APPENDIX E: URBAN RECHARGE ESTIMATE

A.1 Objective

A primary objective of this research is to predict urban subsurface drainage volumes under variable forecast climates. This appendix provides the methodology to estimate an urban recharge rate for the Whiteman Edge (WE) development. The residential density of WE is considered to be representative of other developments of the Swan Coastal Plain, however the methodology herein can readily be applied to developments of different density. The methodology consists of two components:

1. Recharge rate estimation for specific landuses and various rainfall scenarios, based on a literature review and an Excel based groundwater recharge function

2. Estimation of urban landuse component areas (e.g. roofs, pavement etc), via an urban landuse model.

The urban recharge rate for the whole development is estimated by combing these two components.

A.2 Method

A.2.1 Groundwater recharge function

Subsurface drainage volumes are highly contingent on groundwater recharge rates which are typically applied to a groundwater model as a linear rainfall percentage. However, the relationship is not linear; lower rainfall leads to lower recharge percentages and vice-versa. Consequently, an Excel based recharge function was developed to incorporate this non-linear relationship to groundwater recharge. This function is a compromise between the complexity of a fully coupled unsaturated/ saturated zone model and linear recharge rates (cf Heathcote, Lewis, and Soley, 2004; Westenbroek et al., 2010). The recharge rate is calculated using the hydrological parameters of rainfall, irrigation, runoff, interception loss, soil ET and groundwater ET if applicable (Figure 1), as described in the following points.

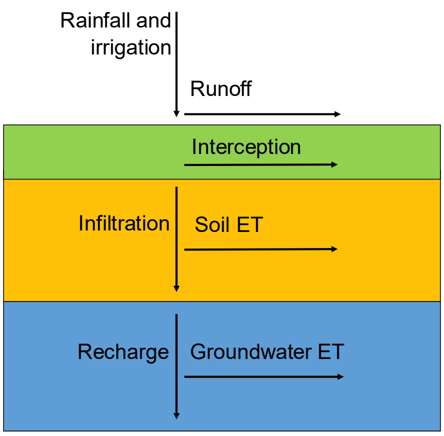


Figure 1 Recharge function concept

- The function is calculated on a daily time step using daily rainfall (measured at site) and potential ET (PET) from SILO (Queensland Government 2019).

- Irrigation can be applied at a user defined depth per event (e.g. 10 mm) over any number of days in the week.

- Runoff. The urban developments are predominantly covered by sand and hence runoff is not a large component of the water balance (cf Xu, C. Canci, M. Martin, M. Donnelly & Stokes, 2009). However, the function has the capacity to remove water by surface runoff at a specified fraction of rainfall, after a user defined initial rainfall depth is applied. The application of runoff as the first component of loss simplifies the recharge function calculation (Heathcote, Lewis, and Soley 2004).

- Water is removed by interception loss which is constrained by the daily rainfall or PET rate; should interception be omitted more water is available for soil ET. Although termed interception loss, it is a proxy for other hydrological processes such as litter and pavement evaporation, initial loss and depression storage.

- Soil ET. A user defined soil water retention is used to calculate soil moisture available for soil evaporation. A crop factor, or fraction of PET, can be applied to vary crop water usage.

- The net water volume enters the water table as gross recharge which can be input into a separate groundwater model (e.g. by the MODFLOW Recharge Package).

- For shallow water tables (< ~ 1.5 m depth), the PET remaining after the aforementioned processes is the maximum available water that can be removed by ET. This rate is input into a separate groundwater model (e.g. by MODFLOW EVT package) with a user defined linear ET extinction depth from surface. This means that additional water (up to PET) can be removed should the water table rise to within this depth. This ET component is generally applied to pasture/ lawn areas which have shallow roots (< ~1.5 m) and limited capacity to “chase” groundwater should its elevation decrease in the future.

- The recharge function has been modified for woodland areas with roots that reach the water table. A groundwater transpiration component can be applied to these woodland areas, which is a fraction of the remaining PET after the aforementioned water loss processes. This approach will enable roots to chase reducing groundwater levels as long as the groundwater levels remain within the rooting depth. Woodland recharge would be applied to a groundwater model by the Recharge Package only (+ve and -ve values) rather than by the EVT package.

An example recharge function output is provided in Figure 2 which includes irrigation, IL of 2 mm and ASM of 30 mm.

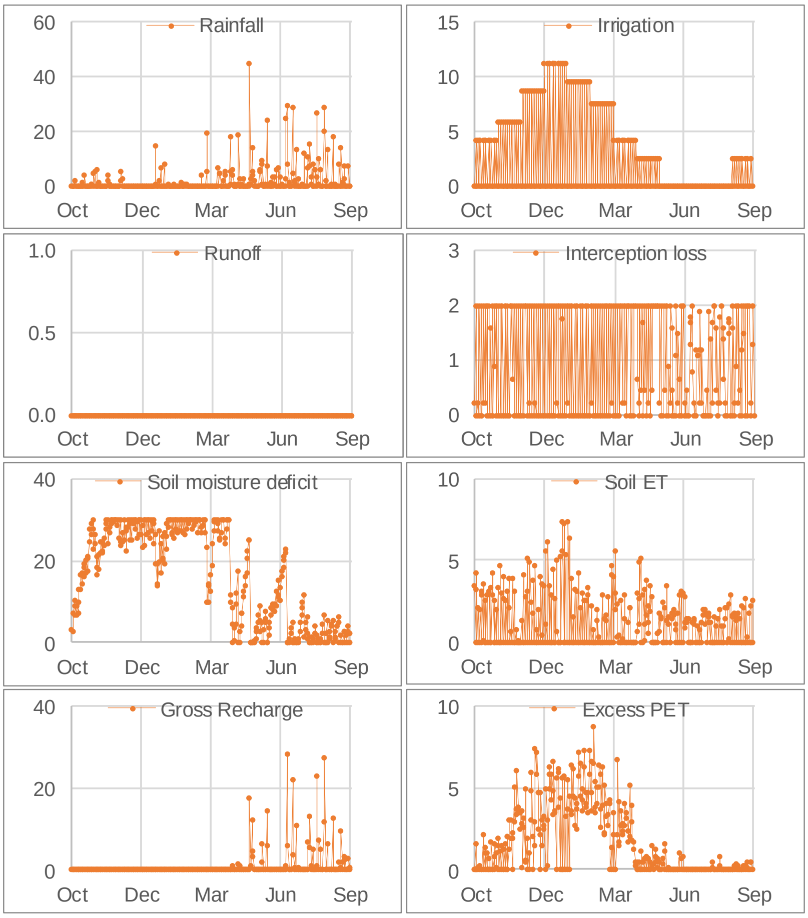


Figure 2 Example recharge function output over full calendar year commencing October 2015. Excess PET is the PET available for groundwater ET if required. All values in mm.

A.2.2 Urban landuse model

An urban landuse model was developed for the 55 ha WE subsurface drainage catchment by dividing the urban area into its landuse components and applying the rates estimated with the recharge function. The 55-ha drainage catchment was subdivided into pervious and impervious areas by visually digitising November 2015 and October 2017 development aerials. Both aerials were selected to assess development progression from the time near to when subsurface drainage monitoring progressed (Nov 2015) to when the sub-catchments were predominantly developed (Oct 2017). At the start of the monitoring period some cleared areas are visible in the southeast of the drainage catchment, however these were largely developed within a year (Figure 3).

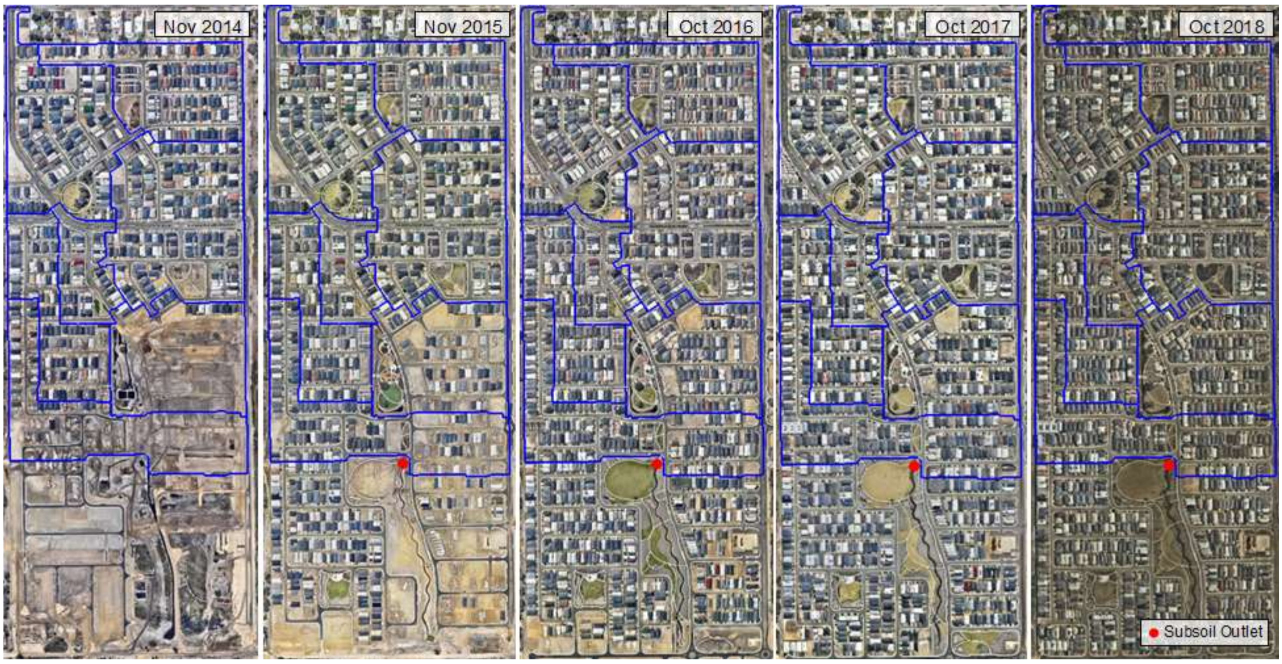


Figure 3 WE development progression (Nov 2014 to Oct 2018). Drainage sub-catchments are shown in blue. Subsurface drainage monitoring commenced in October 2015

The pervious areas were divided into: lawn, garden and bush areas in public open space (POS); garden/ lawn areas in lots, road verges, playgrounds and cleared sand. The pervious areas were further subdivided into irrigated and non-irrigated areas, which were subjectively determined from aerial inspection, however generally lot areas and POS were considered to be irrigated while road reserves were not. The impervious areas were subdivided into roofs and pavement (i.e. roads and other impervious areas such as footpaths). All roof areas for smaller lots (< 300m^2) were digitised, while the roof area of a selection (~ 50) of larger lots (> 300m^2) was digitised to represent the large number of lots in this category. This resulted in ~3,000 separate polygons (Figure 4), which were in turn synthesised into four distinct landuse areas for each drainage sub-catchment. These landuse areas included road reserves, POS, smaller lots (< 300m^2) and larger lots (> 300m^2), which are the four broad divisions utilised by planners and engineers (Figure 5).

