
w recharge (m/d)	0.017424	30	2.506008
		35	2.591523
h max (m)	2.6575073	40	2.641527
		45	2.658025

$$h = \sqrt{h_1^2 - \frac{(h_1^2 - h_2^2)x}{L} + \frac{w}{K}(L - x)x}$$

where

h is the head at x (L; ft or m)

x is the distance from the origin (L; ft or m)

h_1 is the head at the origin (L; ft or m)

h_2 is the head at L (L; ft or m)

L is the distance from the origin at the point h_2 is measured (L; ft or m)

K is the hydraulic conductivity (L/T; ft/d or m/d)

w is the recharge rate (L/T; ft/d or m/d)

Figure 16 – Steady State Flow Spreadsheet Darcy/Dupuit Equation

5.2.4 MODFLOW – Steady State

Steady state analysis in MODFLOW works on the principle that all flows entering and exiting the individual cells sum to zero at the end of the simulation. Steady state simulations utilize a single stress period and exclude any storage effects within the cells. MODFLOW utilizes a backwards difference approach in solving the finite difference equation for steady state flow. The equation used for steady state solutions is the same as used for transient solutions with the storage terms removed.

For the steady state analysis, a grid approach was adopted as this method is best suited to small scale scenarios. A grid 100m long by 40m wide and 3m deep was created to represent 4 residential lots in a back to back configuration as shown in figure 17.

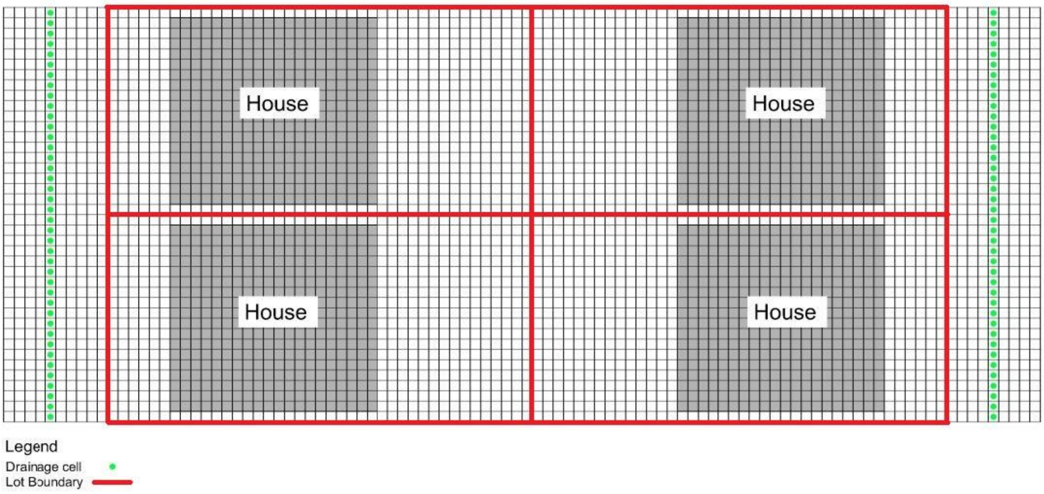


Figure 17 – XY Grid Layout MODFLOW

This three-dimensional box was then divided into 1m x 1m x 1m cells. The bottom of the box represents the clay layer as an impermeable surface with zero hydraulic conductivity. Each cell was assigned a hydraulic conductivity of 5m/day as per the recommended guidelines. This value was the same in both the vertical and horizontal directions to replicate a homogenous soil type.

The optional "Drains" package was utilized to replicate the slotted subsoil drains running parallel within the road reserves. MODFLOW applies a drain function on a cell by cell basis. A row of cells on either side of the grid at the bottom layer were converted to drain cells. These drain points are applied central to the cell with an elevation of 0.05 to simulate a drain laid just above the impermeable surface. MODFLOW requires a conductance to be specified for the drainage cells, for the purpose of this analysis it is assumed that the drains would be suitably designed to handle the subsurface flow rates so that the controlling factor influencing mounding will be the hydraulic conductivity of the soil and not the capacity of the subsoil drains. As such, a high value of conductance was applied to the drainage cells of 1000 m^2/d.

The solver package selected for the analysis was the Preconditioned Conjugate-Gradient Package. This package utilizes inner and outer iterations that must be user defined. For all the analyses conducted iterations of 50 and 100 for inner and outer were selected respectively. The wetting of cells option was enabled which allows for the calculation of the variance in head between when the cell is wet and dry.

The "Recharge" package was used to simulate rainfall recharge to the soil profile. This package was configured so that recharge was applied at the "highest active cell in the model".

These basic setup configurations remained constant for all the scenarios that were modelled.

5.2.5 MODFLOW – Transient

The base setups used in the MODFLOW steady state model are the same as used in the transient model. The Preconditioned Conjugate-Gradient solver package is used with the wetting of cells option enabled. A time step of 1 day was selected with a stress period of 365 days to model the maximum mounding experienced in a year.

The mean annual rainfall for Dunsborough as listed on the Bureau of Meteorology website is 805.3mm. The rainfall experienced in the year 2000 was chosen for the analysis, as this year had a total rainfall 881.2mm which is slightly above the mean rainfall value and so was seen to be conservative. This year contains 5 daily rainfalls equal to or above the steady state modelled rainfall of 29mm per day.

For all cells above the impermeable layer a specific yield of 0.2 was selected, a specific storage of 0.2 and a porosity of 0.3 for the sand fill layers.

6.0 Analysis

6.1 Theoretical Test Case One (90m Separation)

The first case to be analysed will be a typical back to back lot configuration with a separation of 90m between subsoils. The site is assumed to consist of natural clay soils with no or very low permeability. Fill is required over the site to achieve site classification and to allow for disposal of stormwater through soak wells. Subsoil drainage will be placed in the street verge at the natural clay level. The theoretical site will consist of lots 40m deep giving a separation of 90m between subsoil drains when allowing for a 5m alignment of the drain within the road reserve. The remaining inputs are:

Rainfall intensity – 121mm/hr

Recharge rate – 60%

Recharge to water table (m/d) – 121 x 72/3 x 0.6 = 0.0174m/d

Recharge to water table (m^3/d) – 0.0174 x 45 = 0.783 m^3/d

L = 90m

K = 5m/d

The purpose of this first analysis is to compare the steady state methods against a transient model. With the exception of the Hillman and Cocks model a uniform distribution of recharge across the lots will be assumed.

6.1.1 Results

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient model.

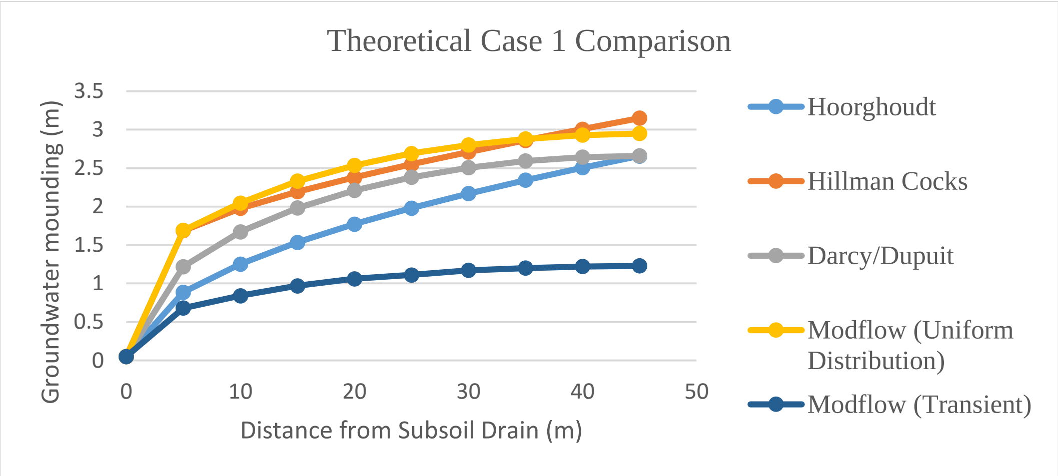


Figure 18 – Theoretical Case 1 Comparison

There are two obvious trends that can be seen in the graph. The Hooghoudt and Hillman Cocks results are relatively parallel with the Hillman Cocks values being slightly higher by a consistent value of approximately 0.5m. This can be attributed to the Hillman Cocks method's allowance for concentrated flow. The concentrated flow equation multiplies the flow rate by a multiple of 2. Although it is not clearly documented this appears to be an allowance for 2 soak well systems, one for each lot (back to back) applied at the midpoint or close to the maximum mounding height.

The second trend can be seen in the comparison between the Darcy/Dupuit and MODFLOW calculations. The results calculated by these two models run parallel in the graph with the MODFLOW results consistently higher by a value of approximately 0.3m. The MODFLOW literature documents that the MODFLOW programme utilises the principles of Darcy's equation to calculate the flow, or specifically the conductance from one cell to another, so it seems reasonable that the two sets of results would be comparable. The variance between the two models could be attributed to MODFLOW's ability to calculate a head variance for individual cells between when they are wet and dry.

The Darcy/Dupuit and Hooghoudt models both converge to the same maximum mounding height while the Hillman Cocks model has the closest result to the MODFLOW software model.

Both the Hooghoudt and Hillman Cocks models have a relatively steep, almost linear, distribution of the groundwater mound between the maximum height and the end of the model at 5m. When reviewing the literature for the two methods, both utilise the recharge rate in calculating the maximum recharge height but ignore this value when calculating the distribution of mounding with (x) distance from the subsoil drain. The other methods consider the recharge when calculating the mound distribution for (x) and as a result have a significantly more curved distribution.

The results for the transient analysis are significantly lower than all of the steady state analysis. The maximum mounding occurs on September the 7th in response to a rainfall event of 62mm, this occurred after 6 consecutive wet days including 4 days where over 10mm of rainfall was recorded. Of the 16 days prior to the maximum mound 13 experienced rainfall. From this data it can be surmised that the maximum mounding occurred on this day due to a long period of inundation plus a significant rainfall event of 62mm recharging the soil profile.

In practice construction sites will have anywhere between 1.0m to 1.5m of sand fill. Through years of application this range of fill has been proven to handle fluctuations in groundwater mounding adequately. Considering this range as a bench mark, the results produced by the transient method are reasonable whereas the steady state results appear to be conservative. A table is shown below listing all of the maximum values and their percentage variance to the transient solution as a comparison.

Method	**Maximum Mounding (m)**	**% variance to Transient Model**
Hooghoudt	2.66	116%
Hillman Cocks	3.15	156%
Darcy/Dupuit	2.66	116%
MODFLOW	2.95	140%
MODFLOW Transient	1.23	0%

Table 8 – Theoretical Test Case 1 Maximum Mounding.

6.2 Theoretical Test Case Two (90m Separation Soak wells at Rear)

With the exception of the Hillman Cocks model the analysis in case 1 assumes uniform recharge of rainfall to the soil profile. However, in a residential context this is unlikely to occur. In practice recharge from rainfall is collected by gutters and hardstand areas and then piped to soak wells, where recharge to the soil is then concentrated at specific locations. To try and simulate these concentrated conditions three additional simulations were run in MODFLOW.

The first simulation was setup to replicate soak wells being positioned at the rear of the property. A house area of 18 x 20 metres was assumed. The cells that represent the house had their recharge value set to zero. The standard requirement for the sizing of soak wells is to allow $1m^3$ per $65m^2$ of hardstand area. Based on an area of $360m^2$ the requirement would be $5.5m^3$ of soak well. For the analysis 6 cells per lot were used, being $1m^3$ per cell, $6m^3$ in total. The rainfall runoff from the hardstand area was added together and applied evenly to the 6 cells. As per the IPWEA guidelines a recharge factor of 90% was applied to the hardstand runoff and 50 % was applied to the remaining uniformly distributed recharge through lawns and gardens.

<u>Steady State</u>

29.04mm/day x 360 x 0.9 = 9408.96mm

9408.96/6 = 1568.16mm = 1.57m/day per soak well.

<u>Transient</u>

As per steady state but calculated for each daily time steps rainfall

<u>Other inputs:</u>

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 60%

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

<u>Spreadsheets</u>

Recharge to water table (m/d) – 121 x 72/3 x 0.6 = 0.0174m/d

Recharge to water table (m^3/d) – 0.0174 x 45 = 0.783 m^3/d

L = 90m

K = 5m/d

A figure showing the application of the recharge values for the soak wells at rear analysis is shown below. The green areas are cells with a uniform recharge rate, the red represents 0 recharge while the 6 purple cells per lot are the theoretical soak well locations.

This model was also run using a transient analysis. The above methodology for calculating the rainfall application to the soak wells was applied for each time step.

