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Stormwater Harvesting by Infiltration – Soil and Groundwater Limitations

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1. INTRODUCTION

Infiltration of stormwater at Lot scale (soakwells) and at Estate scale (infiltration basins) is advocated by both national and state guidelines on Stormwater Management (EA, (2005), DoW (2007)).

Infiltration of stormwater has many advantages over discharged downstream water bodies including:

- Opportunity for subsequent re-use by abstraction bores;
- Natural removal of stormwater pollutants within the soil profile;
- Attenuation of downstream surface water flows, reducing flood risk and requirements for drainage.

The disadvantages of stormwater infiltration can include:

- An increase in groundwater levels (which can result in increased importation fill requirement on sites with shallow water tables);
- Infiltration is generally limited to sandy or limestone soils as silt and clay soils have low infiltration rates;
- Infiltration in areas of very shallow groundwater tables can result in long residence times within basins, leading to possible breeding grounds for nuisance insects.

On sites where the water table is deep and soils are permeable (sandy) the advantages generally outweigh the disadvantages. Much of the development of Perth and Swan Coastal Plain has been on such sites, until recent years.

On sites where water table is shallow and soils are less permeable (clayey) the disadvantages may outweigh the advantages.

Much of current development of Perth and Swan Coastal Plain is occurring on such sites.

This paper builds on earlier work by JDA Consultant Hydrologists in the mid-1990's, using JDA experience in infiltration investigations and modelling on the Perth Coastal Plain. The early work by JDA was reported in two conference papers.

The first paper "Design of infiltration basins, trenches and swales" (Davies *et al*, 1996) was presented at the 13th Annual WA Municipal Engineering State Conference March 1996 Perth. This paper relates to infiltration of stormwater on sandy soils with deep water table.

The second paper "Design of stormwater infiltration basins with shallow water tables comparison of models – MODRET and PCSUMP" (Davies and Van Hall, 1997) was presented at the Engineers Australia Annual Conference on Hydrology and Water Resources. This second paper relates to infiltration in areas of shallow water table.

Copies of these two papers are attached as Appendix A and B to this paper for easy reference.

This paper also includes a summary of recent CSIRO research which maps areas of the Swan Coastal Plain generally suitable for stormwater infiltration in terms of soil type and depth to water table (Smith and Pollock, 2010).

2. REVIEW OF JDA CONFERENCE PAPERS

2.1 JDA (1996) – Deep Water Table

In 1996, JDA Consultant Hydrologists had a paper (Design of infiltration basins, trenches and swales - Davies *et al*, 1996) presented at the 13th Annual WA Municipal Engineering State Conference in March 1996 in Perth. The paper detailed modelling of infiltration where water table depth was large. In the paper an existing infiltration mode, PC-SUMP, was compared with a newly developed model, INFIL.

The model INFIL was developed by JDA and used a time varying infiltration rate, based on the Green-Ampt (1911) equation. During the early period of infiltration after rainfall has been applied, high infiltrations are predicted by modelling, and were also seen from monitoring of an infiltration basin. During later stages of infiltration, the infiltration rate trends to the saturated hydraulic conductivity (K_{sat}). At the time, PC-SUMP used a constant value of one third of the saturated hydraulic conductivity ($K_{sat}/3$), which was viewed as being overly conservative.

As part of the evaluation of the two infiltration models, continuous water level data collected for the McGregor Road Infiltration Basin in the City of Melville during 1993 and 1994 was used for validation.

Comparisons between the two models showed that for the same catchment and soil conditions PC-SUMP required a greater storage volume than INFIL to infiltrate the same rainfall event.

The paper suggests that, given few infiltration basins in Perth overflowed during the February 1992 event (approximately 100 year ARI event), infiltration basins may be overdesigned and that a review of basin sizing requirements would be justified.

2.2 JDA (1997) – Shallow Water Table

In 1997 JDA Consultant Hydrologists followed up with a paper on infiltration with shallow water tables (Design of stormwater infiltration basins with shallow water tables comparison of models – MODRET and PCSUMP" - Davies and Van Hall, 1997) presented at the Engineers Australia Annual Conference on Hydrology and Water Resources. This paper details modelling of infiltration where the groundwater table is reasonably close to the surface, resulting in horizontal as well as vertical flow during an infiltration event. Two infiltration models, PC-SUMP (Shallow Water Table Log Model) and MODRET were compared.

The infiltration model MODRET was developed in the US for infiltration of runoff where shallow water tables exist. This model was developed based on simulations using the groundwater model MODFLOW. MODRET models the vertical infiltration of water through the unsaturated zone and the horizontal flow of water above and below the water table once the wetting front reaches the water table. The PC-SUMP model uses an approximation of the radial flow equations, assuming that the water table is an impermeable surface.

Two infiltration basins, one in the City of Stirling (Pinaster St) and one in the City of Melville (Swan Rd) were used to help calibrate and assess the two models. The Swan Rd basin was equipped with a continuous water level probe, which provided data for three storm events in 1994. The MODRET model calibrated well to each set of data, with hydraulic conductivity values similar to regional values. It also achieved infiltration rates similar to those obtained during onsite investigation using a disc permeameter. The PC-SUMP model, even with a high hydraulic conductivity value, failed to calibrate to the observed data.

It was therefore concluded that the MODRET model, by more accurately modelling the infiltration processes, provides a better estimate for basin design.

3. REVIEW OF SMITH AND POLLOCK (2010)

CSIRO published a study into the potential for artificial recharge of the superficial aquifer from Lake Preston to Moore River (Smith & Pollock, 2010). This study made use of analytic models of water table response to recharge wells and basins, which were applied spatially across the Perth Region. This was done to assess the hydraulic potential for artificial recharge into the superficial aquifer.

The study considered the aquifer properties that control groundwater recharge and flow, the likely water table response to recharge and the available space in the aquifer. Datasets including ground surface elevation, annual mean water table surface, base of superficial aquifer were used to estimate depth to water table below natural surface and saturated aquifer thickness (Figure 1). Aquifer properties including aquifer transmissivity and storage coefficient based on the PRAMS (Perth Regional Aquifer Modelling System) and PHRAMS (Peel-Harvey Regional Aquifer Modelling System) models. Soil infiltration rates were based on soil texture-class units, which were sand, limestone and sand, sand with various amounts of silt, clay and peat, and predominantly clay and silt. Representative constant infiltration rates were based on hydraulic conductivities (Figure 2).

The study found that the coastal limestone and extensive parts of the Gnangara Mound and some parts of the Jandakot Mound were suitable for small, medium and large scale artificial recharge operations. The presence of sandy surface soils and moderate to very large aquifer transmissivities allow large infiltration rates and promote lateral spreading of recharge mounds, rather than excessive vertical rise towards the ground surface (Figure 3).

Conversely, the extensive inland areas south of the Swan-Canning Estuary were assessed to be unsuitable for medium and large scale infiltration of artificial recharge. Groundwater is relatively shallow and soil and aquifer have greater clay and silt content, restricting infiltration and lateral groundwater flow, with the result of large vertical mounding in water table.