Figure 4 WE landuse division

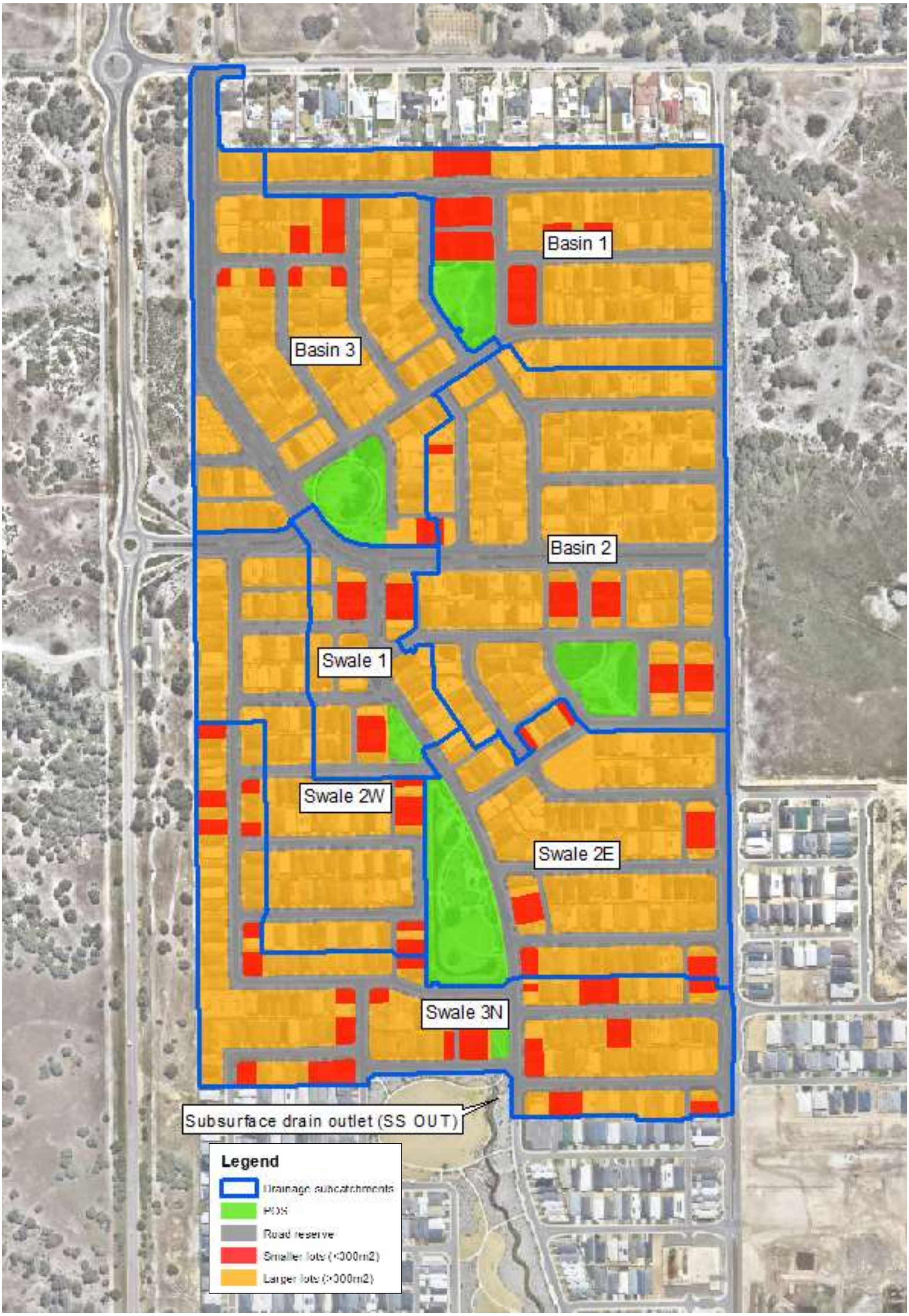


Figure 5 WE urban landuse categories

A.2.3 Urban recharge rate estimate

The recharge rate as determined from the recharge function was applied to each of the urban landuse categories and where relevant irrigation was applied at the designated POS rate. Drainage from the impervious component of the road reserve and smaller lot roofs is assumed to be directed into the sub-catchment bioretention areas (via stormwater and lot connection pits). All other areas recharge the subsurface via soakwells, direct infiltration into pervious areas or runoff from pavement into adjacent pervious areas. The urban landuse model will therefore provide a component of water to subsurface recharge at source ("at source recharge") and a component to the bioretention areas, both of which discharge to the final subsurface drainage outlet ("total recharge"), (Figure 6).

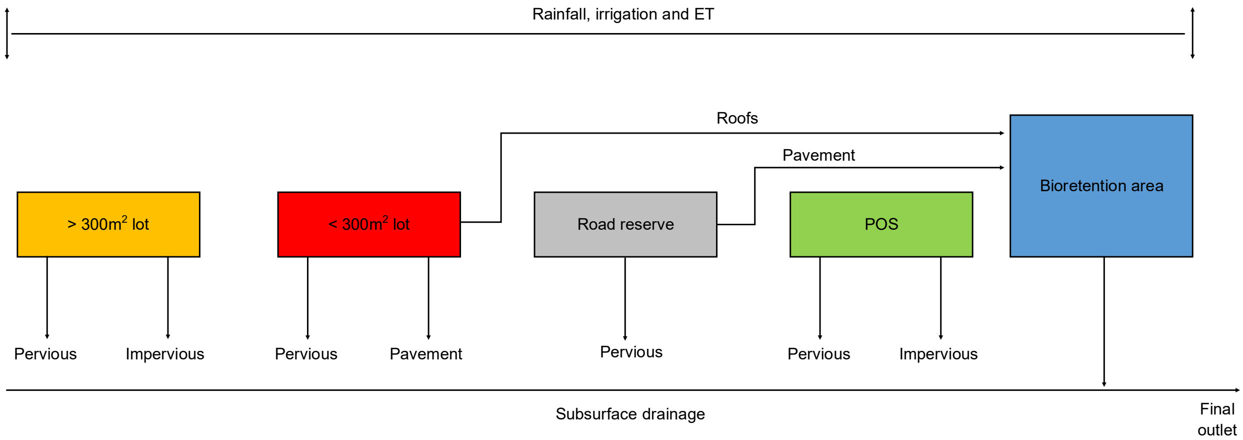


Figure 6 Urban recharge concept

A.3 Urban recharge parameter review

This section provides a literature review of parameters pertinent to urban recharge rate estimation. It includes recharge estimates for individual urban surface components, the urban development scale and landuses in the vicinity of the urban area including pasture and forested areas. Table 2 provides a summary of parameter values and the ranges used for input into the urban recharge function.

A.3.1 Pavement

Ground level impervious surfaces at WE include asphalt roads, and paved and concrete driveways, paths and outdoor areas. The vast majority of road reserve impervious area consists of good condition asphalt. Some portions of the road reserve area include residential driveways and public footpaths which are generally constructed with concrete; however some driveways are also made from clay or concrete pavers which contain gaps. The impervious areas on lots consists of a range of materials such as concrete and pavers, but not asphalt. Driveways generally slope to the road to facilitate surface drainage.

Runoff from impervious areas will commence after interception and depression storages are satisfied. Similar depression storages for ground level impervious surfaces of 1.5 mm have been found for an urban catchment in Poland (Skotnicki and Sowiński 2015) and 1.4 mm for 17 international urban catchments (Boyd, Bufill, and Knee 1993). However, despite these similarities, runoff rates from ground level impervious surfaces are found to be highly variable. Despite being termed "impervious", these surfaces can allow infiltration of water especially if they are deteriorated and contain gaps and cracks. For example, infiltration through the gaps of brick paving in the UK was the largest water balance component (~52% rainfall) with only 9% runoff (Mansell and Rollet 2006). Yet the same study found much higher (56% and 69%) runoff for hot rolled asphalt and flat concrete slab respectively with remaining losses due to evaporation, but minimal infiltration (<1%). Similarly, infiltration through deteriorated asphalt plate in France (annual rainfall 790 mm) was 58% of rainfall (16% runoff) yet only ~3% (~73% runoff) for asphalt plate in good condition. The evaporation of 24-26% was not just from the asphalt surface but also from stored water within the asphalt pores (Ramier, Berthier, and Andrieu 2004).

Further review shows infiltration through asphalt and block pave surfaces (car parks and road) in the UK was estimated at 6–9% of rainfall with 21–24% evaporation and 70% runoff, which was higher in winter (90%) than summer (50%), (Ragab, Rosier, et al. 2003). For two urban streets in France, runoff was 62 to 68% rainfall (rain events > 1mm), surface evaporation comprised 10% losses, while 20 to 30% rainfall infiltrated into the asphalt (of which 30 to 40% re-evaporated). This left a combined 80-82% runoff plus net infiltration, which are the components of the water balance that have the potential to contribute to subsurface drainage flow (Ramier et al. 2006). In Texas, infiltration in urban pavement was estimated at 21% of rainfall (Wiles and Sharp 2008) which is within the large range of 6 to 42% provided by the authors. Despite the variable runoff and infiltration rates in ground level impervious surfaces, it is apparent that older degraded surfaces typically have higher infiltration rates whilst new roads (such as those at WE present) show minimal infiltration (Redfern et al. 2016; Wiles and Sharp 2008).