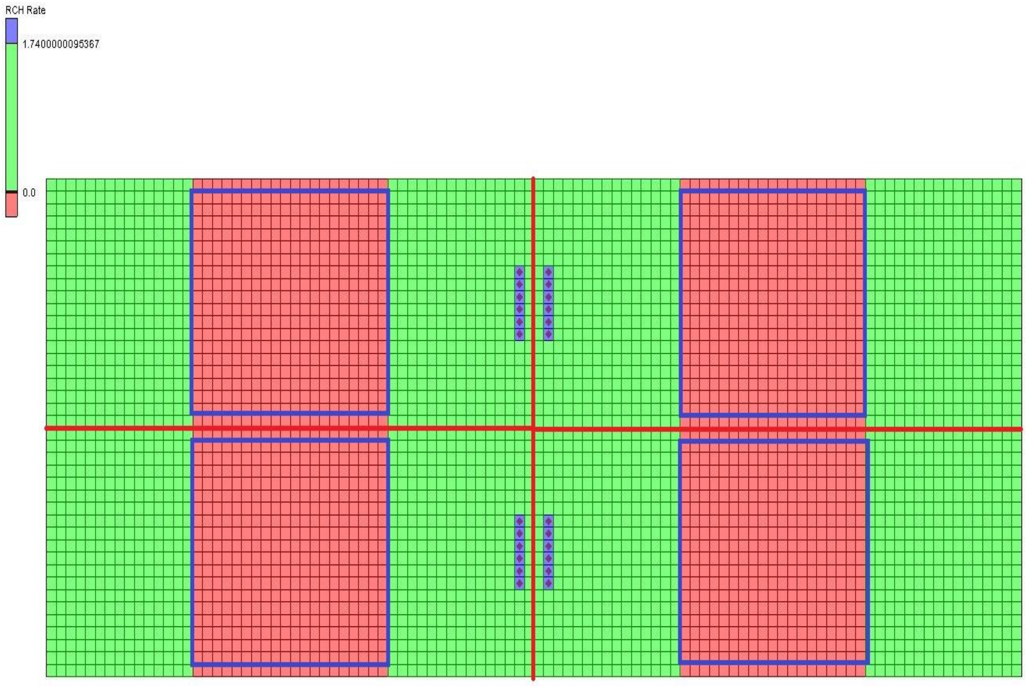


Figure 19 – Distribution of Recharge

A model was also prepared for the situation that occurs when soak wells are installed at the front of the house. The model was prepared on the same principles as the rear of the house simulation but with the six soak wells located within the front 6m of the lot. The figure below shows the distribution of head for this simulation, note the wave or mounded distribution around the soak well locations.

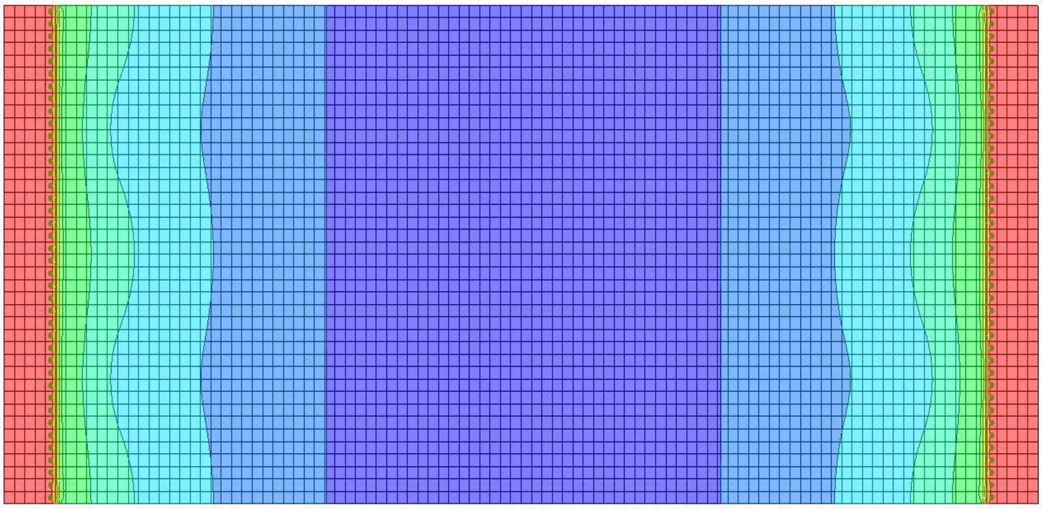


Figure 20 – Head distribution for soak wells located at the front of lot.

Figure 21 shows the head distribution for soak wells located at the rear of the property with the cyan areas representing the highest head or groundwater mounding through to the red areas representing the least.

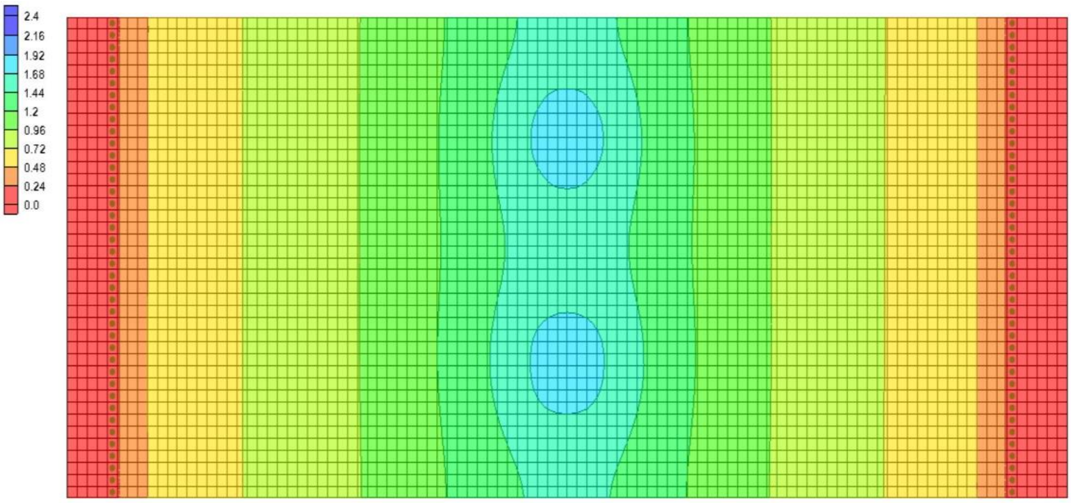


Figure 21 – Head distribution for soak wells located at the rear of lot

6.2.1 Results

The graph below represents the results of theoretical case one overlayed with the rear and front soak well simulations.

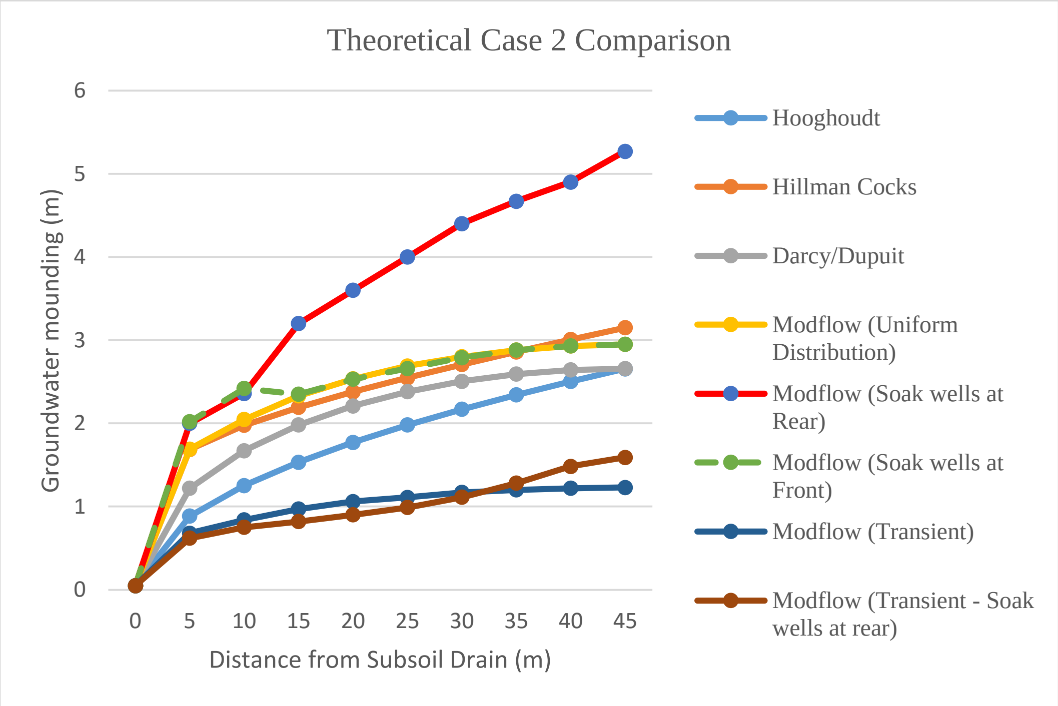


Figure 22 – Theoretical Case 2 Comparison

When considering the above results, the soak wells at rear results obtained from the MODFLOW steady state analysis are significantly higher than all other results. Applying a recharge of 1.57m per day in a steady state analysis appears to give a very conservative result with little design value for engineers when compared with the other methods. This degree of mounding is well in excess of what is seen in practice in Dunsborough.

As previously stated the Hillman Cocks method allows for concentrated flow from soak wells by applying a factor of 2 to the flow, the maximum mounding is slightly higher at the midpoint when compared with the other steady state methods, but the result converges to the MODFLOW uniformly distributed results quickly.

Between distance 10 and 30 the soak wells at rear results graph becomes linear for all three of the additional analysis in this test case. This represents the section beneath the house where the recharge is 0.

When comparing the uniformly distributed transient model to the soak wells at rear transient model, the latter has a higher maximum mounding value at the midpoint as would be expected. The soak wells at rear simulation then dips below the uniformly distributed simulation, this can be attributed to the 0 recharge beneath the house causing the curve to drop off steeply. When comparing the steady state simulations of MODFLOW uniformly distributed and Hillman Cocks a similar pattern can be seen. The Hillman Cocks method is higher at the midpoint which is expected given its allowance for concentrated flow and then dips below the uniformly distributed curve.

As would be expected the soak wells at front results show a spike in the graph at distance 10m. Again it can be seen that there is a linear distribution for the area under the house where there is 0 recharge, although this section between 20 and 35 has moved further toward the rear of the block due to the additional recharge at the front of the block. Due to the uniform distribution of recharge in the rear of the theoretical lot the maximum mounding matches the MODFLOW uniformly distributed result exactly.

For this theoretical case the steady state equations are again significantly more conservative than the transient models with the MODFLOW soak wells at rear simulation giving an extreme result. The Hillman Cocks method however appears to give a good steady state representation of concentrated flow with soak wells at or close to the midpoint when compared to the MODFLOW analysis ignoring its conservatism to the transient models.

The table below lists the maximum mounding heights for all of the models.

Method	**Maximum Mounding (m)**
Hooghoudt	2.66
Hillman Cocks	3.16
Darcy/Dupuit	2.66
MODFLOW	2.95
MODFLOW (Soak wells at Rear)	5.27
MODFLOW (Soak wells at Front)	2.95
MODFLOW Transient	1.23
MODFLOW (Transient Soak wells at Rear)	1.59

Table 9 – Theoretical Test Case 2 Maximum Mounding

6.3 Theoretical Test Case 3 and 4 (60m, 35m Separations)

The next set of analysis was run to test the sensitivity of distance between subsoil drains on mounding height between the various methods. In addition to the simulation modelled in theoretical test case 1, two additional sets of simulations were undertaken for a 60m drain spacing and a 35m drain spacing. The 35m spacing model best represents the onsite situation where a subsoil line would run parallel to the subsoil in the road verge but located at the rear of the property. The same rainfall intensities and methodology for applying discharge to soak wells was used as per the previous analysis. The theoretical house floor area is assumed to remain the same (360m^2) while the length of the property is reduced. This will mean that the backyard areas will be reduced and intern the uniformly distributed portion of the rainfall recharge will also be reduced.

Inputs:

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 60%

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Recharge to water table (m/d) – 121 x 72/3 x 0.6 = 0.0174m/d

Recharge to water table (m3/d) – 0.0174 x 45 = 0.783 m3/d

L = 60m, 35m

K = 5m/d

6.3.1 Results Test Case 3

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient models simulating theoretical test case 3 with 60m subsoil drain separation.