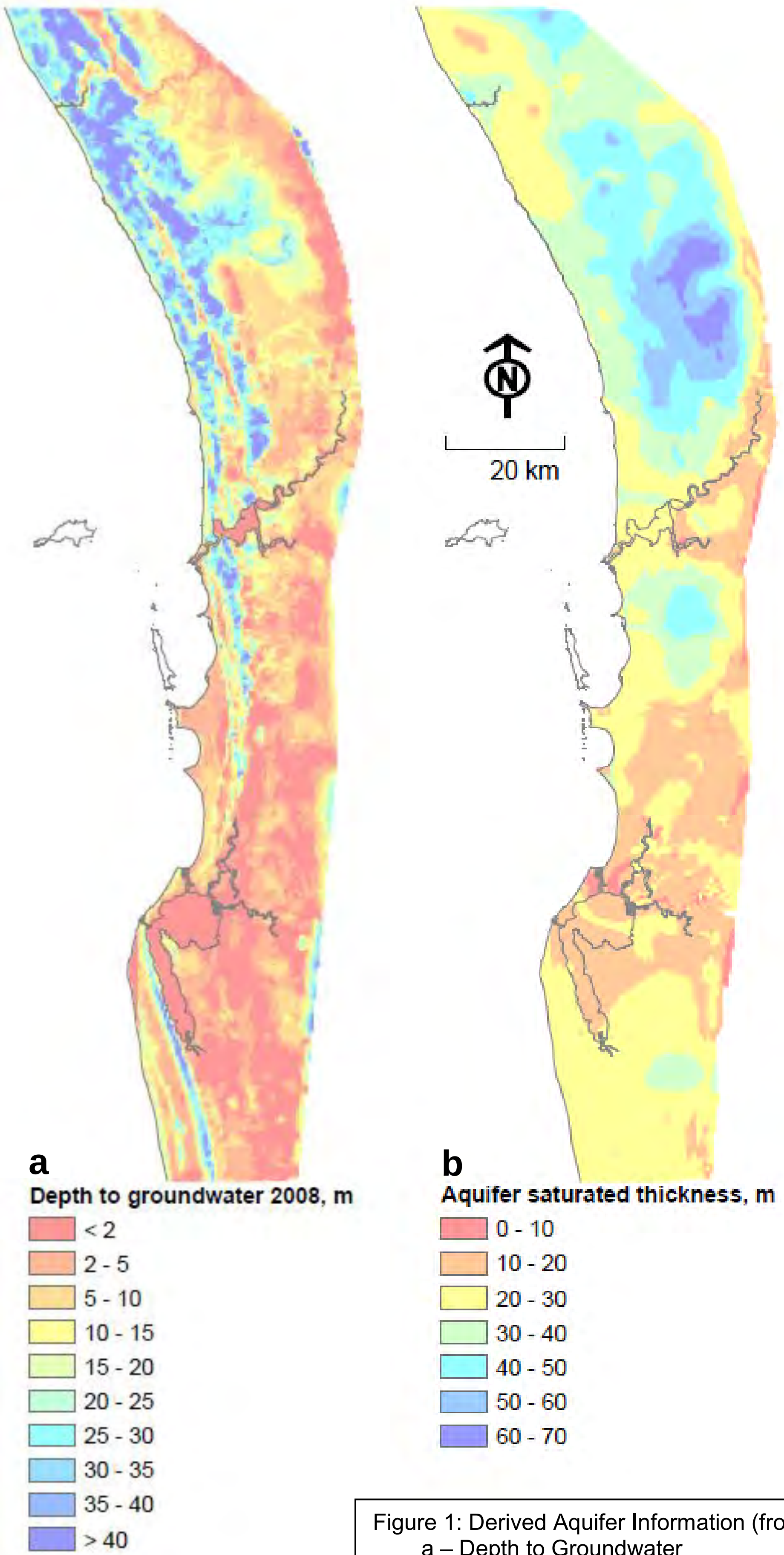

Figure 1: Derived Aquifer Information (from Smith & Pollock (2010))
a – Depth to Groundwater
b – Aquifer Saturated Thickness

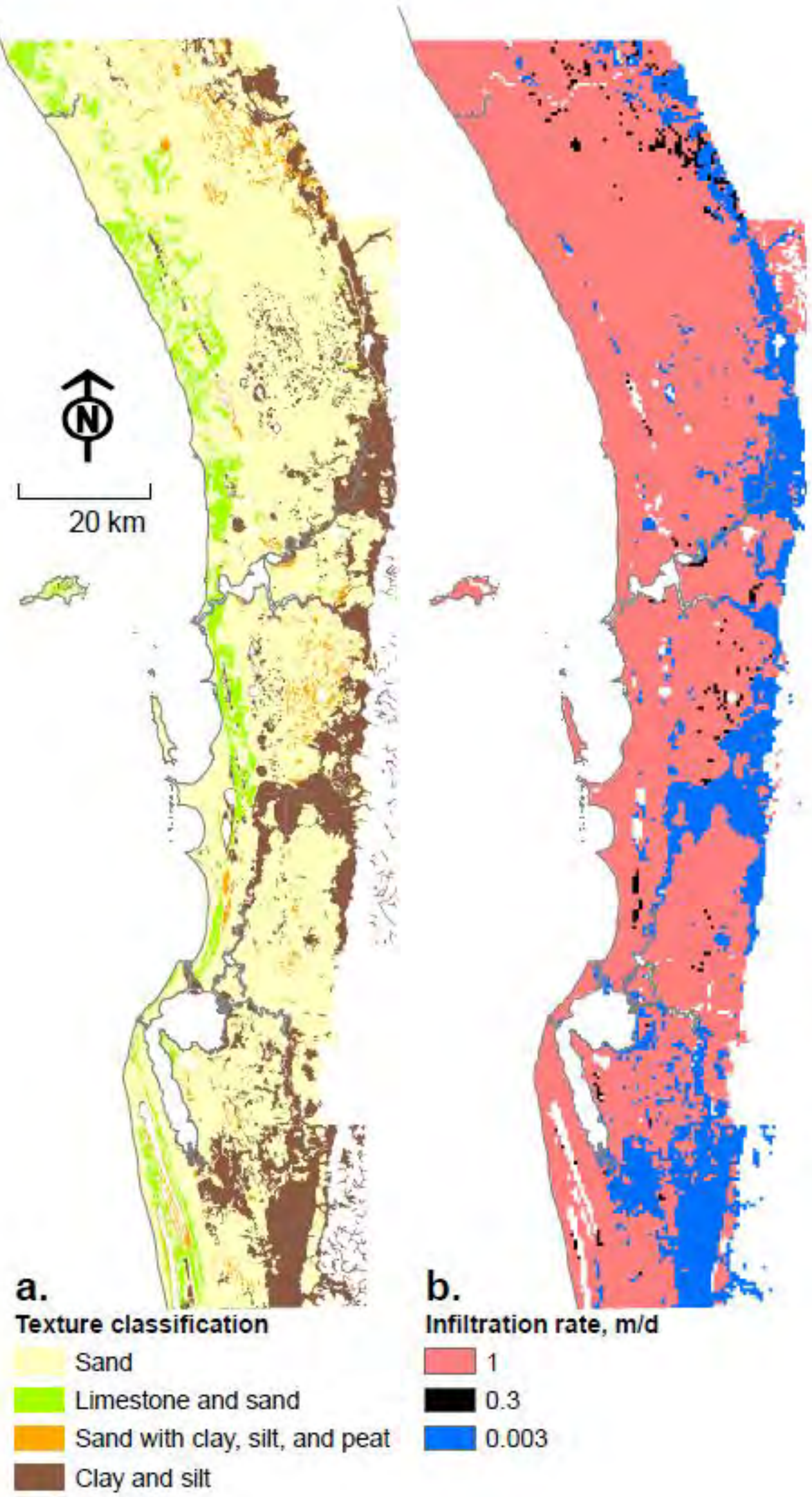

Figure 2: Soil Texture & Infiltration Rate (from Smith & Pollock (2010))
a – Texture Classification
b – Infiltration Rate

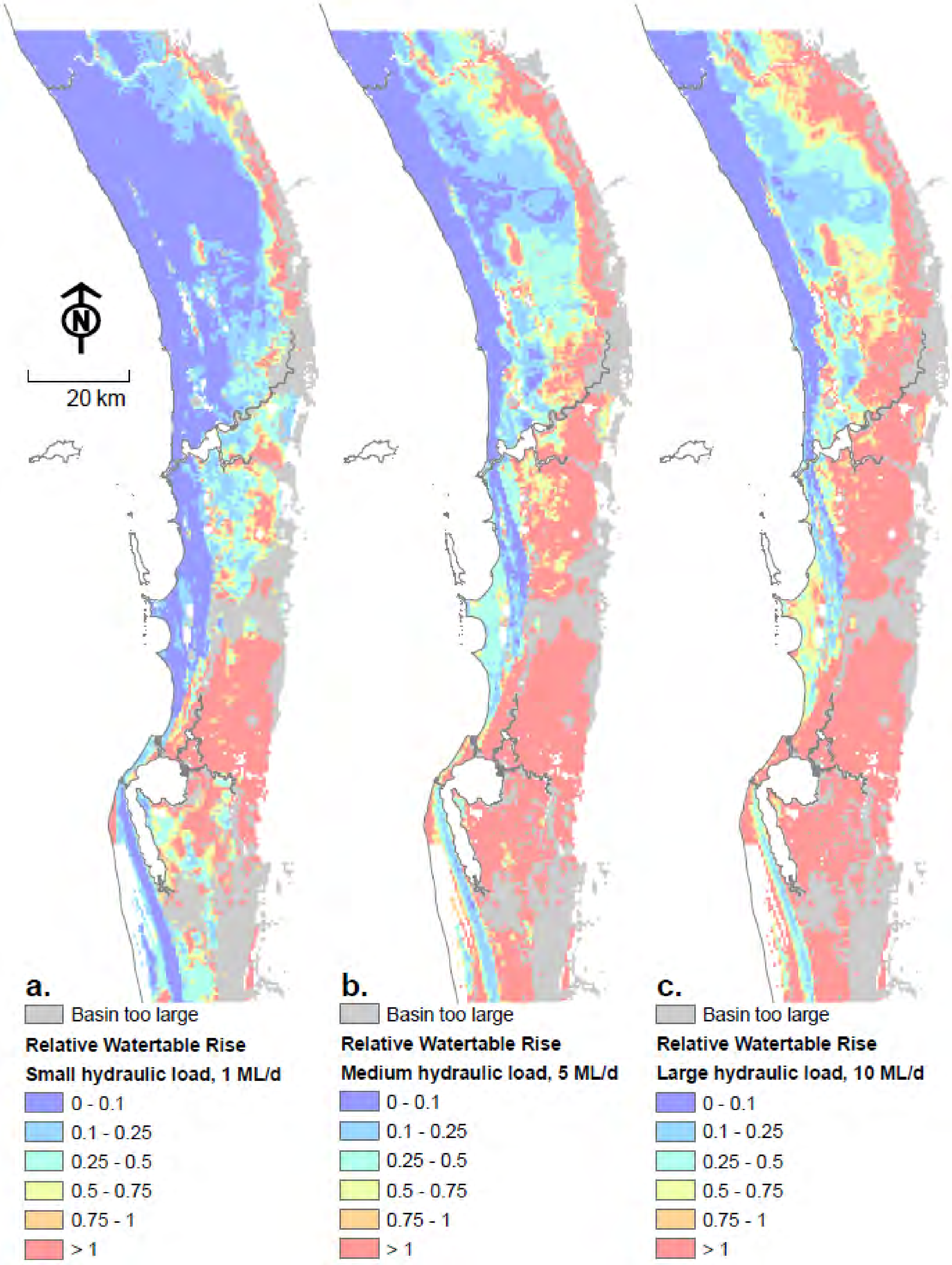

Figure 3: Relative Watertable Rise at 30 days (from Smith & Pollock (2010))
a – Small basin infiltration hydraulic load
b – Medium basin infiltration hydraulic load
c – Large basin infiltration hydraulic load

4. JDA INFILTRATION EXPERIENCE IN WA

JDA has been investigating and modelling infiltration in WA for over 15 years. Infiltration experience has been primarily on the Perth Coastal Plain within the Perth Metro Area, but has also extended north to Geraldton and south to Bunbury and Capel. Table 1 below details Local Government areas where JDA have been involved in infiltration. Appendix C provides a list of some of the infiltration projects JDA have been involved with.