A.3.2 Roofs

The roofs at WE consist of either corrugated metal or glazed clay tiles. Runoff from roofs is generally higher and less variable than for other ground level "impervious" surfaces such as roads and paving, with estimates generally between 70-95% of rainfall (Farreny et al. 2011). Runoff from sloped and flat roofs in the UK was estimated at 76% with depression storage calculated at 0.25 mm (Davies 1981) and similar small depression storage values were found for aluminium (0.2 mm) and concrete tiles (0.6 mm) (Hollis and Ovenden 1988, cited in Ladson 2008).In Spain, runoff rates of 84%, 92% and 91% of rainfall were estimated for clay, metal and polycarbonate roofs respectively (Farreny et al. 2011). Interception loss from a roof in Perth was more than 20% for rain events of <1mm and ~5% for events of ~8mm (McFarlane 1984), while runoff from six tiled roofs (material unknown) in the UK ranged between 62-93% of rainfall with average depression storages before runoff of 0.4-0.7mm. The difference in runoff rates was primarily due to roof slope and orientation with respect to wind (Ragab, Bromley, et al. 2003).

A.3.3 Pervious areas

Urban pervious areas typically consist of lawn and mulched gardens with shrubs, with generally low tree density. POS areas typically comprise 10% of the developable area and consist of lawn, mulched shrub areas and larger trees, especially if natural bushland is retained. Drainage bioretention areas generally contain variable reed density and broadly cover 2% of the development's connected impervious area. For urban lawn areas in Perth, irrigation recharge has been estimated at 49% (Williamson and Cole 1976, cited in McFarlane 1984) and up to 51% (Sharma et al. 1996). Grass root depth has broadly been estimated at 1 m (Water Authority of Western Australia 1987), while the root depth of a common Perth grass, couch (*Cynodon dactylon*) can extend 1.6 m. Based on exponential root density decay with depth, this equates to 50% density at 0.55m, 20% at 0.8m and 10% at 1.15m (McFarlane 1984).

Irrigation is generally applied at an average rate of 6,750 kL/ha/yr in urban developments of the Swan Coastal Plain. This rate (675 mm/yr) equates to 93% of the measured rainfall at WE (average 728 mm/yr over 3 years). Typical monthly irrigation rates for POS areas were provided by local landscape architects Plan E and this same rate was assumed to be applied to private irrigated areas (Table 1).

Table 1 Seasonal irrigation application

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Season	Summer		Autumn (Fall)			Winter			Spring			Summer
Monthly rate (kL)	1,350	1,150	900	500	300	-	-	-	300	500	700	1,050
Per event (mm)	11.3	9.6	7.5	4.2	2.5	-	-	-	2.5	4.2	5.8	8.8

The available soil moisture (ASM), which is the difference between the residual water content and field capacity at -10 kPa (cf Healy 2010) is estimated at 3% and 4% for typical fill sand used in the Swan Coastal Plain (Bassendean Sand and Spearwood Sand respectively), (Silberstein et al. 2009). For cleared areas, analytical modelling of evaporation from bare sand by the author (after Bouwer, 1978) shows it extends up to a depth of ~0.8 m. The analytical model utilised unsaturated Darcy flow and was based on soil moisture characteristic curves derived from Rosetta (Schaap, Leij, and Genuchten 2001) on sand fill samples collected from WE.

A.3.4 Urban areas- development scale

On the broader development scale, a recharge rate of 37% of annual rainfall was reported by (Appleyard 1995) for (then) new urban areas in Perth, which are at a lower residential density than WE. The groundwater recharge range initially used for input into the Swan Coastal Plain vertical flux model (VFM) was 48-60% rainfall in residential areas over sand with deep water tables (Xu et al. 2009). This was based on the combined total of 45-55% rainfall recharge plus 10% losses from the scheme water distribution network which would equate to an additional 3-4% rainfall. The groundwater recharge estimate was based on roof and paved areas of 20% and 15% respectively, and recharge for various urban land components of 80–90% of rainfall from roofs; 60–70% of rainfall from paved areas into infiltration basins; and 30–40% of rainfall for lawns and gardens. These estimates were adjusted during VFM calibration to arrive at gross recharge of 62% rainfall minus an ET coefficient equal to 5% of pan evaporation for residential areas. For commercial/ industrial areas, the range initially used for input to the VFM was 60-70% rainfall, which is based on roof and paved areas of 40% and 35% respectively. For commercial/ industrial land, model calibration arrived at a gross recharge of 75% rainfall and 5% ET coefficient. For averaged rainfall of 800 mm on sandy soil (Bassendean Sand) and deep water table (> 15m) net recharge was estimated as 400 mm (50% rainfall) for residential areas and 500 mm (63%) for commercial/ industrial land.

A.4 Non-urban recharge parameters

Recharge to landuses in the vicinity of developments such as WE have the potential to affect groundwater levels and consequently urban subsurface drainage flows. The most prominent landuse in the vicinity of WE is cleared pasture, with some Banksia woodland and pine plantation across the wider region. Also, forested areas, although generally minor in extent, can impact urban recharge where they have been retained within a development.

A.4.1 Pasture

Recharge beneath pasture in the Perth area has been estimated at 45% using the WAVES model (Zhang and Dawes 1998) for 800 mm rainfall on Bassendean Sand with deep (> 15 m) watertables (Xu et al. 2009). This includes interception and surface evaporation losses totalling ~23% and transpiration of 32%. A localised investigation on pastoral land near Lake Pinjar with a water depth of between 4-7 m estimated rainfall recharge of 50-60%, while acknowledging these rates may not apply on a more regional scale (Sharma, Barron, and Craig 1988, cited in Davidson, 1995). Evaporation of 290 mm was measured for pasture in Nth Bannister (~ 100 km southeast of Perth) in a 680 mm rainfall year, which equates to 43% recharge (Greenwood et al. 1985), a similar value to that found in the Perth area. Although for a much drier climate (255 mm annual average rainfall), interception loss for Mitchell grass (average height 29 cm) in arid western New South Wales was estimated at 1.3 mm or 32% of rainfall (Dunkerley and Booth 1999). The ASM) has been estimated as 3%, 4% and 11% for Bassendean Sand, Spearwood Sand and Guildford Formation respectively, available from a rooting depth of 1 m (Silberstein et al. 2009). This is within the active soil depth (i.e. the depth in which water can be evaporated or used by plants) range of 1-2m for grass, crop and fallow land in Australia (A. R. Ladson et al. 2006).

A.4.2 Forest

For various Australian tree species, interception loss is generally 0-1 mm outside the tropics, up to 6.8 mm in the tropics and 1-3 mm from material on the forest floor (A. Ladson 2008). On the Swan Coastal Plain, recharge beneath native bushland has been estimated at 12% (Sharma and Pionke 1983, cited in Davidson 1995). For Banksia woodland, Farrington and Bartle (1991, cited in Davidson 1995) estimate 22% recharge, while 10%, 18% and 38% recharge have been estimated for high, medium and low density Banksia woodland respectively with a deep water table (Xu et al. 2009). Recharge beneath pine plantations is estimated at 15% (Farrington and Bartle 1991, cited in Davidson 1995), 28% for low density pines and nil beneath higher density (Xu et al. 2009) and mature (Sharma and Pionke 1983, cited in Davidson 1995) pines.

Table 2 Recharge parameter review. Input values in parentheses are losses as percentage of rainfall. Soil evaporation loss values are taken after IL.