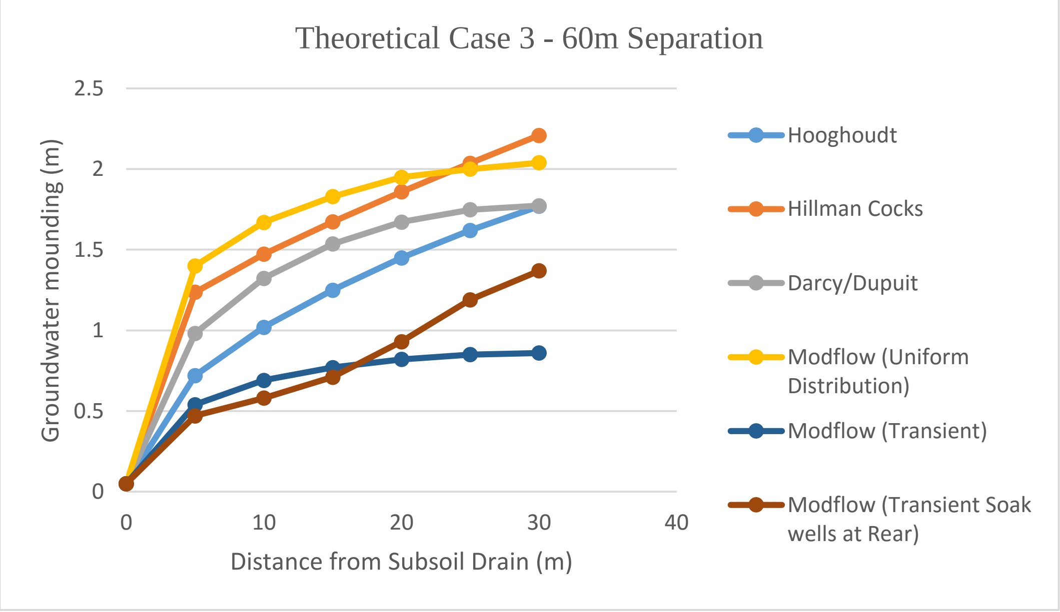


Figure 23 – Theoretical Case 3 – 60m Comparison

From the graph above it can be seen that the Hillman Cocks method produces the highest maximum mounding compared with the other methods, this is consistent with the other two theoretical test cases. The MODFLOW uniformly distributed results compared with the Darcy/Dupuit results are again almost parallel. The Darcy/Dupuit and Hooghoudt equations result in the same maximum mounding value. The results produced by the MODFLOW transient simulation are significantly less than the steady state values, and the curve or rate of change in mounding is significantly less pronounced. The similarity in pattern between the two transient simulations and the MODFLOW uniformly distributed and Hillman Cocks method is again evident.

The maximum mounding values for the 90m and 60 transient soak wells at rear simulations are 1.59 and 1.37m respectively, while the 90m and 60m uniformly distributed values are 1.23m and 0.86m respectively. The variation in maximum mounding height between the uniformly distributed transient model and the soak wells at rear transient model is 510mm, when compared to the previous test case variance of 360mm this is a significant increase. This is largely due to the concentrated flow rate remaining the same for both simulations while the uniformly distributed flow reduces, i.e. the house size remains the same regardless of the block size but the lawn/garden area reduces. This is a true representation of what happens in reality, as house sizes generally remain constant regardless of lot size.

With the exception of the transient models, in general, it could be said that the same patterns and similarities evident in the previous two test cases are again evident here. Perhaps the only slight variance is the difference in values at the 5m chainage for the MODFLOW uniformly distributed and Hillman Cocks results. The Hillman Cocks value is significantly less in this simulation compared with the previous and may indicate that the results obtained using this method are sensitive at or near the subsoil drain location.

6.3.2 Results Test Case 4

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient models simulating theoretical test case 4 with 35m subsoil drain separation. This theoretical test case has been created so that the subsoil drain is located on the rear boundary of the back to back lots as well as a subsoil drain in the street to give the 35m separation. For the steady state simulations replicating soak wells at the rear of the lots, this will mean that the subsoil drain is directly adjacent to the soak well locations. Because of this the steady state model for soak wells at the rear of the lot has been re-included into the set of simulations to see if this has an effect on its previous excessively conservative results.

Inputs:

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 60%

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Recharge to water table (m/d) – 121 x 72/3 x 0.6 = 0.0174m/d

Recharge to water table (m^3/d) – 0.0174 x 45 = 0.783 m^3/d

L = 35m

K = 5m/d

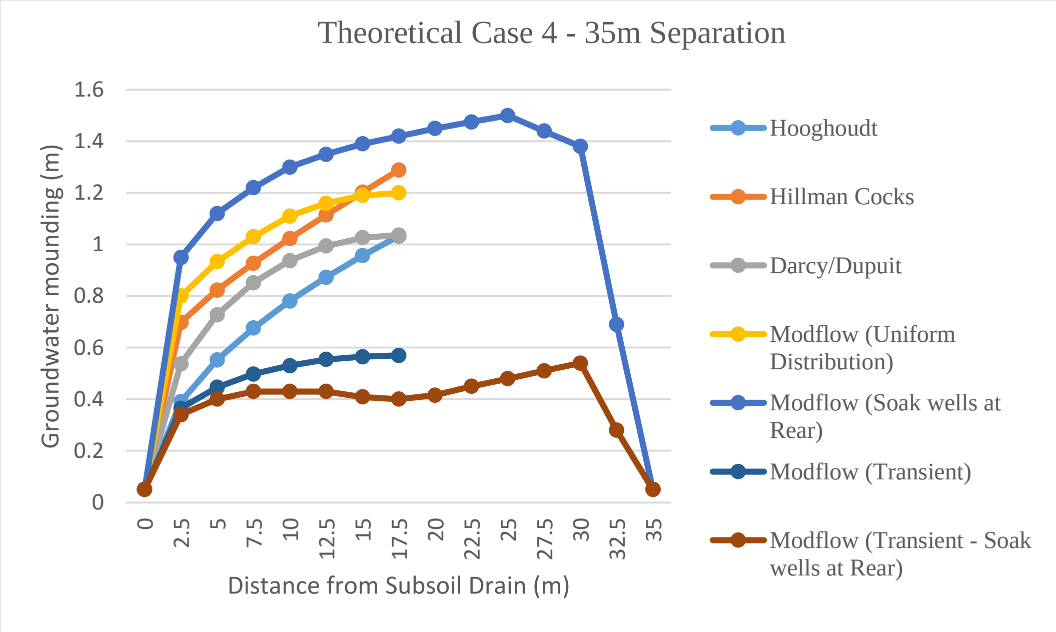


Figure 24 – Theoretical Case 4 – 35m Comparison

From the graph above it can be seen that the steady state MODFLOW soak wells at rear method again produces the highest maximum mounding and has the highest distribution of mounding compared with the other methods. The graph has been extended for the full 35m between subsoil drains. This is to show that the maximum mounding location for the two soak well at rear simulations has moved to the rear of the lots from the midpoint between drains location. The MODFLOW uniformly distributed results compared with the Darcy/Dupuit results are again relatively parallel. The Darcy/Dupuit and Hooghoudt equations result in the same maximum mounding value, which is consistent with the previous theoretical case studies. The results produced by the two MODFLOW transient simulations are significantly less than the steady state values, and the curve or rate of change in mounding is significantly less pronounced.

The MODFLOW transient soak well at rear results show a dip at the midpoint between drains, this represents the area under the theoretical house where the recharge rate is 0. The mounding either side of this midpoint is due to point recharge at the soak well locations and uniformly distributed recharge in the theoretical front yards of the properties. The mounding due to the soak well recharge drops off severely as would be expected given that the subsoil drain is directly adjacent. When comparing the two transient models, although the mounding values at the midpoint are considerably different the maximum mounding values are similar, 0.57m for the uniformly distributed model, 0.54m for the soak wells at rear model, a 30mm difference, significantly less than the 510mm difference in these results in test case 3. It should also be noted that the soak wells at rear model is now less than the uniformly distributed due to the concentrated recharge location being directly adjacent to the subsoil drain.

In general, by introducing a subsoil drain at the rear boundaries of the theoretical lots the maximum mounding height across all the models has been significantly reduced. Comparing the results of test theoretical test cases 1, 3 and 4 the results for the MODFLOW, Darcy/Dupuit, Hooghoudt and MODFLOW transient model follow a consistent pattern. The table below shows the 3 sets of maximum mounding results for the 3 variations in drain separation distance as well as the percentage variation compared to the transient model (uniformly distributed) results.

Method	Maximum Mounding (m) Theo 1	Maximum Mounding (m) Theo 3	Maximum Mounding (m) Theo 4	Theo 1 % variance to Transient Model	Theo 3 % variance to Transient Model	Theo 4 % variance to Transient Model
Hooghoudt	2.66	1.77	1.03	116%	106%	81%
Hillman Cocks	3.15	2.21	1.29	156%	157%	126%
Darcy/Dupuit	2.66	1.77	1.04	116%	106%	82%
MODFLOW	2.95	2.04	1.20	140%	137%	111%
MODFLOW Transient Soak Wells at Rear	1.59	1.37	0.54	29%	59%	-5%
MODFLOW Transient	1.23	0.86	0.57	0%	0%	0%

Table 10 – Mounding comparisons for Theoretical Test Cases 1, 3 and 4

There are several trends that can be observed in the above table. Firstly, with the exception of the Hillman Cocks method the magnitude of variation between the steady state equations and the transient model decreases as the subsoil drain separation decreases and the maximum mounding values decrease. This is probably expected given the flatter curve of the transient simulations and the steeper curves of the steady state models converging as they near the drain on all of the test cases.

The Hillman Cocks method maintains its variance to the transient model until the subsoil drain is introduced at the rear of the properties then it reduces from 156% variance to 126% variance. This is due to the allowance for concentrated flow at the rear of the lot. It could be argued from this set of results that although the Hillman Cocks method results in the largest variation to the transient model it best replicates the patterns demonstrated by the transient model for the test cases. If an adjustment could be made to the model to allow for the variance it may be the best steady state method to use to predict transient results.

Finally, on all of the test cases shown the Darcy Dupuit and Hooghoudt equations produce maximum mounding values that are the closest to the transient model although the variance to these values is still significant, 81% to 116% difference.

6.4 Theoretical Test Case 5 (90m Separation No Soak wells)

Theoretical test cases 5, 6 and 7 simulate the onsite situation where residential lots are directly connected to street drainage. Drainage pits are used to collect and detain storm water runoff from roofs and hardstand surfaces which are then pipe connected to the street drainage. The onsite drainage pits have no soakage function, the only recharge to the water table that occurs is from rainfall that falls directly on lawns and garden areas. As required in the IPWEA guidelines the rainfall recharge rate to be applied is 20% for the uniformly distributed models.

Given that there is no concentrated recharge to groundwater in this set of test cases the equation for concentrated flow used in the Hillman Cocks method has been excluded from the analysis, results calculated using this method will be purely based on uniformly distributed flow. The inputs are given below:

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 20%

Hardstand Recharge rate – 0%

Lawns/Gardens recharge rate – 50%

Recharge to water table (m/d) – 121 x 72/3 x 0.2 = 0.0058m/d

Recharge to water table (m^3/d) – 0.0058 x 45 = 0.261 m^3/d

Transient recharge rates as per year 2000 daily rainfall.

L = 90m

K = 5m/d

All other typical inputs are the same as the previous test cases. A test case labelled "MODFLOW transient drain connected" has been included in the analysis. This simulation reduces the recharge under the theoretical house footprint to 0 while maintaining a consistent uniform recharge rate at the front and back of the house.

6.4.1 Results Theoretical Test Case 5

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient models simulating theoretical test case 5 with 90m subsoil drain separation assuming no soak well recharge to groundwater.

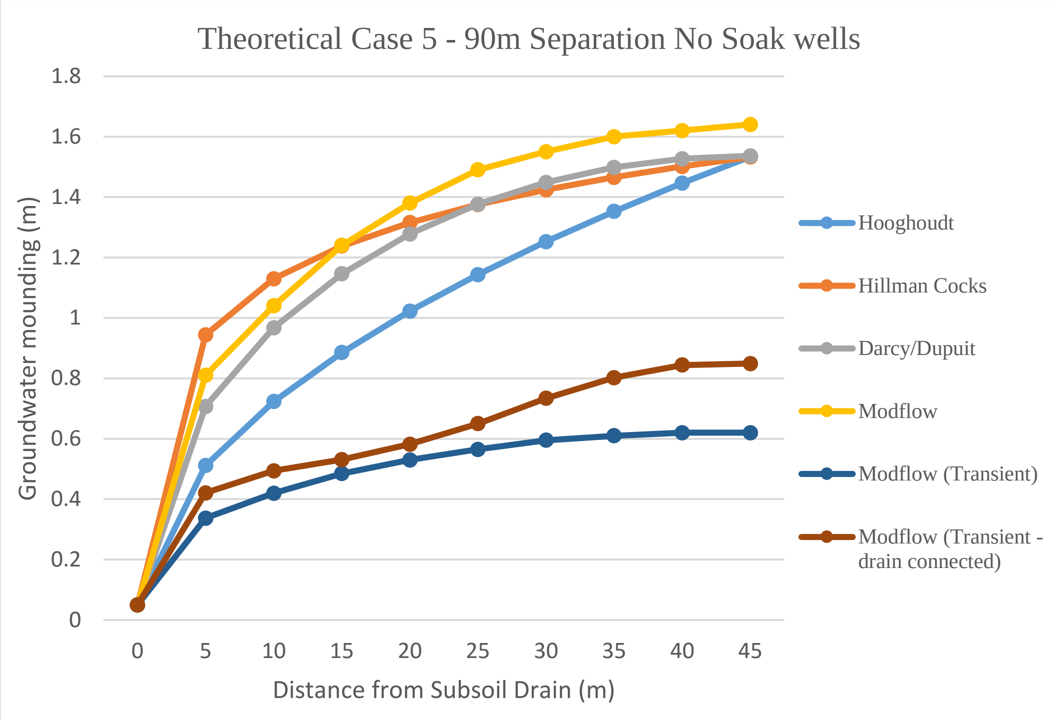


Figure 25 – Theoretical Case 5 – 90m Comparison (no soak well recharge)

The patterns present in previous analysis can again be seen here. The Darcy/Dupuit and MODFLOW steady state simulations are parallel and the Darcy /Dupuit and Hooghoudt equations give the same maximum mounding.