This experience has ranged from coarse sands and limestone to clayey sands, from shallow water tables (<1 m) to water tables of greater than 20 m depth and from deep saturated aquifers (>30 m thickness) to sand fill on impermeable clays. Contributing catchments have ranged from Lot scale runoff to individual catchments of greater than 20 ha.

Onsite investigations conducted by JDA include particle size distributions of soil samples, disc permeameter, borehole permeameter and ring infiltrometer testing, and large scale infiltration testing involving excavation of a test pit, filling using water tankers and monitoring of flows and levels over day long test periods.

TABLE 1: JDA EXPERIENCE OF INFILTRATION IN LOCAL AUTHORITY AREAS

City of Bunbury	City of Fremantle	City of Melville	City of South Perth
City of Canning	City of Geraldton	Town of Mosman Park	City of Stirling
Shire of Capel	City of Gosnells	Shire of Murray	City of Subiaco
Town of Claremont	City of Joondalup	City of Nedlands	City of Swan
City of Cockburn	Town of Kwinana	City of Perth	Town of Victoria Park
Shire of Esperance	City of Mandurah	City of Rockingham	City of Wanneroo

This experience generally agrees with the mapping produced by Smith & Pollock (2010). However in our experience, infiltration in sandy or limestone soils can be retarded if layers such as Coffee Rock or caprock are present. Individual site assessment can be crucial to correctly modelling infiltration.

5. CONSTRAINTS FOR INFILTRATION

There are a number of factors which can impact on infiltration rates and limit the effectiveness of using infiltration as a means of stormwater harvesting.

5.1 Depth to Groundwater

The depth to groundwater from the base of an infiltration basin has a significant impact on the infiltration capacity. When groundwater is very deep, the infiltration rate over time will trend towards the vertical hydraulic conductivity of the soil, with flow occurring at unit gradient. When groundwater depth is shallow, infiltration flow from an infiltration basin is primarily horizontal, with flow rates based on hydraulic gradient. With a shallow water table, the hydraulic gradient is low, given the small head difference between the ponded water level in the basin and the groundwater level. This gradient will be much lower than the unit gradient.

In addition, shallow groundwater table indicate that there is a only a small storage volume available within the aquifer, limiting the capacity for infiltration, unless a mechanism such as subsoil drainage is used to remove excess water and limit water table rise.

5.2 Vertical Hydraulic Conductivity

The vertical hydraulic conductivity has a significant impact on the initial infiltration through the unsaturated zone. Low values of this parameter can limit infiltration resulting in ponding of water at the natural surface. Soils such as clays and silts have low vertical hydraulic conductivities which restrict infiltration of water to groundwater.

Where water table is close to groundwater, infiltration rates are relatively insensitive to vertical hydraulic conductivity as flow is predominantly horizontal.

5.3 Horizontal Hydraulic Conductivity

The horizontal hydraulic conductivity of the aquifer is one of the primary parameters for infiltration where groundwater table is close to the surface. Here infiltration flow is mostly horizontal, with flow rates governed by the hydraulic gradient between the ponded water in the basin and the surrounding groundwater, and the horizontal hydraulic conductivity.

Horizontal hydraulic conductivity also governs lateral spreading of infiltrated water, impacting on ability of the aquifer to distribute infiltrated water. Lower values can lead to excessive mounding of the water table at infiltration basins, with increased groundwater levels requiring greater fill requirements to provide adequate separate to the water table.

5.4 Aquifer Thickness

Aquifer thickness can have a significant impact on infiltration capacity when there is only a small aquifer thickness or if it is absent altogether (for example where there is a perching layer). Perching can result from a clay layer within the subsurface profile above the water table, a relatively impermeable Coffee Rock layer in sand, caprock in limestone, or if sand fill is imported where the native soils are clay.

A low aquifer thickness reduces the capacity of the aquifer to transmit infiltrated water, resulting in flow being almost exclusively horizontal. After the initial stages of infiltration, rates are governed by the hydraulic gradient which can quickly become very low. Due to the low thickness, aquifer transmissivity will be small, resulting in low flow rates.

5.5 Basin Design

Design of infiltration basins can in some circumstances reduce capacity for infiltration. For example, when a large catchment discharges to large infiltration basin of square or circular design where the groundwater table is relatively shallow, infiltration is limited to predominantly horizontal flow through the perimeter of the basin. This can lead to long residence times, even in sandy soils. In this situation, breaking the catchment up with a number of smaller basins will result in improved infiltration capacity. Similarly the use of long infiltration swales would maximise basin perimeter compared to basin volume and will improve capacity.

6. CONCLUSIONS

While infiltration of stormwater runoff is an effective method of stormwater harvesting, it is not necessarily suitable for all areas in the Perth Coastal Plain.

Where soils are silty or clayey, the aquifer parameters of these soil types inhibit the infiltration of water, resulting in long infiltration time scales and long residence time of ponded water within basins, creating environments for nuisance insects.

Where the groundwater table is close to the ground surface, this can restrict infiltration rates, and also limit the storage potential above the groundwater table. Infiltrating water into this environment is likely to raise groundwater levels, increasing potential for waterlogging of soils and resulting in additional fill being required to provide adequate separation to the water table.

Infiltration of harvested stormwater in areas of sand or limestone where there is adequate separation to the water table is the most effective method of utilising infiltration capacity.

7. REFERENCES

Davies J. R., Davies P., Robinson J., and Sim D. (1996) Design of Infiltration Basins, trenches and Swales. Paper was presented at the 13th Annual WA Municipal Engineering State Conference March 1996 Perth – and was awarded Best Paper Award.

Davies J. R., Van Hall S. (1997) Design of Stormwater Infiltration Basins with Shallow Water tables Comparison of Models – MODRET and PCSUMP. Paper presented at the Engineers Australia Annual Conference on Hydrology and Water Resources

DoW (2007) Stormwater Management Manual of Western Australia.

EA (2006) Australian Runoff Quality – A Guide to Water Sensitive Urban Design.

Smith A. J., Pollock D. W. (2010) Artificial Recharge Potential of the Perth Region Superficial Aquifer: Lake Preston to Moore River. February 2010.

APPENDIX A

Davies J. R., Davies P., Robinson J., & Sim D. (1996) Design of Infiltration Basins, Trenches and Swales

DESIGN OF INFILTRATION BASINS, TRENCHES AND SWALES

By: Jim Davies, Paul Davies, Justin Robinson and David Sim

Paper presented at 13th Annual WA
Municipal Engineering State Conference
March 1996 Perth

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Design of Infiltration Basins, Trenches and Swales

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SUMMARY

Perth stormwater is often disposed of in retention basins known locally as sumps. Retention basins are suitable where soils are sandy and the depth to the water table is large. Infiltration of stormwater is recognised as a Best Management Practice advocated by Water Sensitive Urban Design principles. Data collated on a number of retention basins suggest that infiltration rates greatly exceed the saturated hydraulic conductivity (K_{SAT}) of the soil. K_{SAT} is a commonly used estimate of infiltration rate and so Perth retention basins may be over designed, resulting in excess valuable urban land being set aside for drainage management. The methodology of a new design model, INFIL, is described.

1.0 INTRODUCTION

Extensive areas of the Perth metropolitan region are located on sandy soils where the water table is sufficiently deep for infiltration of stormwater to be a preferred option. Perth is unusual in this respect from other major Australian cities, which because of differing soil types, do not have the option of infiltrating stormwater in retention basins. Infiltration of stormwater through retention basins, infiltration trenches and swales are Best Management Practices (BMP's #I4, #I10 and #I11) of Water Sensitive Urban Design (Whelans et al, 1993). By recharging to groundwater rather than exporting stormwater to drains, estuaries and rivers, local councils help to maintain the quality of Perth's surface water bodies.

An important factor in the design of retention basins is the land area required which depends in part on the assumed infiltration rate of stormwater. Because infiltration of stormwater is an option only in Perth, but not in other Australian cities, localised methods of basin design have developed, the most common of which is PC-SUMP (Main Roads, 1992) based on a paper by Cocks and Teague (1987).

This paper describes the infiltration process and uses both observed and modelled data to present a new approach to basin design. Design methodology is then described together with implications for evaluation of existing retention basins and the design of new ones. Application to the design of infiltration trenches and swales is also discussed.

2.0 OVERVIEW OF DEEP WATER TABLE INFILTRATION MODELS

The two modelling approaches to infiltration discussed in this paper are essentially different in that the PC-SUMP deep water table model assumes steady state conditions in which the infiltration rate is constant, while an alternative approach referred to here as the INFIL model uses a variable infiltration rate which is time-dependent.