Parameter	Recharge function inputs	References	Typical detail
Roofs	• IL_{range}: 0.5-2.0 mm (8-23%) • IL_{base}: 1.5 mm (19%) • ASM: 0 mm • RCH_{range}: 77-93% • RCH_{base}: 81%	• International review: Runoff 70-95% (Farreny et al. 2011). • UK: Tiled roofs (material unknown) 62-93% runoff, 0.4-0.7mm depression storage (Ragab, Bromley, et al. 2003). • UK: 76% runoff, 0.25 mm depression storage (Davies 1981) • UK: depression storage of 0.2 mm for aluminium and 0.6 mm for concrete tiles (Hollis and Ovenden 1988, cited in Ladson 2008) • Spain: runoff of 84%, 91% and 92% for clay, polycarbonate and metal respectively (Farreny et al. 2011). • Perth: depression storage < 0.5 mm interception loss > 20% for rain events of <1mm and ~5% for events of ~8mm for metal (McFarlane 1984).	  Colorbond metal (left), tile (right)
Pavement	• <u>Road reserve</u> • IL_{range}: 1.0-2.5 mm (14-25%) • IL_{base}: 2.0 mm (23%) • ASM: 0 mm • RCH_{range}: 75-86% • RCH_{base}: 77% • • <u>Lots</u> • IL_{range}: 1.0-2.5 mm (14-25%) • IL_{base}: 2.0 mm (23%) • ASM_{range}: 0-10 mm (0-26%) • ASM_{base}: 5 mm (18%) • RCH_{range}: 49-86% • RCH_{base}: 59%	• UK: brick paving 9% runoff, 37% evaporation, 54% infiltration; asphalt 56% runoff, 44% evaporation, <1% infiltration; concrete slab 69% runoff, 30% evaporation, 1% infiltration (Mansell and Rollet 2006) • UK: asphalt and block pave surfaces (car parks and road) 70% runoff, 21-24% evaporation, 6-9% infiltration (Ragab, Rosier, et al. 2003). • France: asphalt roads (rain events > 1mm) 62-68% runoff, 16-22% evaporation, 14-18% net infiltration (Ramier et al. 2006). • UK: paved surfaces 17% runoff, 21% evaporation, 36% infiltration, 26% (or 1.0 mm) depression storage (Davies 1981). • France (790 mm rain): poor condition asphalt plate 16% runoff, 26% evaporation, 58% infiltration; good condition asphalt plate 73% runoff, 24-26% evaporation, 3% infiltration (Ramier, Berthier, and Andrieu 2004). • UK: paved surfaces 11%-28% runoff (Hollis and Ovenden 1988, cited in Redfern et al. 2016); asphalt road, 0.6 mm depression storage (Hollis and Ovenden 1988, cited in Ladson 2008). • Texas: urban pavement 21% infiltration (Wiles and Sharp 2008) • International review: 6 to 42% infiltration (cited in Wiles and Sharp 2008) • Poland urban catchment: 1.5 mm depression storage (Skotnicki and Sowiński 2015) • International urban catchments (17): 1.4 mm initial loss (Boyd, Bufill, and Knee 1993). • Sweden: roads 0.77 mm depression storage (Carlsson and Falk 1977, cited in McFarlane 1984)	  Brick paving (left), footpath, driveway and asphalt road (right)
Lawn on sand	• IL_{range}: 1.0-2.5 mm (14-25%) • IL_{base}: 2.0 mm (23%) • ASM_{range}: 20-40 mm (38-39%) • ASM_{base}: 30 mm (38%) • RCH_{range}: 36-47% • RCH_{base}: 39%	• Perth: 1.6 m root depth for couch lawn (Cynodon dactylon); 50% root density at 0.55m, 20% at 0.8m and 10% at 1.15m depths (McFarlane 1984). • Perth: 49% irrigation rch (Williamson and Cole 1976, cited in McFarlane 1984) • Perth: 1 m grass roots (Water Authority of Western Australia. 1987). • Perth: up to 51% rch (Sharma et al. 1996)	  Couch grass (left), WE POS area (right)
Pasture on sand	• IL_{range}: 1.0-2.5 mm (14-25%) • IL_{base}: 2.0 mm (23%) • ASM_{range}: 20-40 mm (38-39%) • ASM_{base}: 30 mm (38%) • RCH_{range}: 36-47% • RCH_{base}: 39%	• Perth (800 mm rain): 45% rch, 23% IL on Bassendean Sand; ~42% on Spearwood Sand (Xu et al. 2009). • Perth: 50-60% rch locally (Sharma, Barron, and Craig 1988) cited in Davidson, 1995). • Nth Bannister (~ 100 km SE of Perth; 680 mm rain): 43% rch (Greenwood et al. 1985). • New South Wales (255 m rain): 1.3 mm (32%) IL for Mitchell grass (Dunkerley and Booth 1999). • Perth: 1 m maximum rooting depth pasture (Silberstein et al. 2009) • Australia: 1-2 m active soil depth for grass, crop and fallow land ET (A. R. Ladson et al. 2006) • Perth: 3%, 4% and 11% available soil moisture for Bassendean Sand, Spearwood Sand and Guildford Formation respectively (Silberstein et al. 2009). • Bare sand evaporation depth ~0.8 m (after Bouwer, 1978)	  Swan Coastal Plain pasture (left), Mitchell Grass (right)
Forest	• IL_{range}: 1.0-3.0 mm (14-25%) • ASM_{range}: 30-300 mm (29-75%) • RCH_{range}: 0-35% • Groundwater ET can be included for water table depth < rooting depth	• Perth: 38%, 18% and 10% rch for low, medium, and high density Banksia woodland; 28% rch low density pines, no rch higher density pines (Xu et al. 2009) • Perth: 12% rch native bushland, no recharge beneath mature pines (Sharma and Pionke 1983, cited in Davidson 1995) • Perth: 22% rch Banksia woodland, 15% rch pines (Farrington and Bartle 1991, cited in Davidson 1995) • Australia: Interception loss trees 0-1 mm outside tropics; up to 6.8 mm in tropics, 1-3 mm forest floor Pinus radiata	  Banksia woodland (left), Pinus pinaster plantation (right)

A.5 Results

A.5.1 Urban landuse recharge estimates

A.5.1.1 Estimates for measured rainfall

Recharge function parameter value and ranges for the urban landuses of roof, pavement (lot and road reserve) and pervious have been estimated from the urban hydrology review (Table 3). The function predominantly utilises interception loss (IL) and ASM which are proxies for the various parameters referred to in the review such as evaporation, infiltration, initial loss and depression storage. In relation to the contribution to subsurface drainage, all runoff and net infiltration are components of “total recharge.” This is because infiltration will contribute to the road reserve subsurface drainage system while runoff from the road reserve and small lot roofs will contribute to the POS subsurface drainage system.

For WE measured annual rainfall (728 mm/yr), roof runoff is estimated to range between 77-92% (81% base), Table 3. Runoff is directed into gutters prior to discharging to soakwells or lot connection pits and the lower end of the range is due to potential losses associated with the guttering (although they are expected to be generally clean with minimal leaves due to tree sparsity). Some runoff losses from small lots may also occur within the lot connection pits, however residual water is expected to slowly infiltrate into the underlying soil via weep holes and still contribute to subsurface drainage.

Road reserve pavement predominantly consists of good condition asphalt, with runoff estimated to range between 75-86% (77% base). Should the asphalt deteriorate with time, runoff may decrease and infiltration increase through secondary permeable features such as cracks. Presently, some lot pavement contains permeable features such as gaps between pavers, hence a lower recharge of 49-86% (59% base) is estimated. The recharge rate for un-irrigated urban lawn and garden is estimated to range between 35-47% (39% base) and assumes an active soil depth of 1 m. Recharge increases by 9-12% of rainfall (44-59% range; 49% base) with irrigation three times per week. This is a relatively small increase in recharge given irrigation application equivalent to 93% rainfall (675 mm/yr). The use of lower permeability fill in pervious areas will increase the ASM and thus decrease recharge rates. However permeable sand fill is required to facilitate groundwater flow to subsurface drainage, hence low permeability fill is not recommended in combination with subsurface drainage.

Table 3 Interception loss, available soil moisture and recharge estimates for pervious and impervious landuses for 728 mm/yr rainfall.

Landuse	Parameter	Base	Max loss	Min loss
Roof	IL (mm)	1.5	2	0.5
	ASM (mm)	0	0	0
	RCH (%)	**81**	**77**	**92**
Pavement (road reserve)	IL (mm)	2	2.5	1
	ASM (mm)	0	0	0
	RCH (%)	**77**	**75**	**86**
Pavement (lot)	IL (mm)	2	2.5	1
	ASM (mm)	5	10	0
	RCH (%)	**59**	**49**	**86**
Pervious (un-irrigated)	IL (mm)	2	3	1
	ASM (mm)	30	40	20
	RCH (%)	**39**	**35**	**47**
Pervious (un-irrigated)	**IL (mm)**	**2**	**3**	**1**
	ASM (mm)	**30**	**40**	**20**
	RCH (%)	**49**	**44**	**59**

A.5.1.2 Estimates for variable rainfall

Utilising the base IL and ASM parameters (Table 3), recharge rates for annual rainfall of 400-1,000 mm/yr are estimated at 70-85% for roof; 65-82% for road reserve pavement; 38-68% for lot pavement; 13-51% for un-irrigated pervious; and 20-59% for irrigated pervious. As depicted on Figure 7, recharge is more affected by reduced rainfall for pervious areas that have ASM as a potential loss component. Although the recharge function is a simplification of the physical system, it does provide non-linear changes to recharge rates with rainfall which is a better approximation than a linear rainfall v recharge function and important in the context of a forecast changing climate. The recharge rates from the individual landuse components can be applied to variable urban densities to estimate urban recharge, the results of which are provided by the urban landuse model.

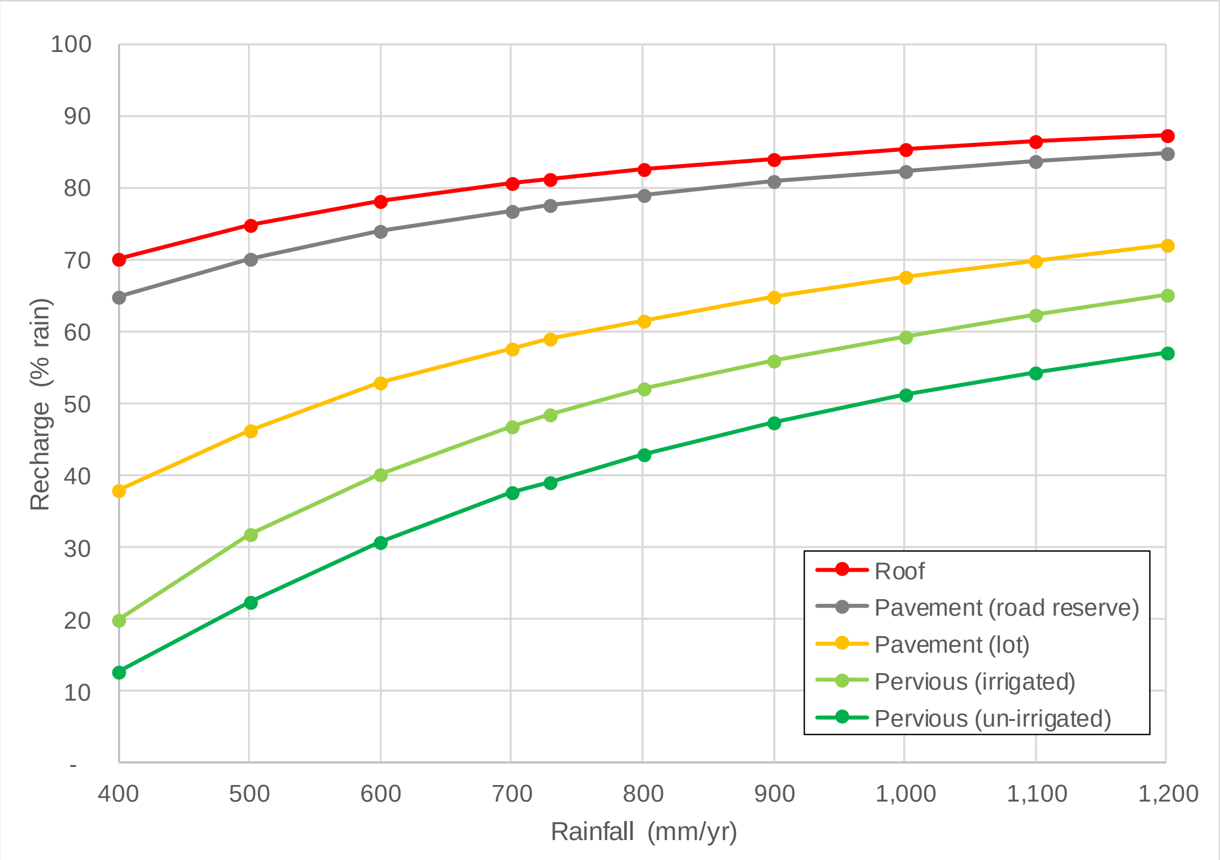


Figure 7 Urban landuse recharge rates with rainfall

A.5.1.3 Water balance components not included in the recharge estimate

There are other hydrological components that have the potential to impact urban recharge, however these are considered to be minor in the context of the entire urban water balance. Condensation will add water in cooler periods while evaporation from bioretention areas will remove water. Phreatophytic vegetation, such as remnant bushland, will generally remove a higher proportion of water than other urban landuses. The recharge function can be utilised for these areas by increasing parameters such as IL and ASM depending on the vegetation density and depth to groundwater, in combination with groundwater ET if required (Figure 8). Water in an urban area can also be removed by increasing urban tree density along streets and residences; the “urban forest”. Leakage from scheme and wastewater pipes are another potential source of recharge, or if below the water table which sewer pipes often are, can remove groundwater. None of these components have been included in the urban recharge rate estimation, however they can readily be included for urban areas on a case by case basis where necessary to refine recharge estimates.