With the removal of the concentrated recharge component from the Hillman Cocks method the maximum mounding value now converges to a similar value as the Hooghoudt and Darcy Dupuit methods although, the distribution of mounding is still significantly different. The variance between the maximum mounding values of the MODFLOW steady state, the Darcy/Dupuit and Hooghoudt methods has reduced significantly from 300mm to 100mm. As can be seen in the table below the variance to the transient model has increased for all steady state models. This may suggest that the steady state models have a lower sensitivity to variations in recharge rate than the transient model.

Method	Maximum Mounding (m)	% variance to Transient Model	% variance to Transient Model Test Case 1
Hooghoudt	1.53	147%	116%
Hillman Cocks	1.53	147%	156%
Darcy/Dupuit	1.54	148%	116%
MODFLOW	1.64	165%	140%
MODFLOW Transient	0.62	0%	0%

Table 11 – Mounding comparisons for Theoretical Test Cases 1 and 5

The other notable result is that the maximum mounding value for the MODFLOW transient drain connected simulation is significantly higher than the uniformly distributed transient simulation. This is due to the difference in recharge percentages between the two simulations. The uniformly distributed simulation uses a 20% recharge rate across the model whereas the drain connected simulation applies a 50% recharge rate to turf/garden areas located at the front and rear of the lot and a 0% recharge rate for the hardstand area. It is the 50% recharge rate to the turf area in the rear of the property compared to the 20% applied in the uniform simulation that causes the increased mounding result. The removal of recharge for the house footprint does not appear to influence the maximum mounding value, it does cause the results to dip between chainage 15 to 35 however, the results are still higher than the uniformly distributed simulation across the model.

6.5 Theoretical Test Case 6 (60m Separation No Soak wells)

Theoretical case 6 is the situation as modelled in Test case 5 but with the separation between subsoils reduced to 60m.

Inputs:

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 20%

Hardstand Recharge rate – 0%

Lawns/Gardens recharge rate – 50%

Recharge to water table (m/d) – 121 x 72/3 x 0.2 = 0.0058m/d

Recharge to water table (m3/d) – 0.0058 x 45 = 0.261 m3/d

Transient recharge rates as per year 2000 daily rainfall.

L = 60m

K = 5m/d

6.5.1 Results Theoretical Test Case 6

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient models simulating theoretical test case 6 with 60m subsoil drain separation assuming no soak well recharge to groundwater.

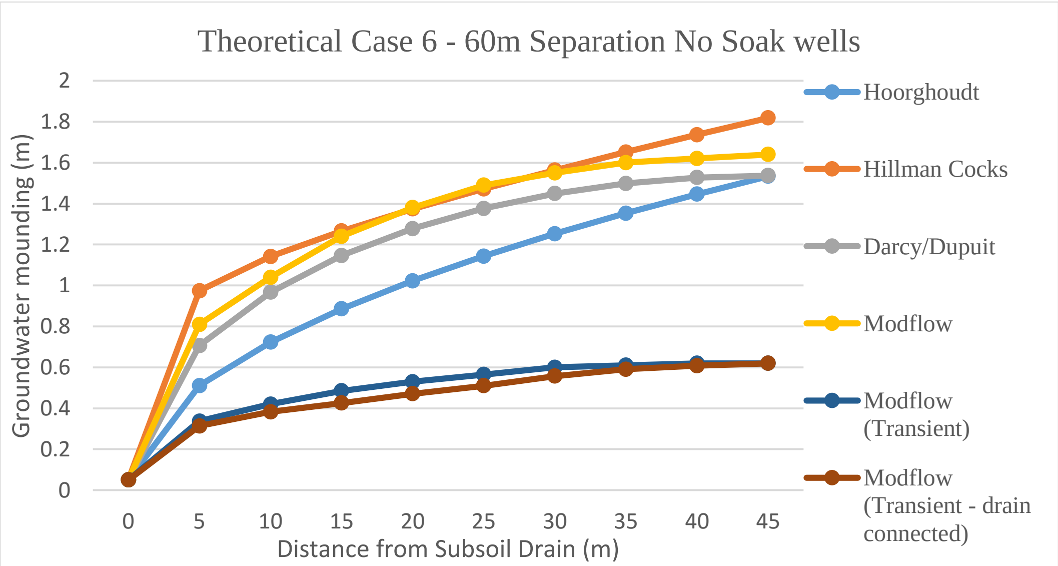


Figure 26 – Theoretical Case 6 – 60m Comparison (no soak well recharge)

The results graphed above replicate the patterns present in theoretical test case 5. The Darcy/Dupuit, Hooghoudt and Hillman Cocks methods converge to a similar maximum mounding value, while the highest value is given by the MODFLOW steady state model.

The comparison of the transient uniformly distributed simulation and the drain connected simulation is significantly different to that of the previous test case. The maximum mounding value of the uniformly distributed model is higher than the drain connected, the results of the uniformly distributed simulation are higher throughout the model. Because the house footprint remains the same between the 90m and 60m models the amount of turf area for the 60m model is substantially less. So even though the drain connected model has a higher recharge for the turf area because there is less area the maximum mounding value is less. The dip in the mounding results corresponding to the 0 recharge beneath the house is again evident.

The variance between the steady state models and transient models has reduced from 0.91m to 0.56m at the midpoint between subsoil drains.

6.6 Theoretical Test Case 7 (35m Separation No Soak wells)

Theoretical case 7 is the situation as modelled in test case 6 but with the separation between subsoils reduced to 35m. This subsoil separation distance replicates a back to back lot configuration with subsoil installed at the rear of the lots parallel to street drainage.

Inputs:

Rainfall Intensity – 121mm/hr

Combined Recharge rate – 20%

Hardstand Recharge rate – 0%

Lawns/Gardens recharge rate – 50%

Recharge to water table (m/d) – 121 x 72/3 x 0.2 = 0.0058m/d

Recharge to water table (m3/d) – 0.0058 x 45 = 0.261 m3/d

Transient recharge rates as per year 2000 daily rainfall.

L = 35m

K = 5m/d

6.6.1 Results Theoretical Test Case 7

Below is a graph showing the groundwater mounding height as calculated by the four steady state models and the MODFLOW transient models simulating theoretical test case 7 with 35m subsoil drain separation assuming no soak well recharge to groundwater.

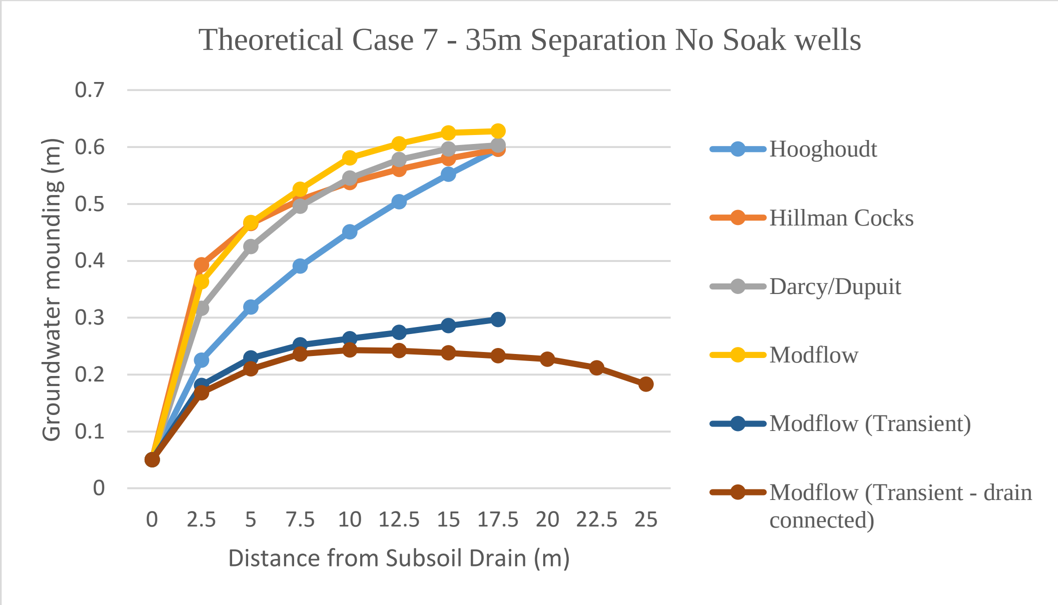


Figure 27 – Theoretical Case 7 – 35m Comparison (no soak well recharge)

When considering the above results the notable variance to the two previous test cases is the MODFLOW transient drain connected result. By installing a subsoil at the rear of the property and allowing for the 0 recharge beneath the theoretical house footprint the maximum mounding location now occurs in the front yard of the lot at a 10m offset from the street drain. The comparison between the two transient models is similar in this location but varies significantly at the midpoint between subsoils and the rear of the lot.

A table showing the variance between the steady state models to the uniformly distributed transient model is shown below.

Method	Maximum Mounding (m) Theoretical Case 5	Maximum Mounding (m) Theoretical Case 6	Maximum Mounding (m) Theoretical Case 7	Theo 5 % variance to Transient Model	Theo 6 % variance to Transient Model	Theo 7 % variance to Transient Model
Hooghoudt	1.53	1.02	0.59	147%	127%	157%
Hillman Cocks	1.53	1.02	0.59	147%	127%	157%
Darcy/Dupuit	1.54	1.02	0.6	148%	127%	161%
MODFLOW	1.64	1.06	0.63	165%	136%	174%
MODFLOW Transient drain connected	0.62	0.46	0.183	0%	2%	-20%
MODFLOW Transient	0.62	0.45	0.23	0%	0%	0%

Table 12 – Mounding comparisons for Theoretical Test Cases 5, 6 and 7

There is no consistency apparent in the steady state variations to the transient models listed in the table. This will make it difficult to justify the use of any of the stead state methods when designing for the no soak well scenario in urban development.

6.7 Theoretical Test Case 8 (Capped Daily Maximum Rainfall)

The transient data used for the analysis thus far is for the year 2000 which has a total rainfall of 881mm for the year. This is 80mm above the average total rainfall recorded for Dunsborough. The rainfall year consists of 146 rain days of which 145 are 31mm per day or less, there is one rain day of 62mm which is double the second highest rainfall day. The maximum mounding values calculated in the MODFLOW transient simulations are in response to this 62mm rainfall event. Given that this rainfall event is a one off and does not represent a typical rainfall event in the Dunsborough region, is it reasonable that it is used as the basis of design for transient models in Dunsborough?

Theoretical test case 8 examines the affect that removing this event has on the mounding calculations. This rainfall day in the transient analysis will be capped at 30mm which is representative of a 2yr 72hr event. The 90m and 60m simulations are re-calculated using this theory for the soak well cases and drain connected cases.

6.7.1 Results Theoretical Test Case 8

Below is a graph showing the groundwater mounding height as calculated by the soak wells at rear simulations for the 60m and 90m subsoil drain separations compared to the 30mm/day capped rainfall simulations.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 90m, 60m

K = 5m/d

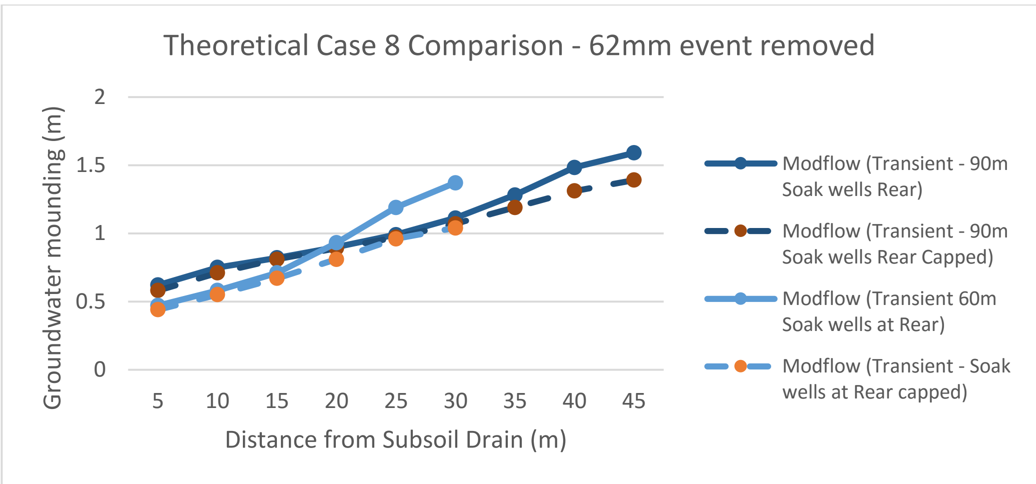


Figure 28 – Theoretical Case 8 – Comparison 62mm event replaced by 30mm event Soak wells at Rear

When reviewing the above results it can be seen that capping the daily rainfall to 30mm has reduced the peak mounding on both the 60m and 90m subsoil separations. The reduction is more significant on the 60m simulation, reducing maximum mounding from

1.37m to 1.04m, a reduction of 0.33m. The 90m separation has been reduced from 1.59m to 1.39m, a reduction of 0.2m. When considering the high cost of imported sand to site these small reductions are significant when considered over an entire development area.