2.1 PC-SUMP Model

PC-SUMP uses a solution for steady state saturated flow adapted from Harr (1962) in which the outflow of water from a basin (infiltration volume) is simply a function of the surface area of the wetted zone and a constant infiltration rate equivalent to $K_{(RESAT)}$ (equation 1). The value of $K_{(RESAT)}$ rather than $K_{(SAT)}$ is prescribed on the basis that entrapped air prevents complete saturation of the soil and is calculated as the input $K_{(SAT)}$ divided by 3 (Bouwer 1978).

$$q_o = K(W + 2H'\sqrt{1+S^2})\text{ per unit length} \qquad (1)$$

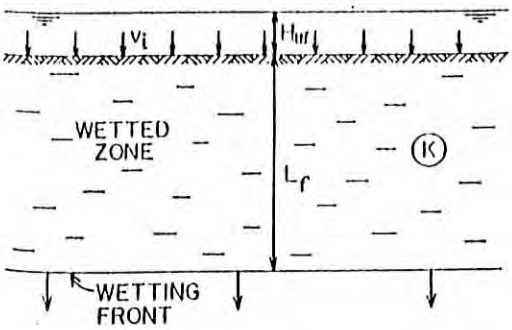
where q_o is the rate of outflow from the sump due to soakage, W is the sump width, H' is half the maximum depth of water in the basin and S is the side and end slopes

2.2 INFIL Model.

We consider that a constant infiltration rate of $K_{SAT}/3$ is an overly conservative estimate of infiltration and that the average rate of infiltration exceeds $K_{(SAT)}$. This is supported by observed infiltration rates in several basins as described in section 3.

The new model INFIL is based on the Green-Ampt (1911) model which applies to infiltration under ponded conditions. The model simplifies the infiltration process to "piston flow" where there is an abrupt change in the soil water content at the depth to which infiltration has occurred, known as the wetting front. The model also assumes vertical flow and uniform water content and hydraulic conductivity above the wetting front, see Figure 1.

Figure 1: Geometry and symbols for piston-flow infiltration systems (Bouwer 1978)



The Green -Ampt equation is given by:

$$vi = K\frac{H_w + L_f - h_{cr}}{L_f} \qquad (2)$$

where vi is the infiltration rate, $K_{(RESAT)}$ is the resaturated hydraulic conductivity, H_w is the depth of ponded water above the soil, h_{cr} is the air entry pressure and L_f is the depth of the wetting front. For sandy soils h_{cr} is less than 0.5 m and can generally be neglected.

In urban catchments stormwater is transported rapidly to retention basins by piped systems and gutters so that initially high rates of infiltration occur when there is a large depth of water in the basin (H_w) and a proportionally small depth to the wetting front (L_f). As the wetting front depth L_f increases during an infiltration event, it becomes the most significant factor and the infiltration rate tends to a constant rate equal to $K_{(RESAT)}$ (Bouwer 1978).

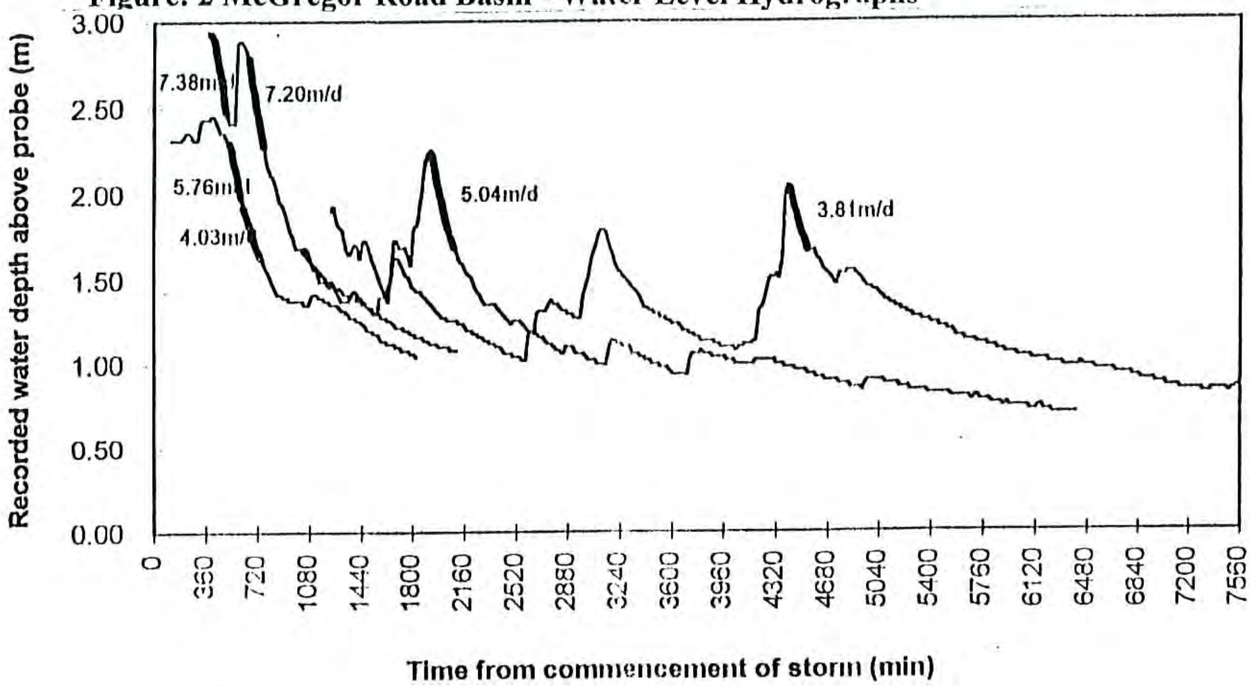
The INFIL model uses the AR&R 1987 rainfall temporal patterns and intensities (I.E. Aust. 1987) to produce inflow hydrographs to retention basins. Time increments are the same as those for the temporal storm patterns. At each time step INFIL calculates the infiltration rate, basin water level and storage and depth to wetting front.

3.0 RETENTION BASIN WATER LEVEL DATA

On the 8 and 9 of February 1992 Perth experienced a severe storm of an average recurrence interval (ARI) of around 100 years for durations between 3 and 24 hours (Davies 1991). A number of Perth retention basins overflowed including the McGregor Road basin in the City of Melville. To assist analysis of existing basins and to improve the design of new basins the City commenced monitoring of infiltration rates with water level probes and data loggers on five retention basins. Over the next two years infiltration rates have been measured providing a dataset with which to evaluate the existing design method (PC-SUMP) and the INFIL model.

Only the data for McGregor Road retention basin are reported here. Figure 2 shows water level hydrographs in McGregor Road basin between October 1993 and August 1994. During individual storm events the peak recorded basin water depths ranged from 0.5 m on 1 October 1993 to 2.3 m on 30 June 1994.

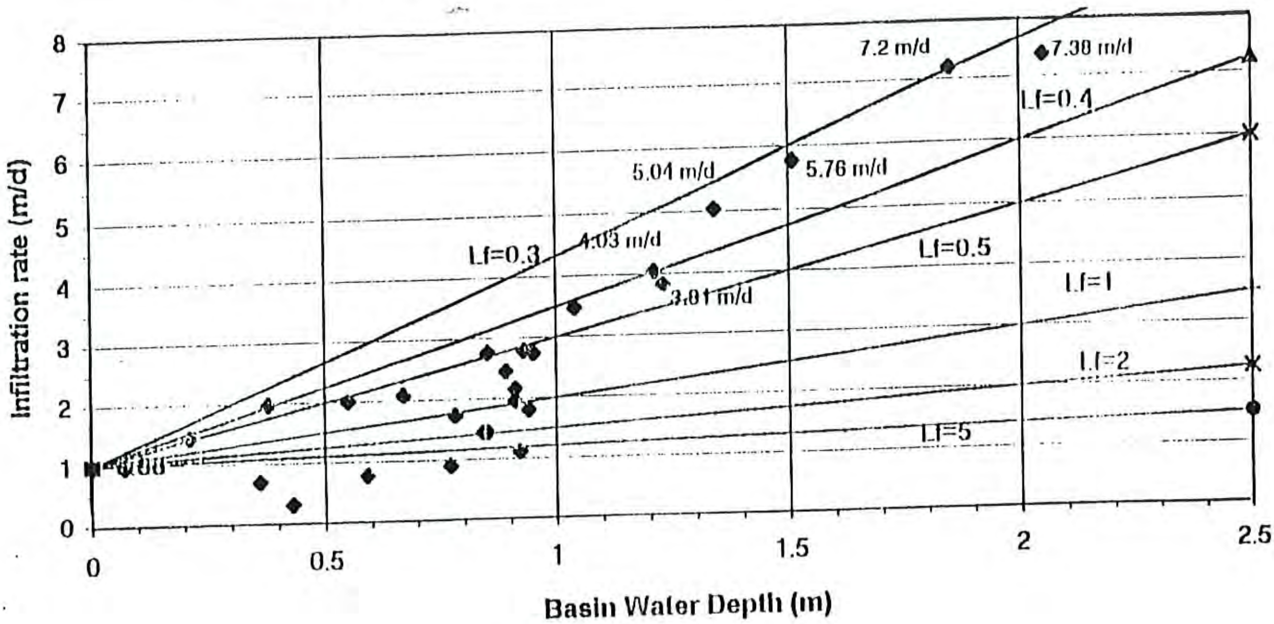
Figure: 2 McGregor Road Basin - Water Level Hydrographs



For each event the water level rises rapidly to a peak level at which time the inflow rate of water into the basin is equivalent to the infiltration rate. When the rate of infiltration increases above the inflow then the water level recedes at a gradually decreasing rate as the basin empties by soakage. The rates of water level recession shown on Figure 2 are estimated averages over the time period highlighted on the graphs. These recession rates were calculated over intervals in which the infiltration rate appeared uniform such that zero inflow to the basin was assumed. Variation in the infiltration rates of between 3.8 m/day and 7.2 m/day immediately following peak levels on Figure 2, and the much slower rates during the subsequent recessions, is of considerable interest and is directly related to the depth of water in the basin. In particular the highest infiltration rates are well correlated with largest depths of water. This is well illustrated on the 30 June 1994, which experienced the highest water levels and a maximum infiltration rate at 7.2 m/day.