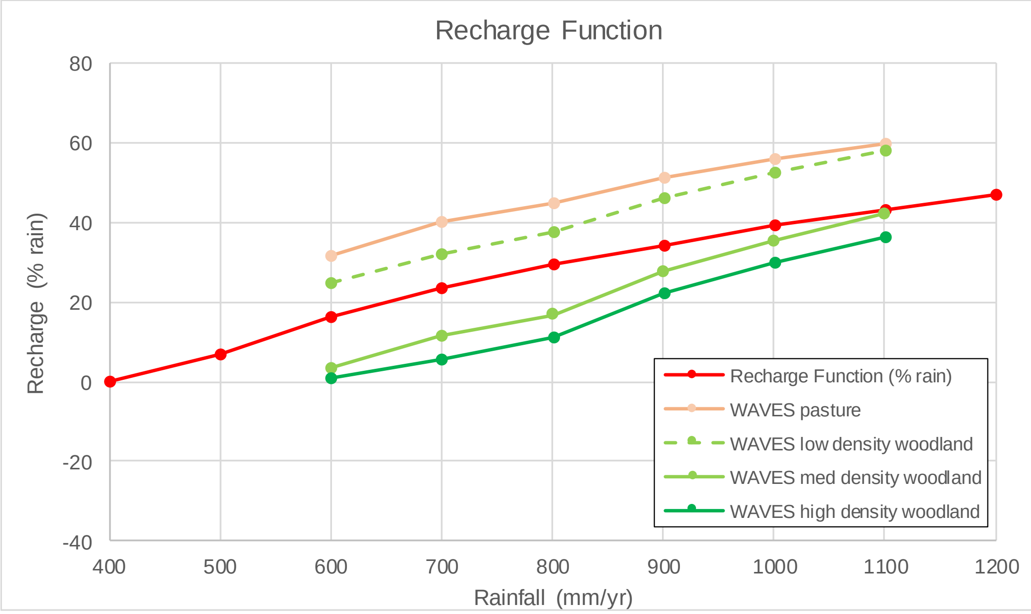


Figure 8 Example recharge function output beneath woodland v WAVES. Function inputs include 2 mm IL and 90 mm ASM.

A.5.2 Recharge function sensitivity

A.5.2.1 Interception loss

Interception loss (IL) for the measured rainfall (728 mm/yr) is up to 28% of rainfall (4 mm IL), with minimal change for higher IL values (e.g. <1% increase from 4-5 mm IL). As expected, relative loss is higher with less rainfall (up to 42% for 400 mm rain), while for a 1,000 mm rainfall year, IL comprises 22% of loss (Figure 9).

Interception loss

Recharge

Available soil moisture	0.5 mm	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm	4.0 mm	5.0 mm
Rainfall	Percent rainfall							
400	87	78	70	65	61	59	58	57
500	89	81	75	70	67	65	63	63
600	91	84	78	74	71	70	68	67
700	92	86	81	77	74	73	71	70
728	92	86	81	77	75	74	72	71
800	92	87	82	79	77	75	74	73
900	93	88	84	81	79	78	76	75
1000	94	89	85	82	80	79	78	77
1100	94	90	86	84	82	81	79	79
1200	95	91	87	85	83	82	81	80

Loss

Available soil moisture	0.5 mm	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm	4.0 mm	5.0 mm
Rainfall	Percent rainfall							
400	13	22	30	35	39	41	42	43
500	11	19	25	30	33	35	37	37
600	9	16	22	26	29	30	32	33
700	8	14	19	23	26	27	29	30
728	8	14	19	23	25	26	28	29
800	8	13	18	21	23	25	26	27
900	7	12	16	19	21	22	24	25
1000	6	11	15	18	20	21	22	23
1100	6	10	14	16	18	19	21	21
1200	5	9	13	15	17	18	19	20

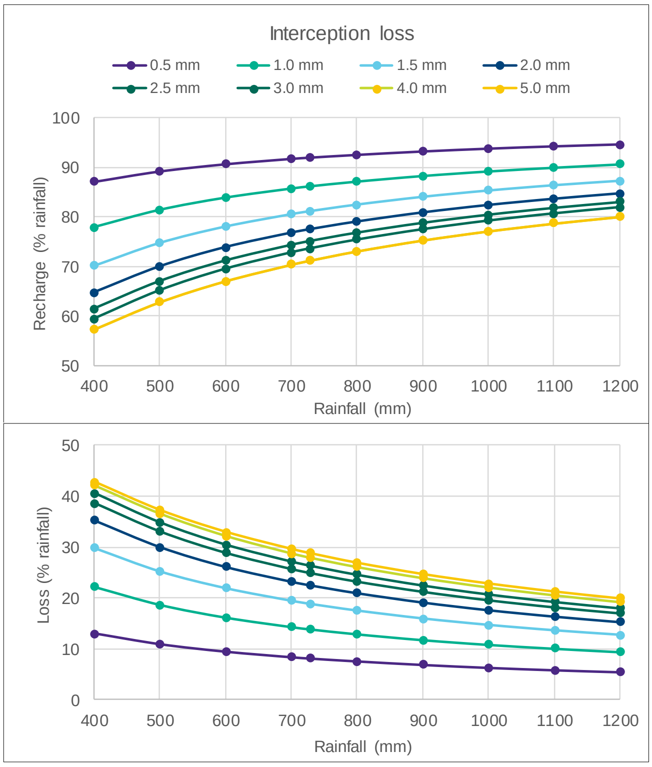


Figure 9 Interception loss with rainfall

A.5.2.2 Available soil moisture

It is evident that IL contributes significantly to water loss in an urban area. However, ASM generally has a more significant impact on the water balance. For example, an ASM value of 30 mm (3% over 1 m of soil), which is considered a reasonable value for the Bassendean Sand fill used at WE, will remove over half (52%) of rainfall assuming no IL, or 38% of rainfall after an IL of 1.5 mm (Figure 10). This means that where soil surfaces are exposed, groundwater recharge will be lower than where covered with impervious surfaces. Similarly, while good condition asphalt will inhibit soil evaporation, deteriorated asphalt has the potential to infiltrate into the underlying soil and evaporate. As an example, an ASM of just 5 mm has the potential to remove 28% of rainfall by soil evaporation, or 20% of rainfall after an IL of 1.5 mm. The same can be said for brick paving which contains significant gaps that can have the potential to increase both IL and soil evaporation. As is evident in the literature review and the ASM sensitivity, there is significant uncertainty in groundwater recharge values from deteriorated roads and block paving. Groundwater recharge sensitivity to ASM for various rainfall and IL scenarios (0 mm, 1.5 mm, 3.0 mm) is provided in Figure 11 to Figure 13.

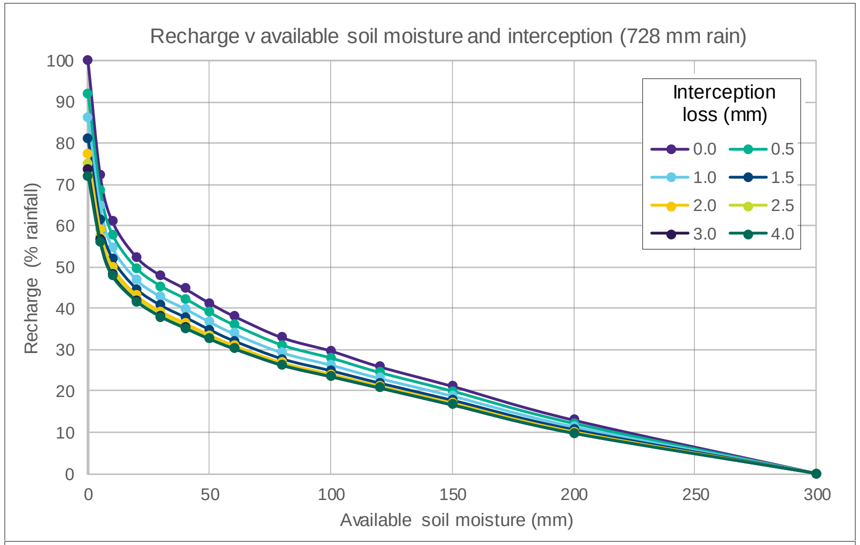
Recharge and loss v available soil moisture and interception (728 mm rain)

Recharge (% rainfall)

ASM (mm) / IL (mm)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0
0	100	92	86	81	77	75	74	72
5	72	68	65	61	59	57	57	56
10	61	58	55	52	50	49	48	48
20	52	50	47	45	43	42	42	42
30	48	45	43	41	39	38	38	38
40	45	42	40	38	36	36	35	35
50	41	39	37	35	34	33	33	33
60	38	36	34	32	31	30	30	30
80	33	31	29	28	27	26	26	26
100	30	28	26	25	24	24	23	23
120	26	24	23	22	21	21	21	21
150	21	20	19	18	17	17	17	17
200	13	12	11	11	10	10	10	10
300	0	0	0	0	0	0	0	0

Loss (% rainfall)

ASM (mm) / IL (mm)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0
0	0	8	14	19	23	25	26	28
5	28	32	35	39	41	43	43	44
10	39	42	45	48	50	51	52	52
20	48	50	53	55	57	58	58	58
30	52	55	57	59	61	62	62	62
40	55	58	60	62	64	64	65	65
50	59	61	63	65	66	67	67	67
60	62	64	66	68	69	70	70	70
80	67	69	71	72	73	74	74	74
100	70	72	74	75	76	76	77	77
120	74	76	77	78	79	79	79	79
150	79	80	81	82	83	83	83	83
200	87	88	89	89	90	90	90	90
300	100	100	100	100	100	100	100	100