Below is a graph showing the groundwater mounding height as calculated by the drain connected simulations for the 60m and 90m subsoil drain separations compared to the 30mm/day capped rainfall simulations.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 90m, 60m

K = 5m/d

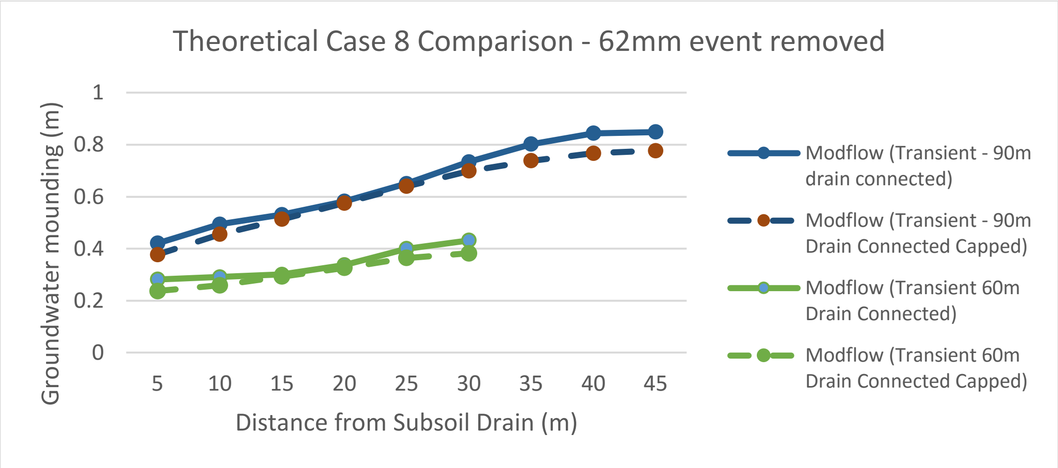


Figure 29 – Theoretical Case 8 – Comparison 62mm event replaced by 30mm event drains connected

The above graph again shows a reduction in both the 90m and 60m subsoil drain separation mounding heights. As would be expected the reduction is less pronounced due to the reduced recharge to groundwater simulated in the drain connected simulations. The 90m simulation shows a reduced maximum mounding height of 70mm from 0.85m to 0.78m. The 60m simulation shows a reduced maximum mounding height of 50mm 0.432 to 0.382.

Both of these simulations show that by removing the extreme rainfall event considered to be an outlier when compared to the rainfall events experienced over 12months a more cost effective design can be established that more accurately reflects the rainfall conditions experienced in the Dunsborough region.

6.8 Theoretical Test Case 9 (Hillman Cocks Modifications)

Designers working in urban development do not always have access to software programmes such as MODFLOW to run transient simulations. Using MODFLOW to check drainage designs and earthwork levels can be time consuming and costly. Theoretical test case 9 examines whether a spreadsheet steady state method can be modified to closely replicate the results of the transient simulations. This would be a useful tool for designers as well as design checkers as it would allow them to quickly examine critical cross sections in developments to assess compliance. From the previous test cases it has been established that the recommendations of the IPWEA guidelines for steady state analysis are far too conservative. Rather than use a 2 yr 72 hr event averaged daily, this analysis averages the 2 yr 72 hr event over a month to give a more realistic daily rainfall and response period. In an attempt to replicate a transient analysis where mounding exists from the previous day's rainfall (rather than fully draining the profile each day) the average monthly rainfall, averaged daily is added to the 2 yr 72 hr event. This method of applying the rainfall averaged monthly to steady state equations was previously introduced by Wayne Edgeloe of Calibre Consulting (Aust).

As mentioned previously the Hillman Cocks method is the only steady state model that makes an allowance for concentrated flow. Table 11 shows that for the 60m and 90m simulations the Hillman Cocks method holds a similar variance to the two transient model results. For these two reasons the Hillman Cocks method was chosen for this analysis.

As previously discussed the Hillman Cocks method multiplies the flow rate by a factor of 2 to allow for the 2 systems of soak wells that would exist at the midpoint between subsoil drains in a back to back lot configuration. Rather than apply a factor of 2 to all simulations the Hillman Cocks method is modified so that the factor is calculated as the ratio of hardstand area to lot area. The theory behind this is that it is only the hardstand areas that are directed to soak wells as concentrated flow, so by using a factor of 2 the flow rate is increased too conservatively.

6.8.1 Results Theoretical Test Case 9

Below is a graph showing the groundwater mounding height as calculated by the soak wells at rear simulations for the 60m and 90m subsoil drain separations compared to the results of the modified Hillman Cocks steady state simulation.

Inputs:

Steady State Recharge rate – 60%

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

2year 72 hr event – 1.21mm/hr

1.21 x 72/31 = 2.81mm/day

Average Maximum monthly rainfall – 162.9mm

162.9/11 = 5.25mm/day

Total rainfall recharge – (2.81 + 5.25) x 0.6 = 4.84mm/day

Theoretical hardstand area = 360m^2

Theoretical lot area = 800m^2 for 90m separation, 600m^2 for 60m separation

L = 90m, 60m

K = 5m/d

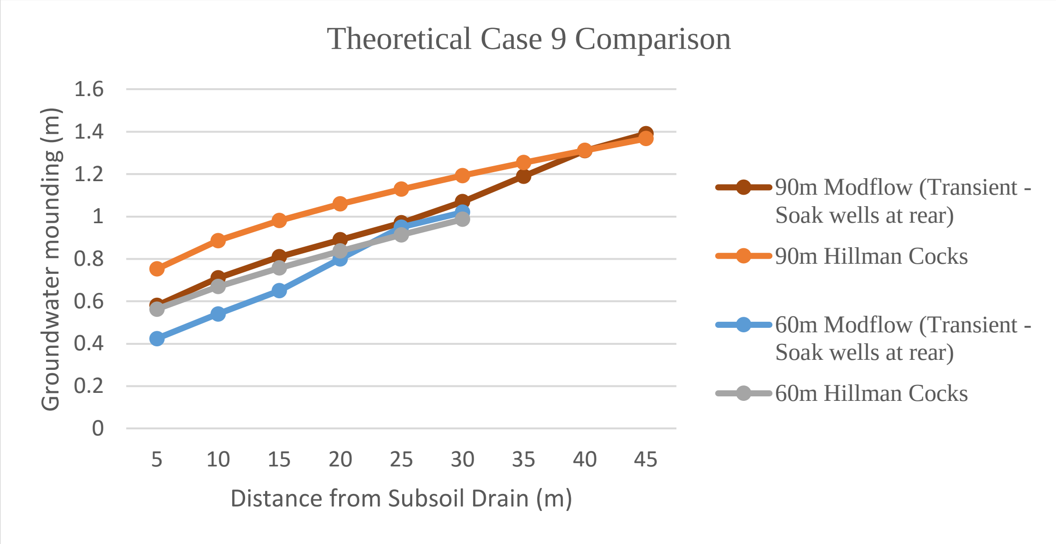


Figure 29 – Theoretical Case 9 – Comparison Soak wells at rear to modified Hillman Cocks Method.

The results shown above are positive in that the maximum mounding values are very similar for both the 60m and 90m simulations. For the 90m simulation the modified Hillman Cocks value is 1.37m, being 20mm lower than the transient simulation. For the 60m simulation the modified Hillman Cocks value is 0.97m being 50mm lower than the transient simulation. The distribution of mounding throughout the simulation has a lot greater variance. This is not seen as a significant issue as designers in urban development are primarily concerned with the maximum mounding values only for setting earthworks levels. For cases involving proposed soak wells at rear in the Dunsborough region the modified Hillman Cocks method will be a useful tool in carrying out time efficient checks on earthworks designs as well as completing actual designs when software modelling is not available.

Below is a graph showing the groundwater mounding height as calculated by the drain connected simulations for the 60m and 90m subsoil drain separations compared to the results of the modified Hillman Cocks steady state simulation. Because the comparison is to the drain connected model the concentrated flow portion has been removed and the recharge percentage has been calculated based on the ratio of hardstand to lot area.

Inputs:

Steady State Recharge rate – 15% for 60m, 27.5% for 90m

Hardstand Recharge rate – 0%

Lawns/Gardens recharge rate – 50%

2year 72 hr event – 1.21mm/hr

1.21 x 72/31 = 2.81mm/day

Average Maximum monthly rainfall – 162.9mm

162.9/11 = 5.25mm/day

Total rainfall recharge – (2.81 + 5.25) x 0.6 = 4.84mm/day

Theoretical hardstand area = 360m^2

Theoretical lot area = 800m^2 for 90m separation, 600m^2 for 60m separation

L = 90m, 60m

K = 5m/d

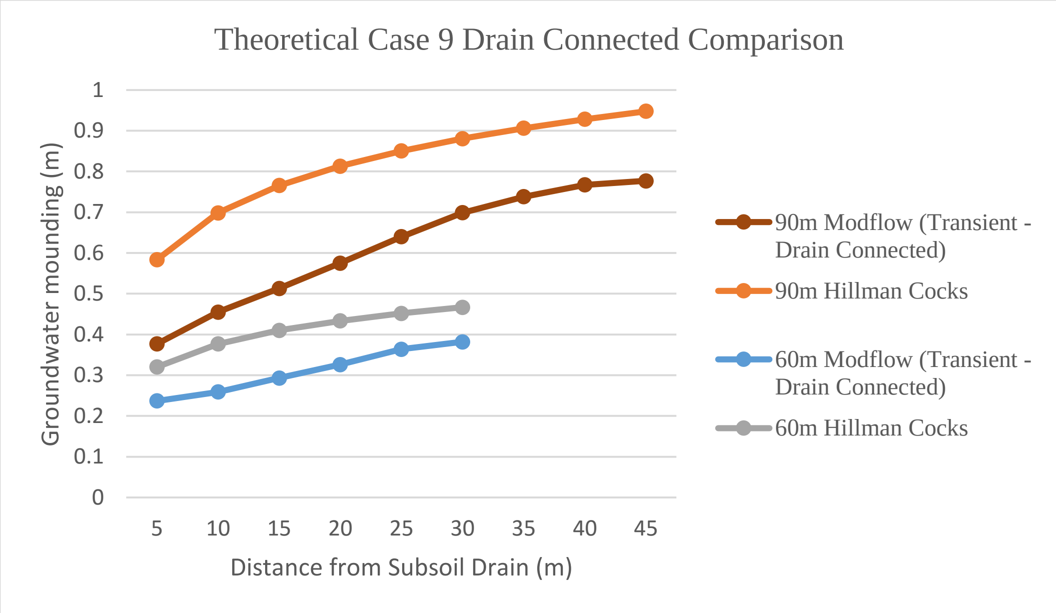


Figure 30 – Theoretical Case 9 – Comparison Drain Connected to modified Hillman Cocks Method.

The modified Hillman Cocks method results are 0.17m and 0.08m higher than the 90m and 60m transient simulations respectively. This represents a difference of 21% for both separation distances. Because the percentage variance is consistent for the two models this indicates that the Hillman Cocks method could be further calibrated to give a closer result.

6.9 Theoretical Test Case 10 (90m Transient Soak wells at Rear, Soak wells at Front Comparison)

In practise it is quite common for builders to install soak wells in the front yards of houses as opposed to the rear and sometimes there is a combination of both. Theoretical test cases 10 and 11 explore the variance in mounding experienced when soak wells are installed at the front of lots. A transient model was developed for both the 90m and 60m separation distances that allowed for a 360m^2 house footprint which discharges to six soak wells positioned 3m off the front of the theoretical house. For the house footprint a 90% recharge factor was applied while for the front and back yards a 50% recharge was applied as required for turf/gardens in the IPWEA guidelines. For both of the following test cases the 62mm event has been capped at 30mm as explored in test case 8. The soak well at front simulation will be compared against transient simulations for soak wells at rear and drain connected.