The data from Figure 2 are shown replotted as infiltration rate versus basin water depth in Figure 3, with the six highest infiltration rates annotated. The lower infiltration rates (calculated during water level recessions) shown on both Figures 2 and 3 occur when the retention basin water depth is generally below 1.0 m. Theory for ponded infiltration from a retention basin into dry soil, with a deep water table, predicts that a rapid infiltration rate would occur, decreasing as the depth of soil wetting increases (Bouwer, 1978) which is consistent with the observed data.

Figure 3: McGregor Road Basin - Infiltration Rate as a Function of Basin Water Depth



Indicated on Figure 3 are a series of straight lines (annotated L_f = 0.3 to 5.0 m) radiating from 1.0 m/d infiltration rate and zero water depth, calculated using the equation 2 with K_{RESAT} = 1.0 m/d. These lines correspond to the depth of the wetting front (Lf) and indicate that when the wetting front depth is small infiltration rates will be relatively high for a given basin water depth. As the wetting front depth increases then the infiltration rate for an equivalent basin water depth decreases. When the wetting front is at a depth of say 5.0 m, then the infiltration rate becomes virtually constant at the specified K_{RESAT} value 1.0 m/d. Note that the straight lines on Figure 3 are based on a resaturated hydraulic conductivity (K_{RESAT}) of 1.0 m/d which appears consistent with the McGregor Road water level data, a figure that has been confirmed through laboratory analysis (K_{RESAT} = 0.84 m/d). If the $K_{(RESAT)}$ value of the soil at McGregor Road retention basin were actually 5.0 m/day then these straight lines would radiate from the 5.0 m/d infiltration rate on Figure 3. Clearly this would not be consistent with the observed data.

Typically a value of $K_{(SAT)}$ is estimated based on the particle size distribution and/or porosity and for Perth sandy soils this generally results in saturated hydraulic conductivity of 1 to 5 m/d.

4.0 COMPARISON OF RETENTION BASIN DESIGN USING PC SUMP AND INFIL MODELS

In this section of the paper we compare the INFIL model with the PC-SUMP model for the design of retention basins. To compare the two models we assume a deep-water table with basin and catchment parameters stated in Table 1, referred to here as Example 1. We then compare the maximum storage requirement and water levels from the two models for 10 year ARI storm events of varying durations. Table 2 presents a comparison of the results.

Table 1: Example 1 - basin, soil and catchment parameters.

Model Parameters	Parameter Value
$K_{(RESAT)}$ (m/d)	1
Air entry pressure h_{cr} (cm)	-50
Effective porosity, e	0.3
Basin width, W (m)	10
Basin length, L (m)	10
Basin side slopes, S	0.111
Storm ARI (years)	10
Catchment area (ha)	10
Runoff coefficient	0.5

Note: PC-SUMP does not use h_{cr} or e

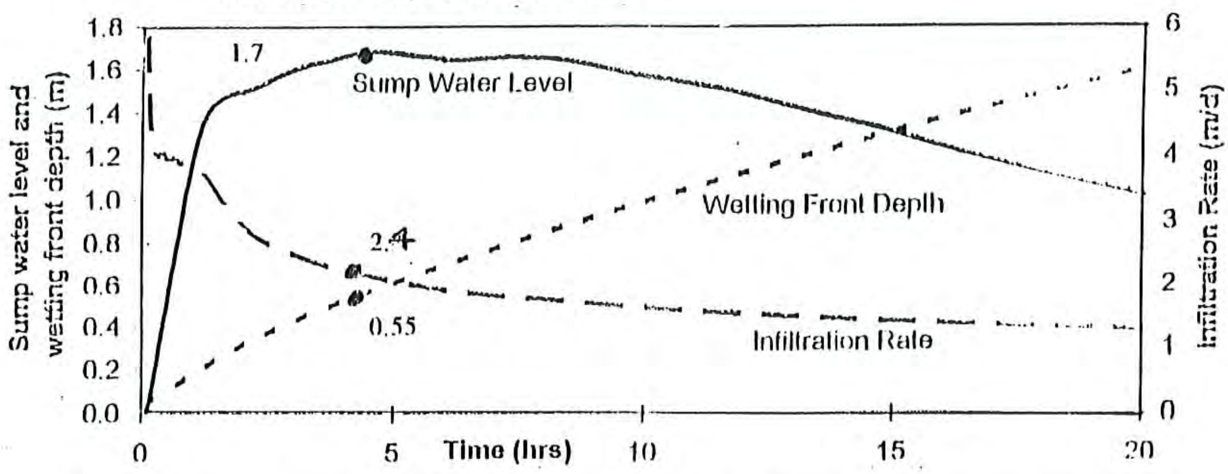
Table 2: Example 1 - Comparison of PC-SUMP and INFIL model results

	PC-SUMP MODEL		INFIL MODEL	
STORM DURATION (hr)	STORAGE (m^3)	BASIN WATER DEPTH (m)	STORAGE (m^3)	BASIN WATER DEPTH (m)
6	2400	2.3	1700	1.7
12	2800	2.4	1700	1.7
24	3200	2.6	1800	1.8
48	3400	2.6	1800	1.8
72	3200	2.5	2100	1.9

From Table 2 the maximum storage requirement from the INFIL model is 2100 m^3 for the 72 hour duration storm. The maximum storage requirement for the PC-SUMP model is 3400 m^3 for the 48 hour duration storm, a value 62% higher than for the INFIL model. The difference between the models is that in INFIL the infiltration rate always exceeds the $K_{(RESAT)}$ = 1.0 value which is approached at long duration whereas in PC-SUMP an infiltration rate of $K_{(RESAT)}$ is used throughout. For Example 1, to allow PC-SUMP to reproduce the INFIL model results a hydraulic conductivity closer to $K_{(SAT)}$ should be used.

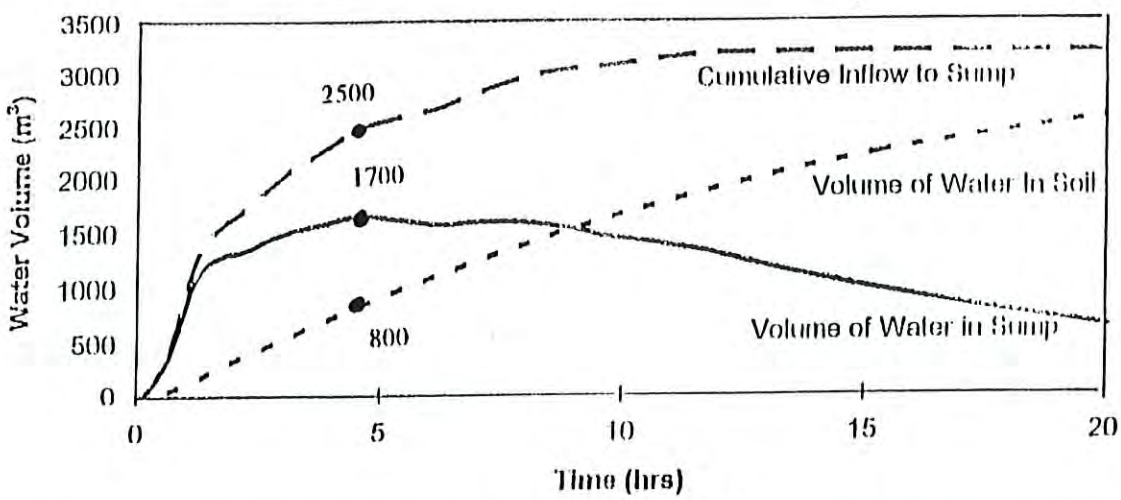
For a 12 hour duration storm Figure 4a illustrates the relationship between basin water level, wetting front depth and infiltration rate over time. The initially high rates of infiltration decline as the depth of the wetting front in the soil increases consistent with the observed data from McGregor Road Basin. The inflow rates to the basin peak in the first hour and over this time the infiltration rates in the basin stay relatively constant and even increase slightly which is against the general trend of an exponentially decreasing rate of infiltration over time. The plot of water volumes over time, Figure 4b, shows the basin volume increasing at a rate equal to the difference between the inflow and infiltration rates.

Figure 4a: Inflow model example 1 - Basin Water Level, Wetting Front Depth and Infiltration Rate Variation



Note: Maximum water level of 1.7 m occurs after 4.5 hours, with infiltration rate of 2.4 m/d and wetting front depth 0.55 m.