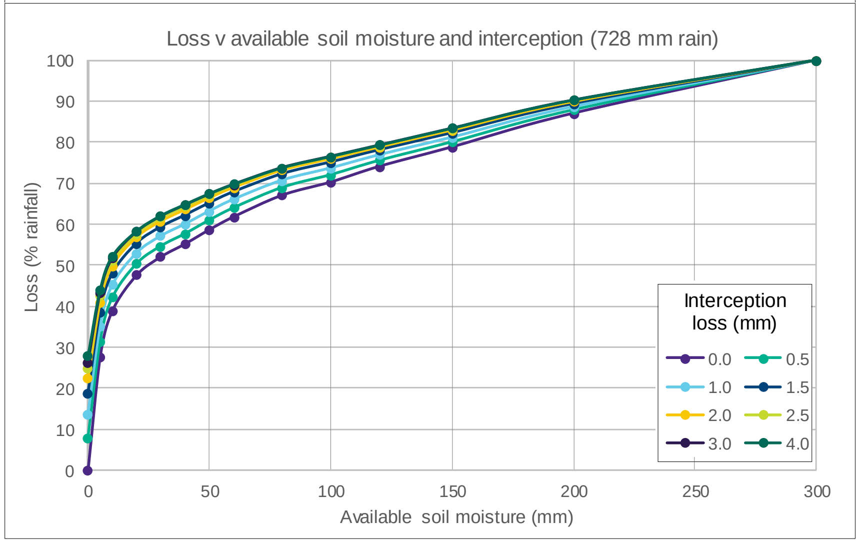


Figure 10 Groundwater recharge v interception loss and available soil moisture for 728 mm rain

Soil evaporation with 0 mm interception loss

Recharge

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall	Percent rainfall													
400	100	54	38	25	17	12	9	5	1	0	0	0	0	0
500	100	62	47	37	31	25	20	17	12	7	2	0	0	0
600	100	68	54	44	40	35	32	28	23	19	14	8	0	0
700	100	71	60	51	46	43	40	36	31	27	24	18	10	0
728	100	72	61	52	48	45	41	38	33	30	26	21	13	0
800	100	74	64	56	52	48	45	43	37	34	31	26	19	4
900	100	77	67	60	56	53	50	48	43	39	36	32	26	13
1000	100	79	70	63	59	56	54	51	47	43	40	37	30	19
1100	100	81	72	66	62	59	57	55	51	48	44	40	35	25
1200	100	82	74	68	65	62	60	58	55	52	48	44	39	30

Loss

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall			Percent rainfall											
400	0	46	62	75	83	88	91	95	99	100	100	100	100	100
500	0	38	53	63	69	75	80	83	88	93	98	100	100	100
600	0	32	46	56	60	65	68	72	77	81	86	92	100	100
700	0	29	40	49	54	57	60	64	69	73	76	82	90	100
728	0	28	39	48	52	55	59	62	67	70	74	79	87	100
800	0	26	36	44	48	52	55	57	63	66	69	74	81	96
900	0	23	33	40	44	47	50	52	57	61	64	68	74	87
1000	0	21	30	37	41	44	46	49	53	57	60	63	70	81
1100	0	19	28	34	38	41	43	45	49	52	56	60	65	75
1200	0	18	26	32	35	38	40	42	45	48	52	56	61	70

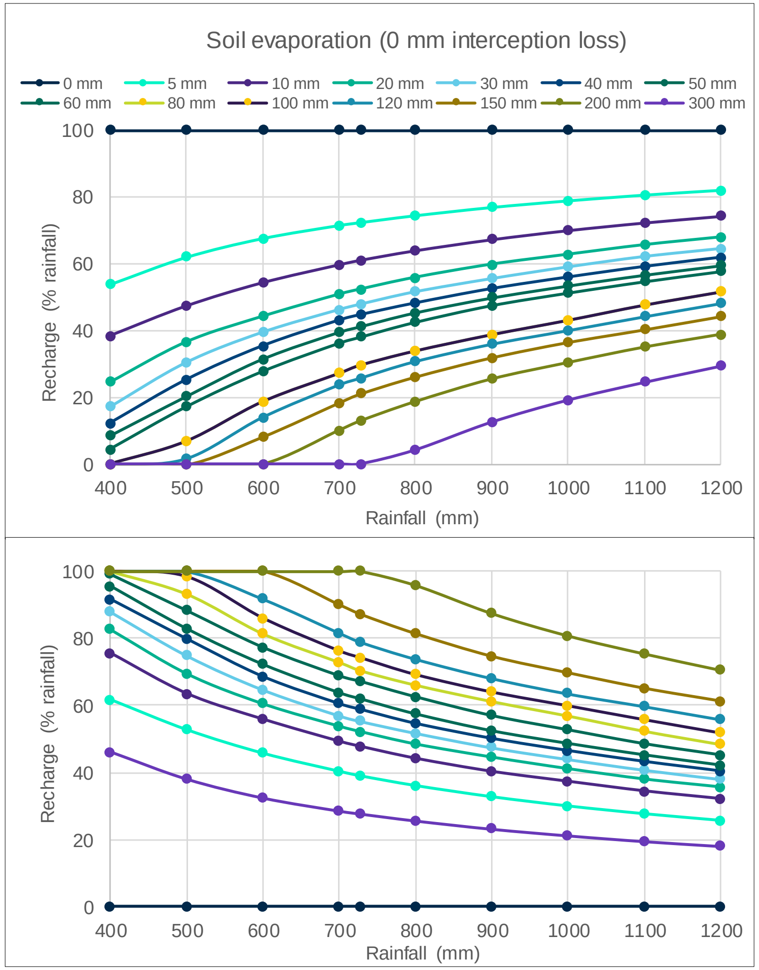


Figure 11 Recharge sensitivity to available soil moisture for 0 mm initial loss

Soil evaporation with 1.5 mm interception loss

Recharge

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall	Percent rainfall													
400	70	40	29	19	13	9	6	4	1	0	0	0	0	0
500	75	49	38	29	24	20	16	14	10	5	1	0	0	0
600	78	55	45	36	32	29	25	22	19	15	12	7	0	0
700	81	60	51	43	39	36	33	30	26	23	20	16	8	0
728	81	61	52	45	41	38	35	32	28	25	22	18	11	0
800	82	64	55	48	44	42	39	36	32	29	26	22	16	3
900	84	67	59	53	49	46	44	42	38	34	31	28	22	11
1000	85	70	62	56	53	50	48	46	42	38	35	32	27	17
1100	86	72	65	59	56	53	51	49	46	43	40	36	31	22
1200	87	74	67	62	58	56	54	52	49	47	43	40	35	27

Loss

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall			Percent rainfall											
400	30	60	71	81	87	91	94	96	99	100	100	100	100	100
500	25	51	62	71	76	80	84	86	90	95	99	100	100	100
600	22	45	55	64	68	71	75	78	81	85	88	93	100	100
700	19	40	49	57	61	64	67	70	74	77	80	84	92	100
728	19	39	48	55	59	62	65	68	72	75	78	82	89	100
800	18	36	45	52	56	58	61	64	68	71	74	78	84	97
900	16	33	41	47	51	54	56	58	62	66	69	72	78	89
1000	15	30	38	44	47	50	52	54	58	62	65	68	73	83
1100	14	28	35	41	44	47	49	51	54	57	60	64	69	78
1200	13	26	33	38	42	44	46	48	51	53	57	60	65	73

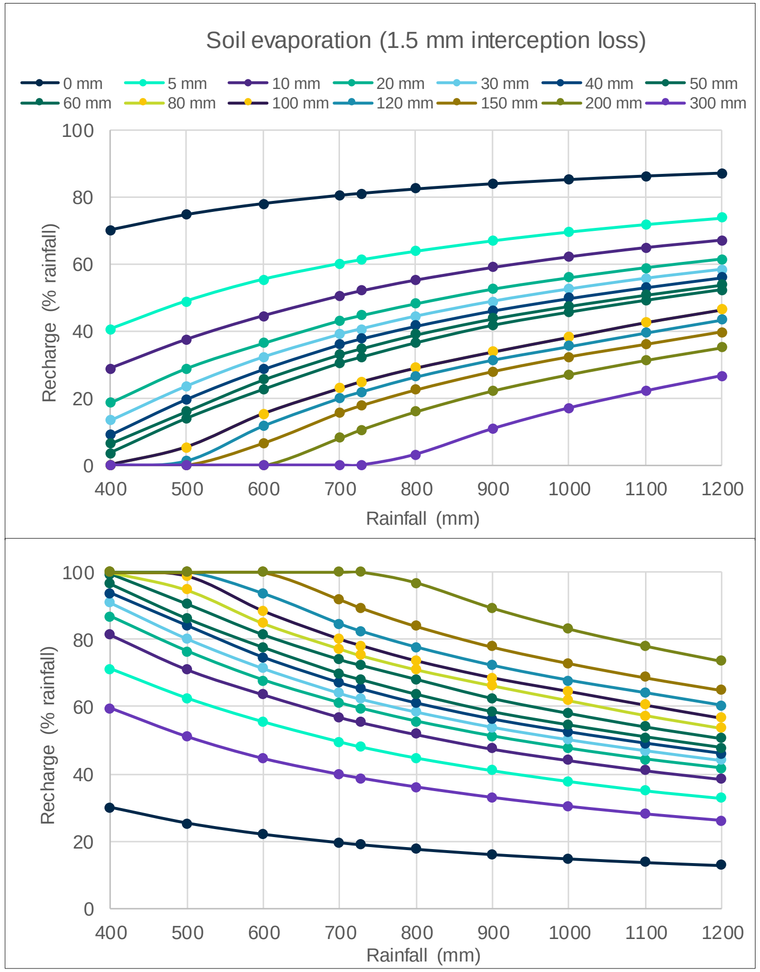


Figure 12 Recharge sensitivity to available soil moisture for 1.5 mm initial loss