6.9.1 Results Theoretical Test Case 10

Below is a graph showing the groundwater mounding height as calculated by the soak wells at front simulation for the 90m subsoil drain separation compared to the soak well at rear and drain connect transient simulations.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 90m, 60m

K = 5m/d

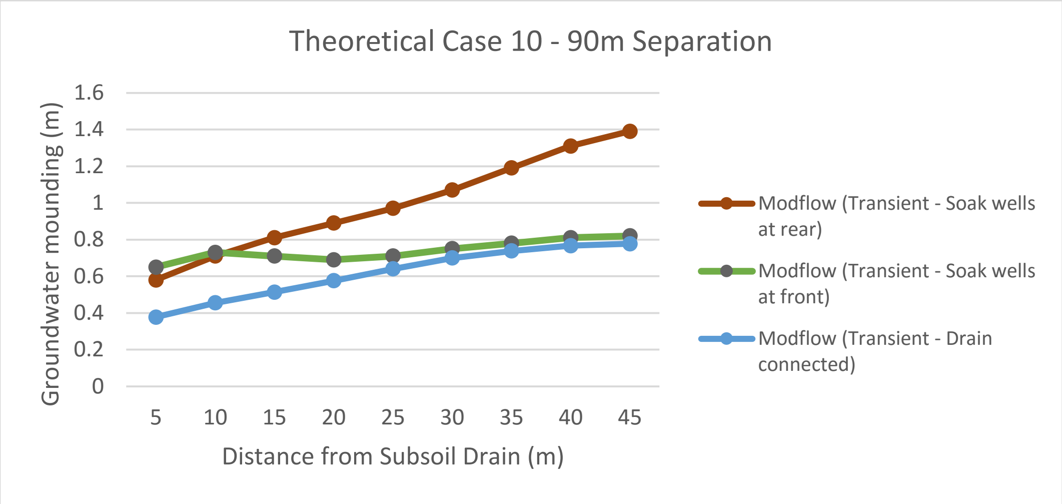


Figure 31 – Theoretical Case 10 – Comparison Soak wells at front to transient models.

The shape of the soak wells at front distribution is as would be expected. The mounding is slightly higher in the rear due to the larger back yard present in the 90m separation model and the 50% recharge rate. The results then dip under the house footprint and rise again due to the concentrated recharge from the soak wells at the front of the property. Note how the curve follows that of the drain connected simulation through the rear of the lot but approximately 50mm higher. Given that the recharge areas and percentages are the same for both of these simulations it would be reasonable to assume that the results should be identical. The slightly higher mounding seen in the soak well at front simulation is assumed to be due to the flooding of cells a t the front slowing the movement of water to the subsoil drain. It should be noted that the maximum mounding value for the soak well at front simulation (0.82m) occurs at the rear of the property. It may have been reasonable to assume the maximum mounding would occur at the front due to the concentrated recharge but the close proximity to the subsoil drain pulls it down.

6.10 Theoretical Test Case 11 (60m Transient Soak wells at Rear, Soak wells at Front Comparison)

Test case 11 is another comparison between a transient soak well at front simulation and the soak well at rear and drain connected simulations but with this model being over the separation distance of 60m.

6.10.1 Results Theoretical Test Case 11

Below is a graph showing the groundwater mounding height as calculated by the soak wells at front simulation for the 60m subsoil drain separation compared to the soak well at rear and drain connect transient simulations.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 60m

K = 5m/d

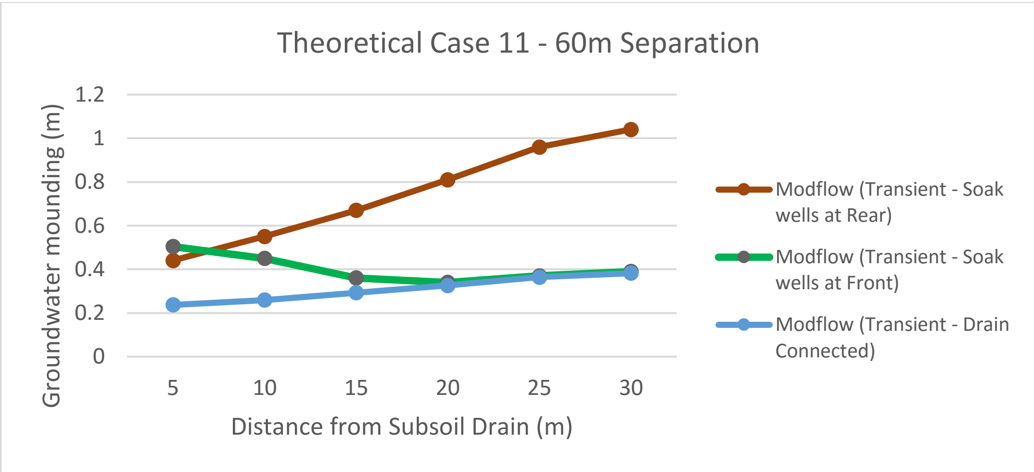


Figure 32 – Theoretical Case 11 – Comparison Soak wells at front to transient models.

For the 60m separation shown above the soak wells at rear simulation is again significantly higher. Again the curves for the drain connected and soak wells at front simulations are very similar at the rear of the theoretical house lot due to the uniform recharge. The soak wells at front simulation is marginally higher (10mm), again this is considered to be due to the cells being flooded at the front of the lot slowing the movement of water from the rear to the subsoil drain. The difference of only 10mm compared to 50mm for the 90m case is due to the smaller back yard and the reduced uniform recharge area. The major notable difference in this test case is that the maximum mounding value (0.504m) now occurs at the front of the lot due to the concentrated recharge flow from the soak wells. Because the backyard is smaller the uniform recharge in the back of the lot has reduced to an amount that is now lees than the soak well recharge at the front of the property.

6.11 Theoretical Test Case 12 (Street Drainage Model)

Generally, in urban development designers will design subsoil drainage on one side of proposed subdivision roads only, this is to save cost and for efficiency of installation as generally the subsoil would be installed in a common trench with the stormwater drainage. A thin layer of clean free draining sand is installed below road pavements, on top of impermeable clay layers, to allow water to move from one side of the road to the other and intersect with the subsoil drainage. The depth of the sand layer varies with the longitudinal grade of the road, but generally has a minimum depth of 0.3m. This sand layer intersects with the parallel subsoil drainage to allow the sand layer to be drained. This is illustrated in the figure below.

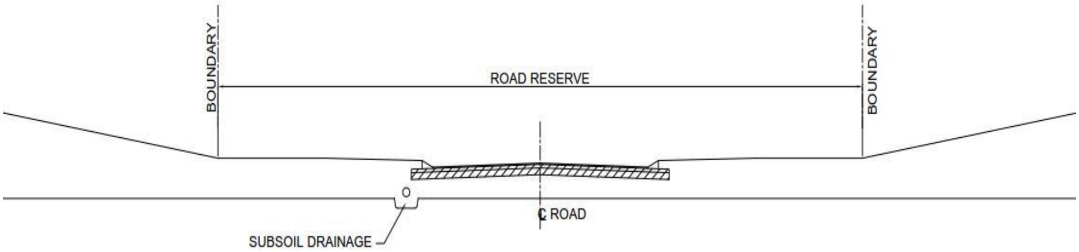


Figure 33 – Typical road profile.

A model was developed that replicated this situation to see whether the sand layer under the road pavement had a "choking" effect on the rate of water movement, resulting in a higher mounding value on one side of the road compared to the other. A grid was setup similar to the previous models but with the depth of the cells amended from 1m to 0.2m. Cells were then nulled from the model to replicate the road reserve profile shown in the above figure. The resulting model is illustrated in the elevation shown in the figure below.

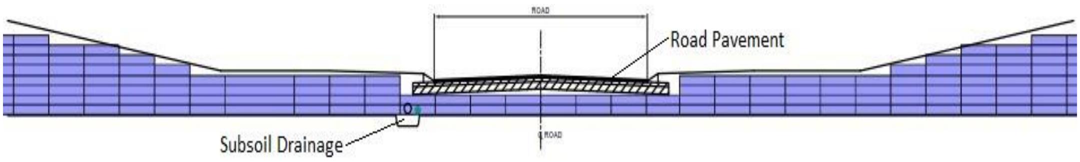


Figure 34 – MODFLOW Grid layout.

All other inputs used for the previous transient models were again used, the soak wells at front model was chosen for the analysis as it was considered to be the most likely have an impact given the concentration of recharge directly adjacent to the road.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 60m

K = 5m/d

6.11.1 Results Theoretical Test Case 12

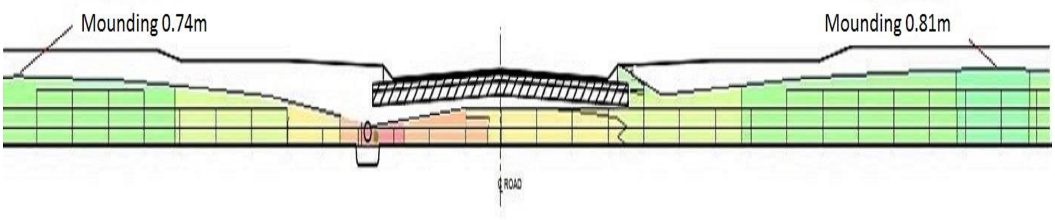


Figure 35 – Street Drainage Mounding Distribution.

The above cross section has an exaggeration on the vertical scale so that detail associated with the mounding and the road pavement is easier to assess. The mounding curve on the left of the road pavement (subsoil drainage side) is as would be expected, resulting in a maximum mounding height of 0.74m. The results on the right hand side of the road are more interesting. Firstly, the maximum mounding result is 0.81m, being 0.07m higher than the other side of the road. The mounding distribution intersects the road pavement on the right hand edge causing some localised mounding behind the kerb. Although it is not shown it is likely that this would result in some flow over the kerb and onto the road, the road verge in this area will become saturated with the majority of rainfall that falls directly on the verge sheeting off on to the road. The slightly higher mounding can be attributed to the "choking" or throttling effect the thin layer of sand beneath the road pavement has on flow. Because there is a smaller cross section of free draining sand for flow to move through, the mounding behind the kerb occurs, with this mounding increase being reflected back into the property. Because the subsoil drain is on one side of the road and the lot dimensions are the same, the groundwater has slightly further to travel before it is drained, this is also a contributing factor. A minimum depth of sand below the road pavement of 0.6m will allow the groundwater to drain freely and minimise the increased mounding on the non- subsoil side or alternatively subsoil could be installed both sides of the road. Designers will need to make an assessment as to whether the modelled scenario is sufficient as the temporary mounding behind the kerb will only occur at the lowest points of the road and for a relatively short period of time.

6.12 Theoretical Test Case 13 (One Out of the Box!)

Theoretical test case 13 was developed to test a methodology outside of the typical industry accepted methods of controlling groundwater. As discussed previously subsoil drainage is typically installed parallel to roads behind the kerb line, additional subsoil is sometimes installed at the rear of properties to control groundwater mounding in extreme cases. For this model subsoil drainage was configured to run along the proposed lot side boundaries, perpendicular to roads. No subsoil drainage was allowed for parallel to roads.

The theory behind the model is that by running the subsoils along the side boundaries the separation distances between subsoil drains will be much less (in this instance 20m). This should significantly reduce the amount of groundwater mounding. Because there is no subsoil within the road reserve the total length of subsoil is not significantly larger and it is expected that the costs saved by reducing the amount of mounding and subsequently the quantity of fill will far out way the additional length of subsoil drain. A negative could potentially be that without the subsoil drainage behind the kerb line of the road groundwater may mound to a level that may compromise the integrity of the road pavement. For this reason, the soak wells at front simulation was used in the model as the concentrated flow adjacent to the road is the situation most likely to affect the road pavement. The lot configuration is as per the 90m separation models as the larger backyards produce a higher amount of groundwater recharge. The proposed model is shown in the figure below.

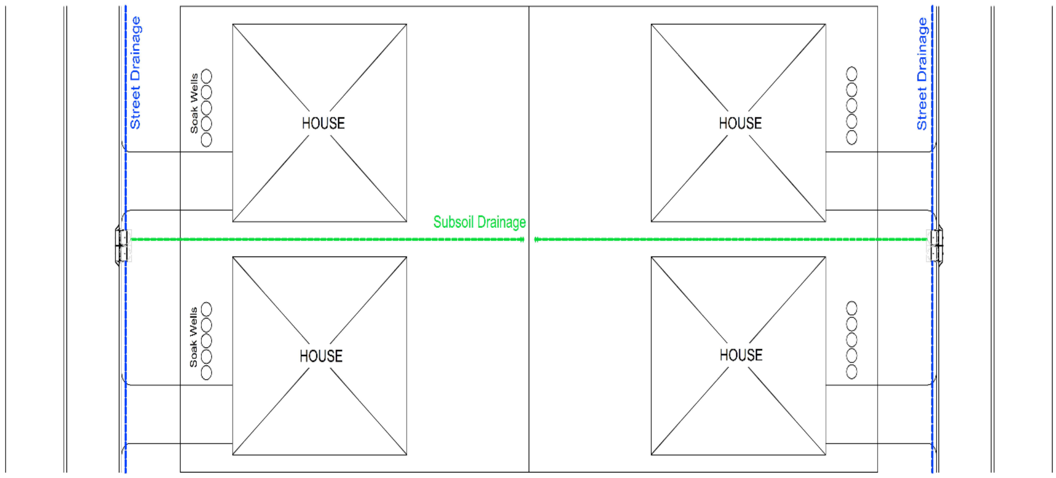


Figure 36 – Alternative Groundwater Control Method.

6.12.1 Results Theoretical Test Case 13

Below is a graph showing the groundwater mounding height as calculated by the soak wells at front simulation for the alternate subsoil drain model.

Inputs:

Hardstand Recharge rate – 90%

Lawns/Gardens recharge rate – 50%

Transient recharge rates as per year 2000 daily rainfall capped at 30mm/day.