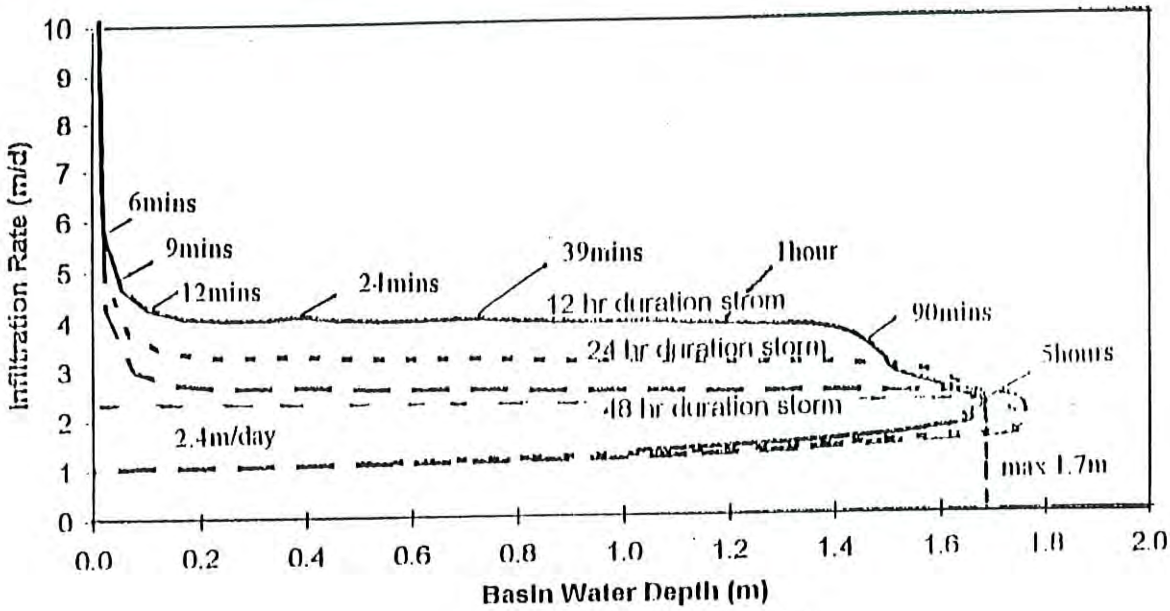
Figure 4b: Infiltration model example 1 - Cumulative Basin inflow, infiltration and Water Storage



Note: Maximum water volume in basin of 1700 m^3 occurs after 4.5 hours with corresponding to 2500 m^3 cumulative inflow and 800 m^3 cumulative infiltration (volume of water in soil).

Figure 4c shows infiltration rate plotted against basin water depth for storm durations of 12, 24 and 48 hours, all 10 year ARI. Time during the 12 hour storm is indicated from which it is clear that the initial large infiltration rates associated with small L_f values occur for approximately 12 minutes and therefore make minimal difference to the total basin storage requirement. Over the period for which inflow rates are large the increasing depth of water in the basin counteracts the effects of the increase in wetting front depth such that the infiltration rate stays virtually constant at a rate of 4 m/d over the first hour. The infiltration curves calculated using the Green-Ampt model tend to a infiltration rate of $K_{(RESAT)}$ which is set at 1, the constant rate specified by the PC-SUMP model.

Figure 4c



Note: For 12 hour storm maximum water depth of 1.7 m occurs with infiltration rate of 2.2 m/d.

5.0 DISCUSSION

We believe that using a variable infiltration rate as estimated with the Green-Ampt model will significantly improve the accuracy of designing storage capacities above that of models in which the infiltration rate is assumed constant during a storm event. A simulation model such as INFIL in which the rate of infiltration is variable allows both calculation of required storage capacities of retention basins as well as more detailed studies of the infiltration process to be performed.

That the capacities of drainage basins are currently above drainage requirements is argued as even in storm events equivalent to ARI of 100 years, such as the 8-9 of February 1992, very few basins in the metropolitan area were recorded as having overflowed. Generally in instances where basins have a safe overflow area such as public open space and road reserves then basin design capacities are for ARI's of 10 years. When these basins fail to flood in a 100 year storm then there is clearly a case for overdesign. The costs associated with this overdesign may be substantial particularly in developments where space is critical.

As a component of Water Sensitive Urban Design, infiltration in a spatially uniform manner is preferable, so that with better estimates of critical storage capacities we can design smaller basins but distribute them more evenly across catchments. Smaller basins receiving lower inflow volumes of stormwater have been identified as being of lower potential risk in terms of pollution to groundwater supplies. By maintaining an even spatial distribution of recharge to the groundwater across catchments the natural water balance at some of our urban lakes can be maintained or re-established and one constraint in locating basins in this manner are suitable sites, some of which may be overlooked due to inefficient basin design procedures.

The higher actual infiltration rates documented in this paper are probably most significant for basins which have small contributing catchments and small basin sizes, the effect being proportionately less for larger catchments and larger basin sizes for which the critical storm duration will be longer. However in absolute terms the land area which could be made available for other purposes other than drainage requirements could well be greater for the larger catchments and basins.

Infiltration in trenches and swale drains, which are effectively long, narrow basins can also be performed with the INFIL model.

6.0 CONCLUSION

Observed data on infiltration rates in Perth sumps indicates that infiltration rate varies considerably during storm events from a high initial value tending to a constant value at long time.

The PC-SUMP model (Main Roads, 1992) assumes a conservatively low and constant estimate of infiltration rate compared with observed data.

A new model INFIL which simulates infiltration events and allows for varying infiltration rates to be included in the design procedure leads to significantly smaller basin sizes. For the example basin described in the paper the volume required is 2100 m^3 compared with 3400 m^3 calculated with an alternative model PC-SUMP.

A review of basin size requirements for many Perth sumps is probably justified.

Other Perth retention basins should be instrumented for continuous water level measurement to verify the INFIL model parameters.

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APPENDIX B

Davies J. R., Van Hall S. (1997) Design of Stormwater Infiltration Basins with Shallow Water Tables Comparison of Models – MODRET and PCSUMP

Design of Stormwater Infiltration Basins with Shallow Water Tables Comparison of Models – MODRET and PCSUMP

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Summary: The highly permeable sandy soils of the Swan Coastal Plain in Western Australia allow infiltration of stormwater to be a Best Management Practice (BMP). Data collected by two local councils suggest that infiltration basins in Perth are overdesigned. This study investigates two infiltration basin design models for areas of shallow groundwater. The current local standard infiltration basin design software, PCSUMP, is seen to be conservative and may preclude sites that may be adequately sized. This will result in polluted water being discharged to receiving water bodies rather than being infiltrated. MODRET models the infiltration processes more thoroughly and results in best estimate basin design.

1.0 INTRODUCTION

Stormwater infiltration is a common practice along the Swan Coastal Plain of Western Australia particularly between the urban centres of Wanneroo, Perth and Mandurah, due to the highly permeable sandy soils and sufficient depth to water table in many locations.

During February 1992 rainfall exceeded the 100 year average recurrence interval (ARI) over durations of 3 to 24 hours over most of Perth (1). As a consequence City of Melville commenced monitoring the performance of several infiltration basins and the City of Stirling measured peak water levels during the February storm. These data allow alternative infiltration models MODRET, developed by Andreyev Engineering (2) and PCSUMP, developed by Main Roads Western Australia (3) to be tested and evaluated for shallow water table situations.

For deep water table situations a comparison between PCSUMP and another model INFIL has been reported on (4).

2.0 MODEL DESCRIPTION

2.1 General

Both MODRET and PCSUMP allow for either rectangular or user defined inflow hydrographs to be used. The essential difference between the models is that MODRET is a three dimensional finite difference numerical model which allows for infiltrated water to move horizontally below the water table over a specified aquifer thickness with increasing radius of influence with time (Figure 1), whereas PCSUMP uses an approximation to radial flow well equations assuming that the water table itself is an impermeable surface and that the radius of influence is constant. In addition MODRET takes account of the unsaturated soil beneath the basin and its capacity for infiltration whereas PCSUMP assumes the soil profile is saturated initially beneath a basin.

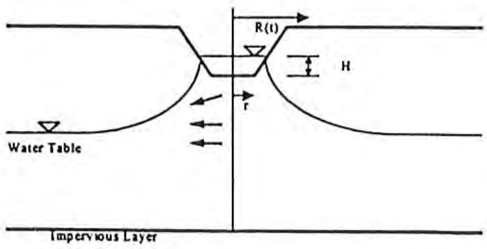

Figure 1a: MODRET Water Table Model

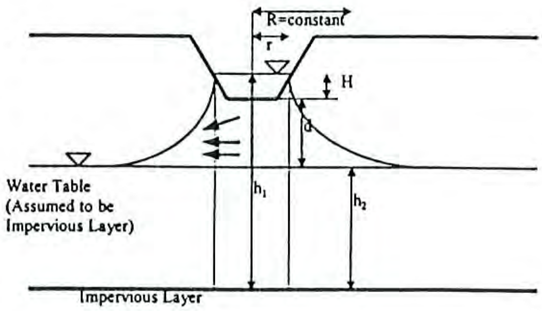

Figure 1b: PCSUMP Shallow Water Table Log Model

Figure 2 shows typical simulated outflow (infiltration) hydrographs from the two models.