Soil evaporation with 3.0 mm interception loss

Recharge

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall	Percent rainfall													
400	59	36	26	17	12	8	6	3	0	0	0	0	0	0
500	65	44	34	26	22	18	15	13	9	5	1	0	0	0
600	70	50	41	34	30	27	24	21	18	14	11	6	0	0
700	73	55	47	40	36	34	31	28	25	22	19	15	7	0
728	74	57	48	42	38	35	33	30	26	23	21	17	10	0
800	75	59	52	45	42	39	37	35	30	28	25	21	15	3
900	78	63	56	50	46	44	42	40	36	32	30	27	21	10
1000	79	65	59	53	50	48	45	44	40	37	34	31	26	16
1100	81	68	62	56	53	51	49	47	44	41	38	35	30	21
1200	82	70	64	59	56	54	52	50	47	45	42	38	34	26

Loss

Available soil moisture	0 mm	5 mm	10 mm	20 mm	30 mm	40 mm	50 mm	60 mm	80 mm	100 mm	120 mm	150 mm	200 mm	300 mm
Rainfall			Percent rainfall											
400	41	64	74	83	88	92	94	97	100	100	100	100	100	100
500	35	56	66	74	78	82	85	87	91	95	99	100	100	100
600	30	50	59	66	70	73	76	79	82	86	89	94	100	100
700	27	45	53	60	64	66	69	72	75	78	81	85	93	100
728	26	43	52	58	62	65	67	70	74	77	79	83	90	100
800	25	41	48	55	58	61	63	65	70	72	75	79	85	97
900	22	37	44	50	54	56	58	60	64	68	70	73	79	90
1000	21	35	41	47	50	52	55	56	60	63	66	69	74	84
1100	19	32	38	44	47	49	51	53	56	59	62	65	70	79
1200	18	30	36	41	44	46	48	50	53	55	58	62	66	74

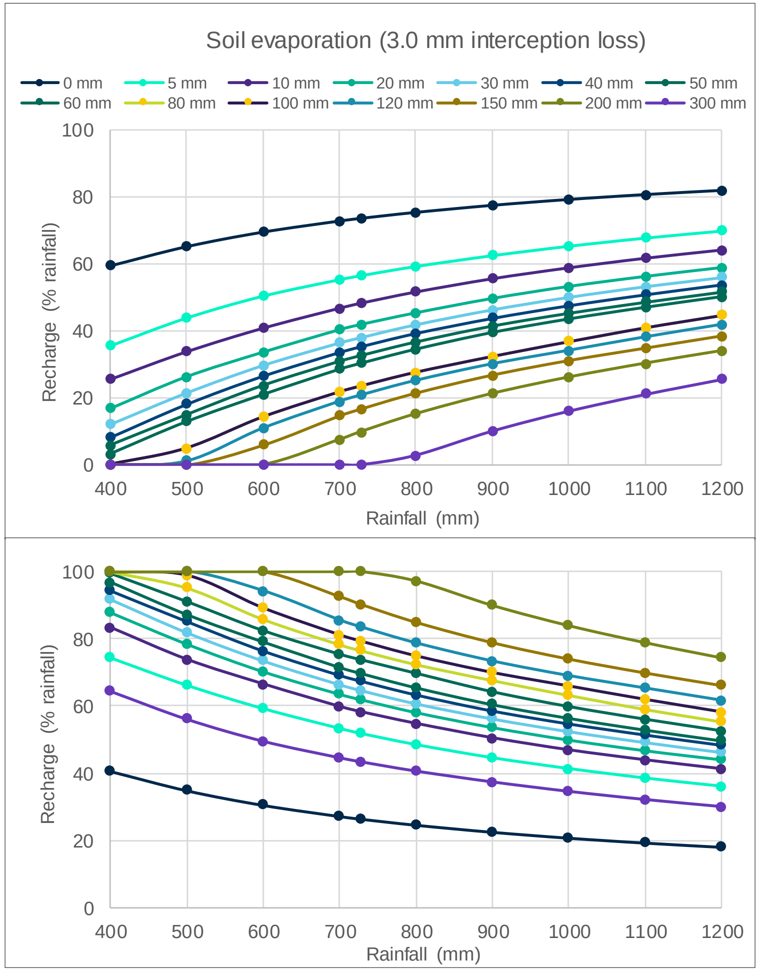


Figure 13 Recharge sensitivity to available soil moisture for 3 mm initial loss

A.5.3 Urban landuse areas

WE is estimated to be covered by 75% impervious, or 81% outside of POS areas. For context during the subsurface drainage monitoring period, the imperviousness at the start of the monitoring period of 69% is ~ 6% lower than that in October 2017 when the subsurface drainage catchment was nearly fully built out. WE has less than the typical 10% developable area as POS and one of its drainage sub-catchments (Swale 2E) still contained some cleared areas during the subsurface drainage monitoring period. Consequently, urban landuse cover was estimated for several additional development scenarios,

- Scenario 2: WE sub-catchments exclusive of Swale 2E (which represents the site at full build);
- Scenario 3: Scenario 2 areas outside of POS; and
- Scenario 4: Scenario 2 areas with 10% POS.

The impervious component is 73% for standard POS (Scenario 4), which is 2% lower than measured at WE (Table 4). The Scenario 4 area consists of 42% pavement, 31% roof, 21% irrigated and 6% un-irrigated which is similar to that measured at WE (43%, 32% 17% and 8% respectively). By urban landuse subarea, the Scenario 4 consists of 30% road reserve, 10% POS, 5% smaller lots (<300m^2) and 55% larger lots (>300m^2) which are similar to that measured at WE (31%, 6% 5% and 58% respectively) as shown on Figure 14 and Figure 15 respectively.

Table 4 Urban landuse areas

Landuse	Subarea	Subarea scenario (% of landuse area)				Subarea scenario (% of total urban area)			
		1) WE All	2) No Swale 2E	3) No POS	4) 10% POS	1) WE All	2) No Swale 2E	3) No POS	4) 10% POS
Road reserve	Pavement	75	75	75	75	23	24	25	23
	Irrigated	12	11	11	11	4	4	4	3
	Un-irrigated	13	13	13	13	4	4	4	4
POS	Pavement	2	1	-	1	0	0	-	0
	Irrigated	80	88	-	88	5	4	-	9
	Un-irrigated	17	11	-	11	1	0	-	1
Lots<300m	Pavement	23	25	25	25	1	1	1	1
	Roof	59	67	67	67	3	4	4	3
	Irrigated	5	6	6	6	0	0	0	0
	Un-irrigated	13	1	1	1	1	0	0	0
Lots>300m	Pavement	32	32	32	32	18	19	20	18
	Roof	50	50	50	50	29	29	31	28
	Irrigated	15	15	15	15	9	9	9	8
	Un-irrigated	3	2	2	2	2	1	1	1
Totals	Pervious	**25**	**23**	**19**	**27**	**25**	**23**	**19**	**27**
	Impervious	**75**	**77**	**81**	**73**	**75**	**77**	**81**	**73**

An urban development with the same density as Whiteman Edge and 10% POS is covered with ~73% impervious surfaces.

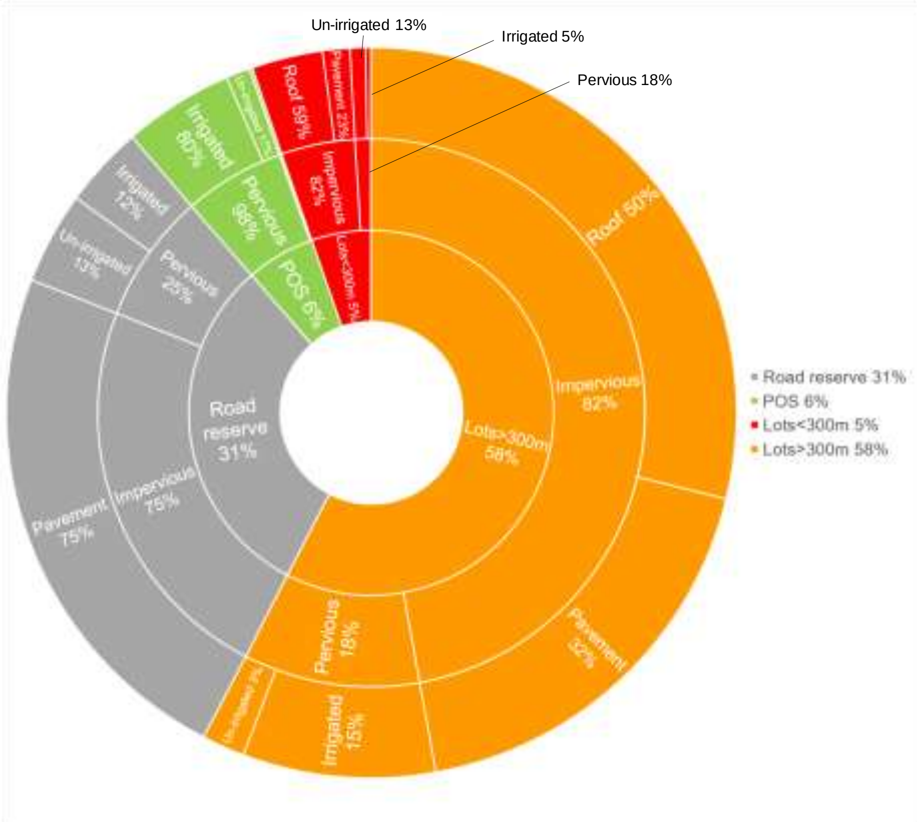


Figure 14 WE measured urban landuse percentages (Scenario 1)