L = 20m

K = 5m/d

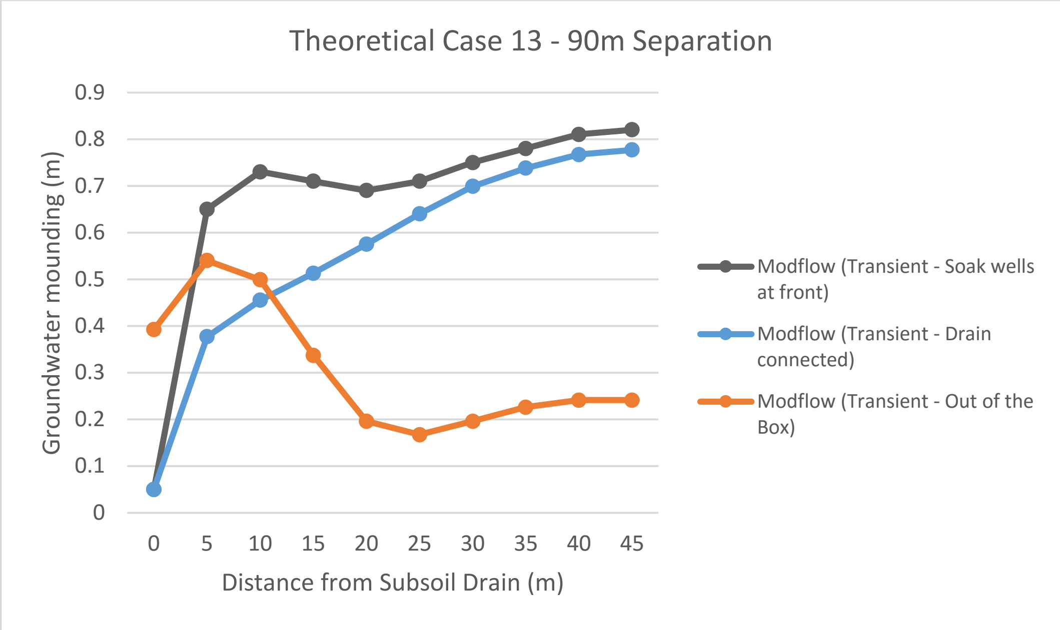


Figure 37 – Theoretical Case 13 – Comparison Alternative Subsoil Model.

The results of the alternative model are compared against the standard soak wells at front and drain connected transient models in the above graph. The "Out of the Box" simulation produces a maximum mounding 0.24m less than the drain connected simulation and 0.28m less than the traditional soak wells at front simulation. It should be noted that the maximum mounding location has moved from the rear of the lot to the front. Positioning the subsoils on the side boundaries has dramatically reduced the mounding caused by the uniformly distributed recharge at the rear of the lot, the level here is now only 0.24m compared with 0.777m in the traditional simulation. The maximum mounding is now a result of the concentrated recharge from the soak wells at the front of the lot. This is demonstrated further in the figure below. This is a plan view of the model with the mounding contours overlayed. Note the circular concentration of flow at the front of the houses representing the recharge from the soak wells.

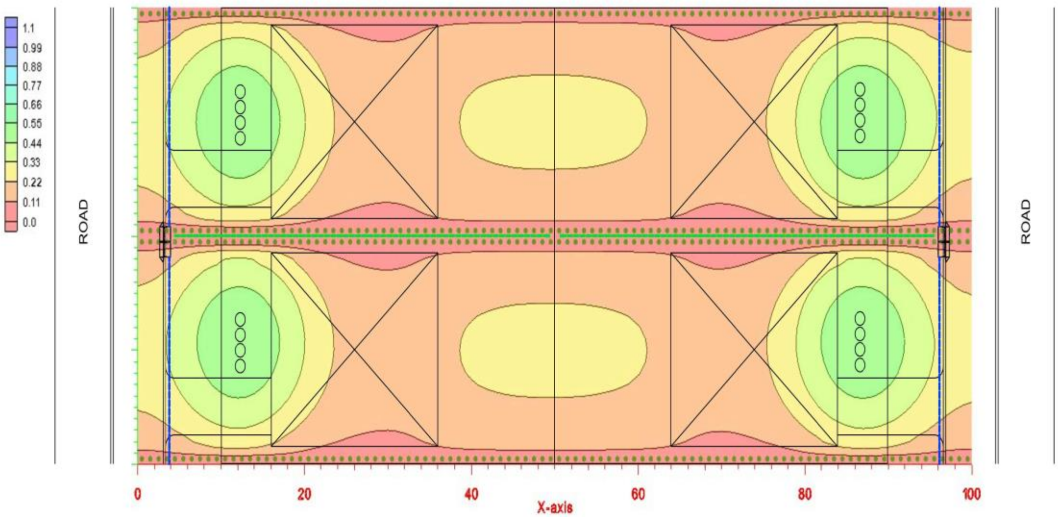


Figure 38 – Theoretical Case 13 – Mounding Distribution.

The mounding result at the edge of the road pavement is 0.39m, while this is probably acceptable given that there would be a 300mm to 600mm of sand beneath road pavements if this configuration of subsoil drainage were to be used it would be beneficial to locate the soak wells at the rear of the property. This is because the distance to the subsoil drains is the same whether the soak wells are located in the front or the back and so the maximum mounding result would remain the same. This would provide a greater factor of safety regarding the separation between the road pavement and the groundwater. This model successfully controls groundwater mounding to a level that is less than the other methods tested without impacting the road pavement and would be an extremely effective method in perched water conditions.

7.0 Results Discussion

The following sections give an overview and comparison of the results achieved in theoretical test cases 1 to 13.

7.1 Steady State Vs Transient

Theoretical test cases 1 to 7 compare the results of the steady state simulations against the results of the transient simulations. All of the test cases show that the results of the steady state models are significantly higher. In practice, urban development sites in WA will generally require 1.2 to 1.5 m of imported sand to gain clearance to high groundwater tables and provide separation to mounding. This has proven to be sufficient over many years of application. The steady state results produced in test cases 1 to 7 are all above 3m with some as high as 5m, these results are not representative of what occurs in practice and are of no value to designers. But, is this because the steady state models are inaccurate or are the rainfall inputs used too conservative? The basis of steady state models is that the water that enters the system equals the water that leaves the system, with no allowance for storage or the transient effects associated with time. Considering this a rainfall event that represents an average rather than a peak may produce results comparable with real world levels. Test case 9 demonstrated that by averaging the 2yr 72-hour rainfall event over a month and adding a monthly average to account for existing groundwater mounding in the system, a more comparable result could be achieved.

The other issue in comparing the steady state and transient simulations is that you are comparing two simulations based on similar spatial dimensions i.e. catchment size and separation between drainage, but with two completely different sets of rainfall data (recharge inputs). For this reason, a steady state model could not be used universally for all locations and rainfall intensities but rather would need to be calibrated for each specific location and rainfall data set.

Additionally, test cases 1 to 7 also demonstrated the effects of concentrated flows on the mounding distribution. It is very difficult to make allowance for concentrated flows within a steady state simulation. Test case 9 used a modified version of the Hillman Cocks method to achieve comparable maximum mounding results to the transient soak wells at rear simulation. However, the distribution of mounding throughout the cross section was still significantly different. Again this steady state model would need to be calibrated for each different rainfall location used.

7.2 Soak Wells at Back Vs Soak Wells at Front

The inclusion of concentrated soak well recharge in the MODFLOW transient models produced some very interesting results. The IPWEA guidelines allows for concentrated soak well recharge by adjusting the recharge percentage for the uniformly distributed models. The reasoning behind including this type of analysis was to assess whether this approach is valid and to see what impact varying the soak well locations had on the maximum mounding values and also the location of the peak of the mound.

The addition of soak wells to the rear had a dramatic impact on maximum mounding. For both the 60m and 90m drainage separations modelled, the mounding increased 30% to 60% compared to the uniformly distributed models. The models were created on the basis that the size of houses on various lots remain the same regardless of the size of the lot, so all that varies with lot size is the size of the back yard and hence, the area of uniform recharge. This is why the inclusion of the soak wells at rear model had the biggest impact on the smaller lots when compared to the uniformly distributed model. The same recommended recharge percentage was used for both 60m and 90m models but in reality, assuming the size of the house remains the same, the percentage recharge rate should change as the portion of concentrated flow to uniformly distributed flow is higher. If designers choose to use uniformly distributed techniques to analyse groundwater mounding, then close attention needs to be given to the recharge rates used. These should be varied given the lot dimensions and situations where they are to be applied. The impact of the introduction of the concentrated recharge was less significant for the 35m simulation, this was demonstrated in test case 4. The variance in mounding height to the uniformly distributed simulation was 0.025m. The soak wells at rear simulation is still higher but with minimal variance due to the subsoil drainage being located at the rear of the property, directly adjacent to the soak wells.

While the soak wells at rear simulations had a negative effect in that they increased the maximum mounding results, the soak wells at front simulations were positive, producing results less than the soak wells at rear and uniformly distributed simulations. By positioning the concentrated recharge directly adjacent to the subsoil drain the recharged groundwater has less distance to travel before it is drained and the overall mounding is reduced. The introduction of the soak wells at front reduced the maximum mounding values by 52% and 41% for the 60m and 90m simulations respectively when compared to the soak wells at rear simulation. The reduction is 41% and 33% for the 60m and 90m simulations respectively when compared to the transient uniformly distributed simulation.

For low to medium density urban development where disposal of stormwater drainage through soak wells is preferred, locating the soak wells at the front of the proposed lots is definitely the most economical and efficient method of controlling groundwater mounding. On high density developments like unit complex’s, strata developments and retirement villages there may not be sufficient space within the lots for soak well recharge, in these scenarios hardstand areas may need to be direct connected to street drainage.

7.3 Soak Wells Vs Drain Connected

Theoretical test cases 5, 6 and 7 analyse the scenario where hardstand areas within the lots are direct connected to street drainage, removing the need for soak wells. In these models there is no concentrated recharge, all recharge is uniformly distributed in the front and rear of the properties. As per the soak well at rear and front simulations this set of simulations was developed to compare results to the uniformly distributed simulation. The results for the 60m and 90m simulations are 13% and 8% less respectively than the uniformly distributed simulations with the 60m simulation having a larger discrepancy due to the ratio of hardstand to uniformly distributed recharge areas. The 35m (subsoil at rear of lot) simulation was also less with a variance of 18% to the uniformly distributed model. Again the variance of the models is due to the ratio of hardstand to uniformly distributed turf/garden areas and how this correlates to the percentage recharge rates suggested in the IPWEA guidelines.

When comparing the results obtained from the soak wells vs drain connected models, as expected the drain connected simulations produce a reduced mounding height. This is demonstrated in theoretical test case 11. The soak wells at front simulations produced the lowest results of the soak well simulations. Comparing this to the drain connected simulations for the 60m and 90m models the drain connected results are 24% and 5% less respectively. When considering mounding height only, the drain connected model is the most efficient. The use of this method needs to be considered on a case by case basis.

When large urban areas are all direct connected to street drainage there is little to no recharge to groundwater at source, as all stormwater is discharged at the end of the drainage system. This can lower groundwater systems considerably and can have detrimental effects to vegetation and natural ecosystems in the area. Lowering of groundwater systems can also trigger the oxidisation of acid sulphate soils within the soil profile.

7.4 Validity of the IPWEA Guidelines

The research conducted in this project has identified two main areas within the IPWEA guidelines that require further analysis. The suggested storm event for steady state analysis (2yr 72-hour event) and the requirement for it to be averaged daily is far too conservative, as it produces mounding heights that are not comparable to the more accurate transient analysis and real world practices. As suggested in theoretical case 9 the 2yr 72-hour event averaged over a month, plus the monthly average rainfall averaged daily, produces results that are comparable to the transient results for the Dunsborough test case location. Rather than stipulating a requirement in the IPWEA guidelines, a suggested method as per theoretical test case 9 could be included in the guidelines but it should be clarified by a statement that all steady state models should be calibrated to the location and rainfall data used. The intended drainage method can also have an impact on the accuracy of steady state models. If a soak wells at front method is intended, steady state models will not be able to accurately predict mounding values that close to the subsoil drain location. Steady state models should not be used with soak well at front models.

The second area requiring further analysis is the accuracy of the specified recharge percentages. The guidelines recommend 50% recharge for turf and 30% recharge for mixed turf/gardens. Variations to these rates can have a significant impact on mounding results. Further research needs to be undertaken to provide some accuracy for these percentages.

7.5 Efficiencies in Design

The table below lists the maximum mounding results achieved by the various simulations. As discussed the drain connected results produced the lowest maximum mounding values. The drain connected methodology is ideal for perched groundwater situations where recharge to water table is not a concern. This method has the added benefit of *not* recharging excessive water above clay layers which may potentially cause shrink/ swell reactions.

Simulation	60m Maximum Mounding (m)	90m Maximum Mounding (m)
Soak Wells at Rear	1.04	1.39
Soak Wells at Front	0.504	0.82
Drain Connected	0.382	0.78
Out of The Box	_	0.54

Table 13 – Maximum Mounding Results.