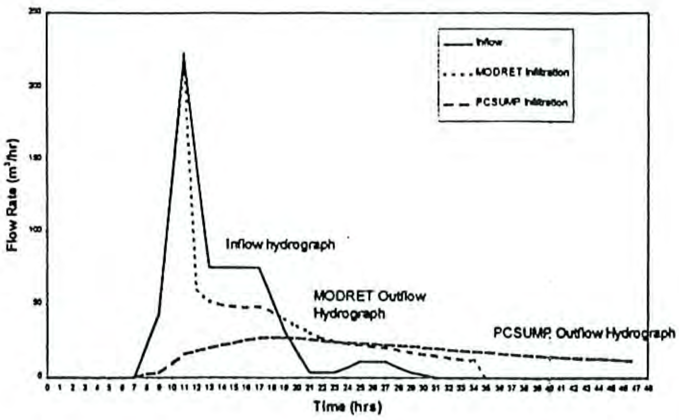

Figure 2: Schematic of basin Inflow and Outflow Hydrographs

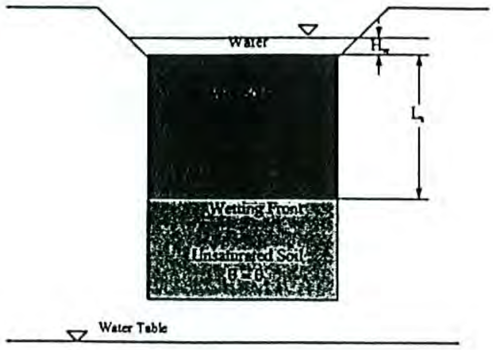

Figure 3: MODRET Unsaturated Flow Model

2.2 MODRET Model

2.2.1 MODRET Unsaturated Infiltration Analysis

MODRET models infiltration in the unsaturated zone as the movement of a sharp wetting front below a basin. A modified

Green and Ampt infiltration equation see Bras (5) is used, see Figure 3. This equation applies over the plan area of the water within the basin with no lateral movement. The original Green and Ampt equation is

$$I = K_{VU}\frac{H + L_S + \psi}{L_S} \qquad (1)$$

where,
K_{VU} is unsaturated vertical hydraulic conductivity (m/day)
H is depth of water in the basin (m)
L_S is depth of wetting front below basin bottom (m)
ψ is wetting front suction (negative) head (m), typically 0.1 to 0.3 for sands

During runoff events into basins the depth of ponded water H is typically greater than or equal to the magnitude of the wetting front suction ψ. MODRET conservatively assumes that these two terms are equal (i.e H = ψ), such that (1) reduces to $I = K_{VU}$ This assumption also simplifies the equation for the time for the wetting front to reach the water table, $\Delta t = \dfrac{fh_b}{K_{VU}}$

where
f is effective storage coefficient of the soil.
h_b is depth to the groundwater table from the basin bottom.

MODRET includes a safety factor (FS) to allow for pond bottom siltation/clogging such that the design infiltration rate is $I_d = K_{VU}/FS$ and $\Delta t = \dfrac{fh_b}{I_d}$.

from which the duration and rate of unsaturated infiltration can be deduced. The MODRET manual recommends multiplying the vertical saturated hydraulic conductivity K_S by 2/3 to estimate the unsaturated vertical hydraulic conductivity K_{VU} in the transmission zone, based on Bouwer (6).

2.2.2 MODRET Saturated Infiltration Analysis

Once the wetting front has reached the water table MODRET then models the saturated horizontal flow, which is a function of the lateral dissipation through the saturated aquifer (Figure 1a). MODRET uses the 3D Finite Difference Groundwater Flow Model MODFLOW, McDonald & Harbaugh (7) to estimate horizontal infiltration and groundwater contours, including basin water levels.

2.3 PCSUMP Shallow Water Table Model

2.3.1 General

PCSUMP inflow hydrographs are created for user defined ARI's using a simplified Rational Method or based on actual rainfall data as in this study. The model has three options:

1. Shallow water table log model
2. Shallow water table clogged model
3. Deep water table model

2.3.2 Saturated Infiltration Analysis

PCSUMP assumes circular basin geometry and that the outflow due to infiltration is based on a steady state radial flow equation in an infinite aquifer:

$$q_o = \frac{K\pi(h_1^2 - h_2^2)}{\ln(\frac{R}{r})} \qquad (2)$$

where
q_o is rate of outflow from the basin due to infiltration (m^3/s)
K is hydraulic conductivity (m/day)
h_1, h_2, R and r are defined in Figure 1b (m)

By assuming the water table is an impermeable layer, 2 is conservatively simplified to

$$q_o = \frac{K\pi(H+d)^2}{\ln(\frac{R}{r})} \tag{3}$$

where

$$R = 2r + 50(H+d)K \tag{4}$$

Since it is a steady state model it assumes that the soil profile between the base of the basin and the water table is saturated at the beginning of the storm, such that there is no initial unsaturated soil storage. PCSUMP conservatively assumes a value of 1/3 of the saturated hydraulic conductivity input by the user.

3.0 CATCHMENT DESCRIPTIONS

3.1 Pinaster Street, City of Stirling

The catchment is residential with a piped drainage system to the basin. The water table was estimated to be 2.6 m below the base of the basin prior to the February 1992 storm event, HGM (8). The volumetric runoff coefficient was assumed to be 0.6. Basin characteristics are presented in Table 1.

3.2 Swan Road, City of Melville

The catchment is residential with a piped drainage system to the basin and a volumetric runoff coefficient assumed to be 0.55, JDA (12). The basin was instrumented with a water level recorder and data logger between 17/6/93 and 9/8/94. The basin base is approximately at the elevation of the water table. The basin was redesigned and reconfigured following the February 1992 storm during which the peak water level was 6.17 mAHD. The original storage capacity to 6.17 mAHD was 650 m^3 and was increased during 1992 to 910 m^3 at 6.0 mAHD. The invert level is 3.5 mAHD compared with the maximum water table of 3.8 mAHD. Basin characteristics are presented in Table 1.

4.0 RAINFALL AND BASIN WATER LEVEL DATA

4.1 Pinaster Street Basin

Rainfall data for the February 1992 event was between 20 and 100 year average recurrence interval (ARI) over durations of 2 to 24 hours (Figure 4). Basin water level rose from 2 m below the base to 2.1 m above the base, i.e. 22.96 mAHD equivalent to a storage of approximately of 915 m^3 (Figure 5).

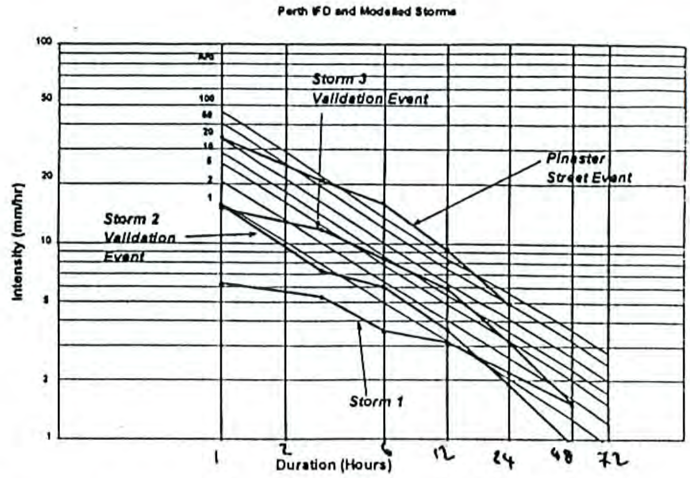

Figure 4: Perth IFD and Modelled Storms

Table 1: Basin Parameters

Parameter	Pinaster Street	Swan Road
Catchment Area (ha)	5.85	2.7
Base Elevation (mAHD)	20.9	3.5
Top Water Level Elevation, TWL (mAHD)	24.1	6.0
Maximum Recorded Groundwater Elevation (mAHD)	18.3	3.8
Elevation of Aquifer Base (mAHD)	-15	-25
Base Area (m^2)	216	310
Basin Volume at TWL (m^3)	1875	910
D10	0.32 mm	0.20 mm
Estimation Method (K/m/d)		
Hazen's Formula (C=0.01) (9)	88	35 to 42
Hazen's Formula (C=0.015) (9)	133	52 to 63
Slichter Formula (10)	21	5.7 to 6.9
Disc Permeameter (11)	31.5	5.2

4.2 Swan Road Basin

The three storms resulting in highest water levels during the monitored period of 1994 were selected (Table 2).

Figure 4 shows Storms 1 and 2 were frequently occurring storms of low intensity (ARI < 2 yrs), whereas Storm 3 had an ARI of 10 years for durations between 8 and 16 hours.

Table 2: Swan Road Rainfall and Peak Water Level Data for Modelled Storm Events

Storm Date	Rainfall (mm)	Peak Water Level (mAHD)	Initial Water Table (mAHD)
Storm 1: 22 to 23/5/94	74	4.0	2.30
Storm 2: 30/6 to 1/7/94	46.1	4.69	2.90
Storm 3: 3 to 4/8/94	75.3	4.48	2.95

Note: Top water level 6.0 mAHD

5.0 MODEL EVALUATION

The values of hydraulic conductivity K referred to in this chapter are values actually used within the model rather than input values.

Pinaster Street Storm February 1992 (Figure 5): MODRET was calibrated to the peak water level of 22.96 mAHD with a value of K of 13.8 m/day which compares with values ranging between 21 and 133 m/day for particle size distribution analyses to 31.5 m/day for permeameter readings, HGM (8). The observed and modelled water levels are presented in Table 3.