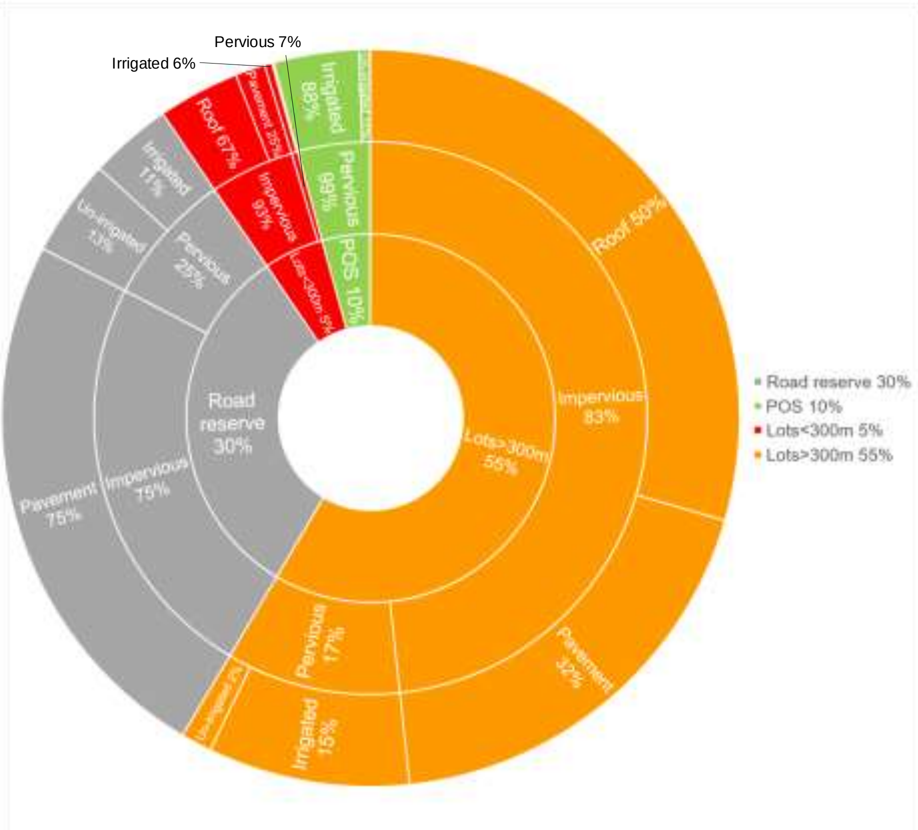


Figure 15 WE measured urban landuse percentages assuming 10% POS (Scenario 4)

A.5.4 Urban recharge rate estimate

The urban recharge rate at WE is estimated to be 67% of measured rainfall (728 mm) with a range of 49-74% for annual rainfall of 400-1,000 mm (Table 5 and Figure 16). Recharge rates for Scenarios 2 (no Swale 2E) and 4 (10% POS) are <1% higher and lower respectively than for WE (Scenario 1), while the recharge rate is ~2% higher for areas outside POS (Scenario 3). Irrigation comprises < 2% of groundwater recharge for all rainfall and development scenarios and hence is a small component of recharge compared with rainfall inputs.

Urban recharge is estimated at 65% plus 2% irrigation for 728 mm rainfall (49-74% for 400-1,100 mm rain)

Table 5 Urban recharge rate v rainfall

Rain (mm/yr)	Scen 1: WE (irr)	WE (un-irr)	Scen 2: No Swale 2E (irr)	Scen 3: No POS (irr)	Scen 4: With 10% POS (irr)	With 10% POS (un-irr)
400	49	48	50	52	49	47
500	56	55	58	59	56	54
600	62	60	63	64	61	59
700	66	64	67	68	66	64
728	**67**	**65**	**68**	**69**	**67**	**65**
800	69	68	70	71	69	67
900	72	70	72	73	71	70
1,000	74	72	75	75	74	72
1,100	76	74	76	77	76	74
1,200	77	76	78	79	77	75

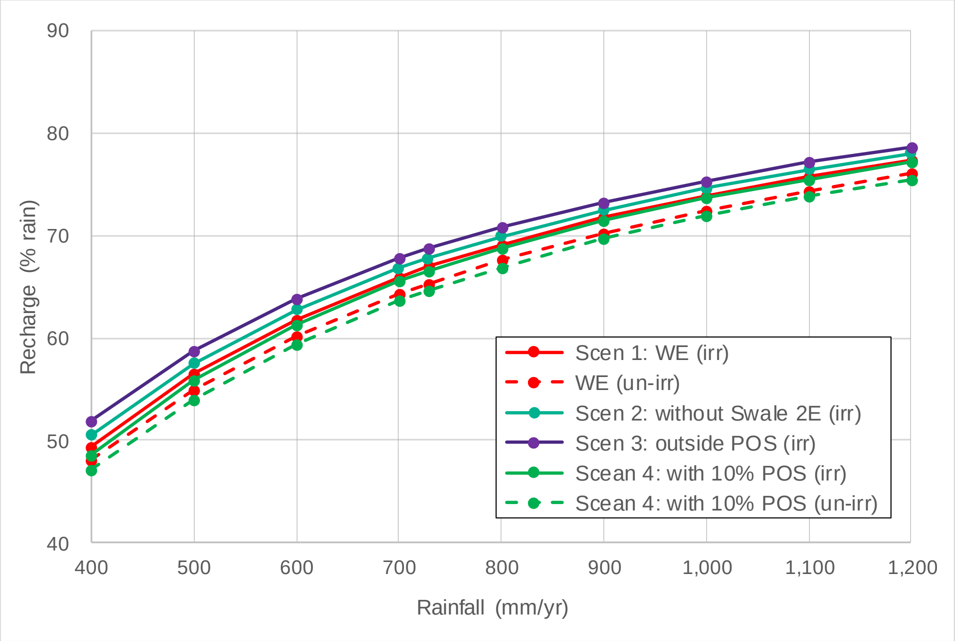


Figure 16 Urban recharge rate v rainfall

Recharge rates have been estimated for the four major urban subareas of road reserve, POS, smaller lots and larger lots, which is the breakdown that will be used for the groundwater modelling (Figure 17). For road reserves, 69% of rainfall contributes to recharge (range 53-76% for 400-1,000 mm rain). Of this, 11% of rainfall is recharged at source (range 4-14%) while 58% of rainfall is piped to the bioretention area (range 49-62%). POS and larger lots that contain soakwells (>300m^2) contribute 48% (range 19-59%) and 68% (range 51-75%) of rainfall to recharge, with no component to bioretention areas. For smaller lots (<300m^2) that drain to lot connection pits, 73% of rainfall contributes to recharge (range 58-79%). Of this, 18% of rainfall is recharged at source (range 11-21%) while 55% of rainfall is piped to the bioretention area (range 47-57%).

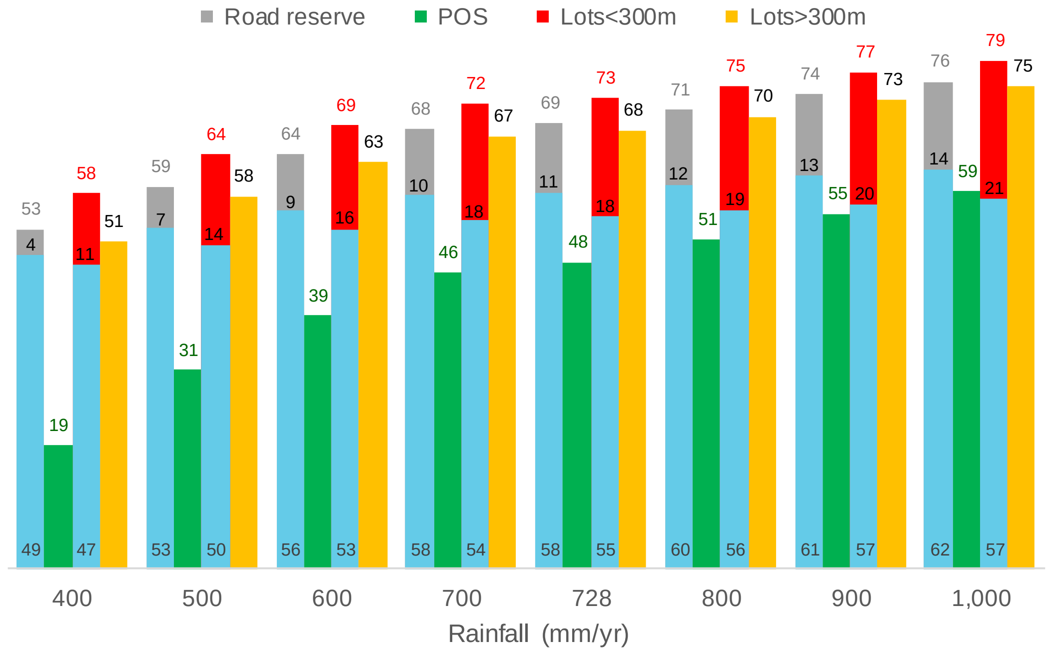


Figure 17 Landuse recharge rates for urban area with 10% POS. Labels above columns show landuse recharge area. Labels at the base of columns show recharge components: blue the component that is directed to bioretention areas, grey the recharge rate beneath road reserves; and red the recharge rate beneath Lots < 300m^2.

Across the development as a whole, at source recharge is 46% for measured rainfall (32-52% range for 400-1,000 mm rainfall). The proportion of stormwater that discharges to the bioretention areas is estimated at 20% (17-22% range), (Figure 18). Hence 30% (range 29-35%) of the water available for subsurface drainage from rainfall is infiltrated through the POS subsurface drainage system, while 70% (range 65-71%) is estimated to be available for the road reserve subsurface drainage system.

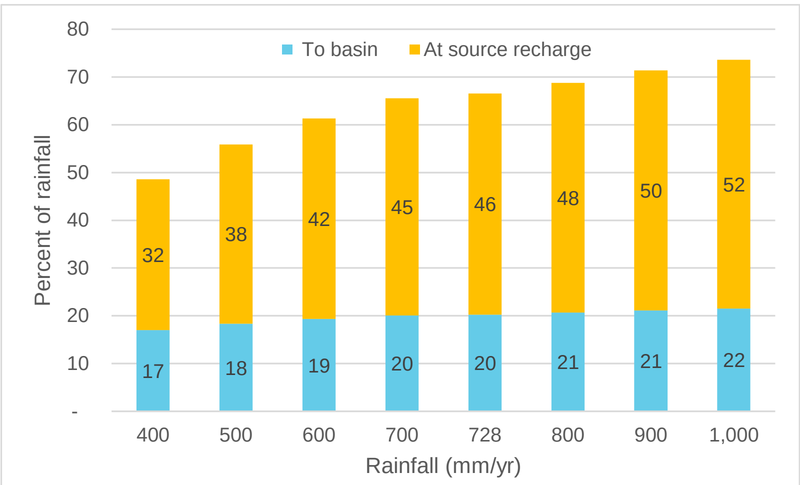


Figure 18: Component of rainfall recharged at source v discharged to bioretention area

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