Where soak wells are the preferred method of onsite stormwater disposal it should be specified to lot purchasers that soak well drainage must be installed at the front of lots as this has been demonstrated to significantly reduce mounding and the required fill levels.

When this method is used designers need to ensure that there is sufficient subsoil drainage in the street and clean free draining fill beneath road pavements.

The alternative “Out of The Box” method demonstrated that further efficiencies in controlling groundwater mounding could be gained by installing subsoils parallel to side boundaries as opposed to parallel to street drainage. As indicated in the above table this method further reduced the maximum mounding value for the 90m simulation by 0.24m. This method would require the approval of local authorities as it is untried in practice.

7.5.1 Cost Benefits

Below is a table showing indicative market rates and the costs associated with the various methods of stormwater disposal.

		60m					
		Soak Wells at Rear		**Soak Wells at Front**		**Drain Connected**	
Item	Rate	Quantity	Value	Quantity	Value	Quantity	Value
Imported Fill (m3)	$ 30	804	$24,120	482.4	$14,472	409.2	$12,276
Soak wells (No.)	$ 925	6	$5,550	6	$5,550		
Drain connected lot connection (Item)	$1,050	-				1	$1,050
Storage Tanks (no soakage) (No.)	$ 925					6	$5,550
Street Drainage (Item)	$ 500	-				1	$500
Total			$29,670		$20,022		$19,376

		90m					
		Soak Wells at Rear		**Soak Wells at Front**		**Drain Connected**	
Item	Rate	Quantity	Value	Quantity	Value	Quantity	Value
Imported Fill (m3)	$30	1352	$40,560	896	$26,880	861.6	$25,848
Soak wells (No.)	$925	6	$5,550	6	$5,550		
Drain connected lot connection (Item)	$1,050	-				1	$1,050
Storage Tanks (no soakage) (No.)	$925					6	$5,550
Street Drainage (Item)	$500	-				1	$500
Total			$46,110		$32,430		$32,948

Table 14 – Cost Comparison.

The 5 key cost items influenced by the different stormwater disposal methods are indicated in the table. The “Street Drainage” item is a lump sum allowance for the increased capacity of the street drainage system that may be required for the drain connected stormwater disposal method. This item is highly variable as depending on the size of the catchment contributing to the street drainage system the increased flows and hence pipe size and end point basin size, will vary if all the lots are direct connected to the system. It also depends on the peak time in concentration for the critical storm duration of the street drainage. If the drainage tanks installed on the lots detain the flow to a degree that the discharge to the street drainage is delayed, then the lot flows will not influence the peak discharge, then there will be little to no impact on the street drainage.

From the table it can be seen that the drain connected method is marginally cheaper than the soak wells at front method for the 60m drain separation. This is due to the reduced fill volumes. For the 90m drain separation, the soak wells at front option is marginally cheaper. This is because the variance in imported sand between the two options has been reduced to an amount that is less than the cost of the additional drainage required for the drain connected model. Because the variance in cost between the soak wells at front and drain connect models is minimal, an assessment will need to be made on a case by case basis based on the current market rates for the location and time.

It is worth noting that the “Out of the Box” method modelled in theoretical case 13 reduces the earthwork level by 0.28m compared to the most cost effective option for the 90m separation. This results in a reduction of 224m^3 of imported sand and an overall cost saving of $5420 per lot, which allows for the additional length of subsoil required for the longer boundary. If this method were to gain approval from local authorities, it would be the most cost effective and efficient method for controlling groundwater mounding.

8.0 Conclusion

Engineers have a moral and ethical responsibility to ensure that they use the most up to date, accurate, site appropriate methodologies and software in design. Inaccurate designs can result in excessive economic and environmental costs, while insufficient designs can result in damage to private property, health risks and degradation of recreation areas. This project has demonstrated some refinement to the current design methodologies and procedures that will minimise the amount of fill required on development sites and assist in producing more efficient designs.

The key findings of this project are listed below:

- The IPWEA Guideline recommendation for steady state recharge to be calculated using a 1 in 2yr 72-hour event averaged daily is too conservative.
- Steady State models can be used for design purposes but need to be calibrated to the location and for the intended drainage disposal methodology.
- Accurate models should be produced modelling hardstand and anticipated turf/soakage areas, as opposed to just applying a uniformly distributed rate with a factor.
- The drain connected method produces the lowest degree of mounding (excluding the “Out of the Box” model).
- If soak wells are the preferred method of storm water disposal, then they should be placed at the front of lots and designers need to check that there is sufficient sand separation below road pavements.
- If authorities were to accept the “Out of the Box” methodology, then there would be considerable efficiencies and cost savings.
- It is not possible to produce a steady state model that will replicate transient results for all rainfall distributions and all stormwater disposal methods, as you are comparing two completely different sets of data. It is the opinion of the writer that steady state models have a place in design as they allow quick efficient checking of critical sections within a development, and can be used by design checkers and engineers that may not have access to modelling software or the skills to use it. As previously stated these models need to be calibrated to the rainfall data and disposal method selected for design.

In general, current practice is to complete designs based on a uniform distribution of recharge. A percentage is applied to the recharge based on the designer’s judgement and the IPWEA recommended guideline, to allow for the proportion of hardstand to turf/garden areas within the site being analysed. This project has demonstrated that this method can produce results that under estimate the mounding. Modelling should be undertaken that makes allowance for concentrated flows from soak wells as well as uniformly distributed areas and zero recharge under hardstand areas. This modelling not only produces more accurate mounding results but the location of the mound is defined more accurately also.

This project has demonstrated that the drain connected model produces the lowest mounding of the industry accepted stormwater disposal methods. As mentioned previously the use of this method needs to be considered on a case by case basis and is probably not desirable when existing groundwater levels need to be maintained. This method is probably best suited to perched groundwater conditions created by the importing of sand fill.

As a general rule, in practice there are very few building controls that dictate where soak wells should be installed by builders. As such designers have to design for the worst case scenario, being soak wells installed at the rear. The soak wells at front storm water disposal method has been demonstrated to be the most efficient soak well stormwater disposal methodology. If local authorities were to put in place building restrictions that enforce the installation of soak wells at the front of properties, designers could then design for this scenario with confidence. This would result in significant efficiencies and cost savings. Alternatively soak wells at rear methodology combined with the installation of subsoil drainage at the rear of the property also provided efficient results. However, the placing of subsoils at the rear requires an easement to be placed on the title of the lots which restricts the lots useable space which is undesirable. As such placing subsoils at the rear of properties is seen as a method of last resort.

The “Out of the Box” method produced results that reduced mounding to below the other stormwater disposal methods. This method has not been trialled in practice. It is expected that local authorities may take issue with critical infrastructure to be installed within lots and as such may request they be covered by an easement on the title. This would devalue the lots and would not be acceptable to developers. It could be argued that the subsoil drainage laid down the side boundary of the lot is the responsibility of the lot owner, as its purpose is to control the lots groundwater, much the same as soak wells and drain connected methodologies deal with the lots stormwater but are not covered by easements and are the lot owner’s responsibility. If this anticipated issue could be overcome, the “Out of the Box” method is the most efficient method for reducing groundwater and the quantity of imported fill required.

A short coming of this project is that the theoretical results have not been verified by any on site testing and monitoring of groundwater levels. Ideally, selected sites replicating soak wells at front, soak wells at rear and drain connected methodologies would be fitted with groundwater bores which would be monitored for an extended period of time. These results could then be verified against transient models based on the same dimensions and rainfall period. This would be very useful data as it would not only confirm peak levels of mounding but also the rate of groundwater rise and fall. Close attention would need to be given to the compacted properties of the imported sand in this type of field test to confirm that the sand inputs such as hydraulic conductivity and porosity are representative of those used in the theoretical analysis.

9.0 Recommendations

The analysis conducted in this project was based on several standard input values. These values represent the properties of the imported fill used on development sites as well as the portion of rainfall recharge to the soil profile and are listed below:

- Hydraulic Conductivity of Imported fill.
- Porosity of imported fill.
- Specific yield of imported fill.
- % recharge rates for gardens/turf.
- % recharge rates for hardstand areas.

The properties indicative of the imported sand have been well researched and investigated. The onsite compaction of the material needs to be regulated closely, however, given the previous investigations the input values for the imported fill are considered satisfactory. The recharge rates however have had very little investigation. The IPWEA guideline recommended recharge rates are:

Soak wells

- Hardstand 80 – 90%
- Vegetation 10 – 20%
- Turf 40 - 50%
- Uniformly Distributed (combination) 50 – 60%

Drain connected

- Hardstand 0 – 10%
- Vegetation 10 – 20%
- Turf 40 - 50%
- Uniformly Distributed (combination) 10 – 20%

Even minor variations to the recharge percentages have notable effects on the mounding results. Given that the percentage of recharge to the soil profile is a key factor it is recommended that further investigation be undertaken into the validity of the suggested percentage recharge rates.

It is considered that the transient results are accurate as they produce mounding heights that are comparable with earthwork levels used in practice without issue. However, it is recommended that field testing be undertaken to provide some correlation between the levels calculated in theory and the actual groundwater mounding levels seen in practice. Ideally this testing would be over an extended period of time to analyse the rate of rise and fall of the groundwater. If monitoring was also undertaken for the different stormwater disposal methods this would comprehensively verify the results and conclusions of this project.

10.0 References

Alley, MA, Reilly, TE, Franke, OL 1999, *Sustainability of Ground-Water Resources*, U.S. Geological Survey Circular 1186, Denver, Colorado, Viewed online 10th May, http://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf.

Barber, C 2005, *How Important is Groundwater?*, in Australian Groundwater School, Fundamentals of Groundwater Science Technology and Management, Centre for Groundwater Studies, South Australia.

Commonwealth of Australia 2016, Bureau of Meteorology, viewed 6th of July 2016. http://www.bom.gov.au/

Davidson WA 1995 '*Hydrogeology and Groundwater Resources of the Perth Region, Western Australia*', *GSWA* Bulletin 142

Department of Planning and Infrastructure 2008, *Better Urban Water Management,* Western Australian Planning Commission (WAPC)

Fetter, C.W. 2001, *Applied Hydrogeology*, 4th edn, Pearson Education International, New Jersey.

Harbaugh, AW, Banta, ER, Hill, MC, McDonald, MG 2005, *MODFLOW – 2005, The U.S. Geological Survey Modular Ground-Water Model-the Ground-Water Flow Process,* U.S. Geological Survey, Reston, Virginia

Harbaugh, AW, 2000, *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide To Modularization Concepts and the Ground-water Flow Process,* U.S. Geological Survey, Reston, Virginia

Hillman, MO, Cocks, GC 2007, *'Subsoil Drainage – Perth residential and Road Developments'*, Australian Geomechanics, Vol 42 No 116

Huxley, WJ 2005, "*Hydrogeology*', in Australian Groundwater School, Fundamentals of Groundwater Science Technology and Management, Centre for Groundwater Studies, South Australia.

Land Development Steering Group 2016, *Draft Specification Separation distances for groundwater controlled urban development*, IPWEA

Leach, L, Volker, RE 2005, “Hydraulics’, in Australian Groundwater School, *Fundamentals of Groundwater Science Technology and Management,* Centre for Groundwater Studies, South Australia.

Ritzema, H. P. 1994, *Drainage Principles and Applications*, ILRI Publication 16, Wageningen, The Netherlands.

Sinclair Knight Merz and National Centre for Groundwater Research and Training, Waterlines Report Series No. 82, June 2012, *Australian groundwater modelling guidelines*, viewed online 11th May 2016, http://www.groundwater.com.au/media/W1siZiIsIjIwMTIvMTAvMTcvMjFfNDFfMzZfOTYwX0F1c3RyYWxpYW5fZ3JvdW5kd2F0ZXJfbW9kZWxsaW5nX2d1aWRlbGluZXMucGRmIl1d/Australian-groundwater-modelling-guidelines.pdf>

UNSW 2007, terra GIS, Australia, viewed 10 May 2016, http://www.terragis.bees.unsw.edu.au/terraGIS_soil/sp_water-saturated_water_flow.html

11.0 Appendix A (Project Specification)

ENG4111/ENG4112 Research Project

Project Specification

For: Luke Rusconi

Title: Modelling Groundwater Mounding on Sand Sites.

Major: Civil Engineering

Supervisor: Elad Dafny

Enrolment: ENG4111 – EXT S1 2016
ENG4112 – EXT S2 2016

Project Aim: To compare the various equations/methodologies for calculating ground water mounding. To also analyse the factors that affect groundwater mounding i.e. distance between subsoil drainage, Sand fill depths and rainfall recharge rates.

Programme: Revision B 16th March 2016

1. Research the background technical information relating to how groundwater travels through soil profiles and what causes the actual "mounding".
2. Research the various documented methodologies for calculating the degree of mounding.
3. Conduct 2d theoretical calculations for a test case.
4. Produce a 3d model using software programme.
5. Evaluate the variance in the different theoretical calculations.

If time permits:

6. Evaluate the effect of the different parameters on the theoretical equations. I.e. depth of fill, distance between subsoils, re charge rates.
7. Conduct a cost benefit analysis based on the results of item 6.