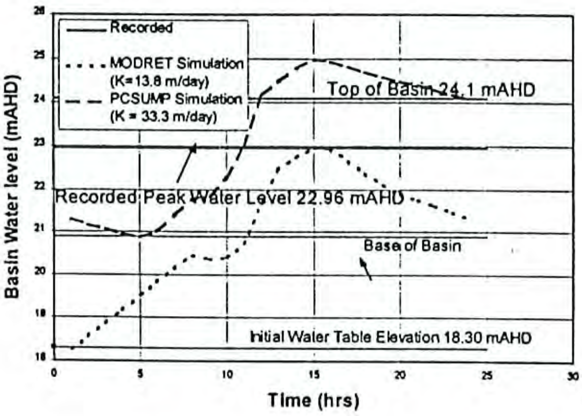

Figure 5: Model Validation: Pinaster Street Basin: 8 February 1992

It was not possible to calibrate PCSUMP to the recorded peak water level. Even using the maximum K value allowed by the model of 33 m/day (100 m/day input value) the model simulated a basin overflow with a water level of 24.96 mAHD (or an overestimation of 95%), which would have resulted in more than twice the recorded storage.

Swan Road Storm 1 (Figure 6): MODRET K was adjusted to 3.1 m/day to match the recorded peak water level of 4.0 mAHD. The calibrated K compares with 5.2 m/day from disc permeameter and 5.7 to 63 m/day from particle size distribution analyses. In addition it can be seen that the calibrated MODRET model is reasonably well matched with the recorded water level throughout the 48 hour period, including the initial phase when the water table is below the base of the basin. PCSUMP could not be calibrated even with K of 33 m/day.

The models were both run using these calibrated K values for two further storms to validate the models. Reproduction of peak water levels for these storms would indicate that parameter sets used described the basin correctly.

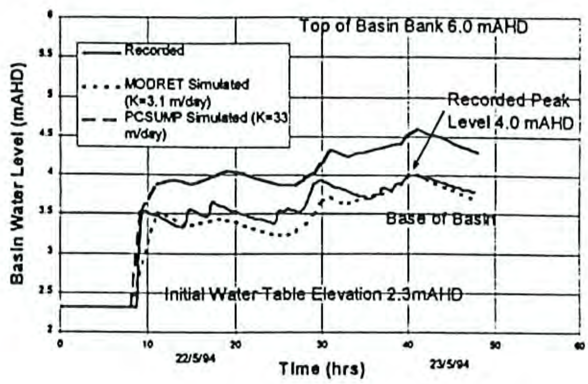

Figure 6: Swan Road Basin: Model Calibration Storm1: 22-23 May 1194

Swan Road Storm 2 (Figure 7): Peak water level for storm 2 was estimated to be 4.33 mAHD compared with the recorded peak of 4.69 mAHD.

PCSUMP modelled peak water level was 4.88 mAHD using the maximum allowable K of 33 m/day.

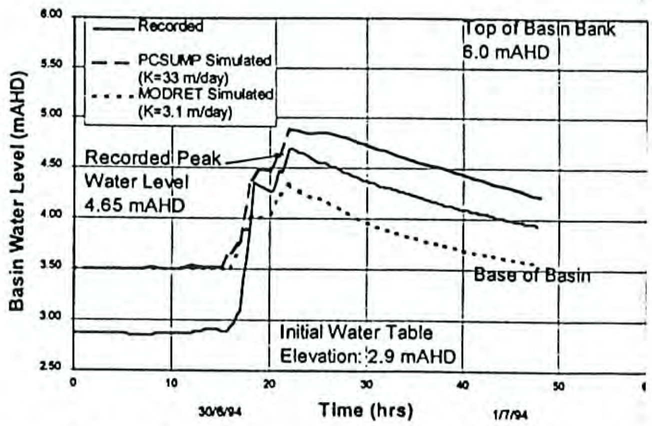

Figure 7: Swan Road Basin: Model Validation Storm 2 30 June – 1 July 1994

Swan Road Storm 3 (Figure 8): Peak water level for Storm 2 was estimated to be 4.84 mAHD compared with the recorded peak of 4.48 mAHD.

The PCSUMP peak level of 5.54 mAHD was 108% greater than the recorded peak recorded water level. The PCSUMP simulation of this storm calculated infiltration over the storm period to be 18% below that calculated from runoff estimation and final recorded basin water levels.

PCSUMP requires more than an order of magnitude greater K than MODRET in order to simulate recorded water levels in this shallow water table basin.

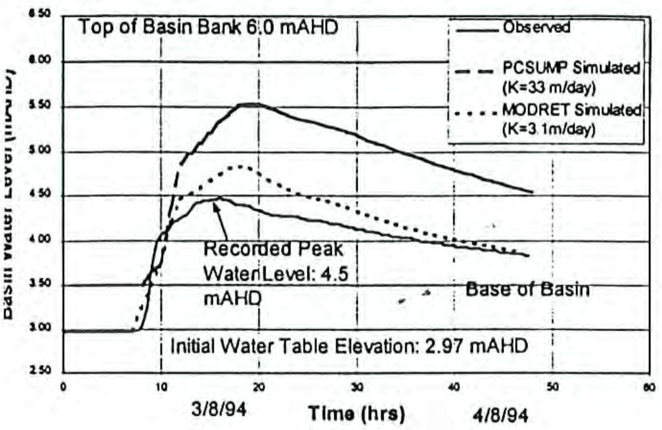

Figure 8: Swan Road Basin: Model Validation: Storm 3 3-4 August 1994

validated for storms with ARI's of the same magnitude commonly used for of basin design methodology.

For PCSUMP the large overestimation of the 10 year ARI event (Storm 3 at Swan Road) and the 100 year event (Pinaster Street February 1992 Storm) water levels indicate that this model is overly conservative for shallow water table basin design.

An implication of these results is that traditional infiltration basin design using PCSUMP for shallow water table locations, precludes sites which are in fact adequately sized. In other words stormwater is being discharged to receiving water bodies (rivers, estuaries etc.) when infiltration could be the preferred management practice. This is highly relevant where surface waters are threatened by eutrophication and there is a growing emphasis on adoption of Best Management Practices (BMP's).

Table 3: Recorded and Modelled Water Levels

Basin and Event	Observed Water Level (mAHD)	MODRET Water Level (mAHD)	K (m/day)	PCSUMP Water Level (mAHD)	K (m/day)
Pinaster Street 8/2/92	22.96	22.96	13.8	24.96	33
Swan Road Storm 2: 30/6 to 1/7/94	4.69	4.33(-30%)	3.1	4.88 (+16%)	33
Swan Road Storm 3: 3 to 4/8/97	4.48	4.84(+37%)	3.1	5.54 (+108%)	33

Note: Numbers in brackets indicate percentage difference of simulated basin water depth to observed water depth.

6.0 CONCLUSIONS

Data used in this study was collected by two local city councils as a reaction to a 100 year ARI event in February 1992. Little or no flood damage occurred during this event which indicated that the existing drainage systems were overdesigned. Of the data collected, two basins could be defined as shallow water table basins, namely Pinaster Street basin, City of Stirling and Swan Road basin, City of Melville. For the simulations at both Pinaster Street and Swan Road basins, MODRET calibrated K values were more realistic than those produced using PCSUMP. For both basins it was impossible to calibrate PCSUMP due to the K values required being larger than the maximum allowed by the program (33 m/day). The calibrated K for MODRET was 13.8 m/day at Pinaster Street and 3.1 m/day at Swan Road. These values compare favourably with the disc permeameter measured infiltration rates of 31.5 m/day and 5.2 m/day respectively.

For "best estimates" to be made in designing stormwater retention basins, designers should use realistic, measurable parameters as input values. The realistic values returned by MODRET in this study indicate that it can be used to provide such best estimates based on field measured values.

For Swan Road Basin the results of the validation showed that MODRET was best validated for Storm 3, which had an ARI of 10 years. This is significant in that MODRET is seen to be

7.0 RECOMMENDATIONS

For areas where the water table is shallow (less than 4 m) MODRET provides the "best estimate" of the two models investigated in this study. This is due to its modelling of the processes involved more accurately and completely. The study shows this best in that the calibrated and validated hydraulic conductivity value obtained by MODRET was of a realistic magnitude and similar to infiltration rates measured at the sites with a disc permeameter.

PCSUMP shallow water table model required unrealistically large K values to model the storms and is not recommended for design purposes.

Therefore for best estimate basin design MODRET should be used with inputs of field measured hydraulic conductivity values using a disc permeameter and depth to the water table.

Determination of the relevant BMP for a given catchment requires the use of an appropriate model.

8.0 ACKNOWLEDGEMENTS

Graham Whithers, formerly of City of Melville, for discussing catchment and basin details. City of Stirling for provision of data.

APPENDIX C

Summary of Investigation by JDA on Infiltration Basins in WA

Appendix C: Summary of Investigation by JDA on Infiltrations Basins in WA.

Year	Location	Client	JDA Ref. No.	Local Authority
2010-2011	Esperance: port shed stormwater management	Cliffs NR Mining	J4587	Shire of Esperance
2009	Churchlands ECU campus: MODRET infiltration basin check	City of Stirling	J4368	City of Stirling
2008	Dawesville development	C & H Consulting Engineers Pty Ltd	J4099	City of Mandurah
2005-2008	Highbury Park, Baldivis	Acalinovich & Company - changed to Urban Endeavour	J3531	City of Rockingham
2007	Millet Selina Community Park: basin undergrounding infiltration analysis	City of Stirling	J3986	City of Stirling
2007	Sumps Undergrounding Suitability Study	City of Stirling	J3615	City of Stirling
2006	Australian Marine Complex, Henderson	Douglas Partners	J3917	City of Cockburn
2006	Lot 18 - Sixty Eight Rd, Baldivis	Fairgroup Pty Ltd	J3914	City of Rockingham
2006	Geraldton: Sunset Beach infiltration basin	Maunsell Australia Pty Ltd (Geraldton)	J3888	City of Geraldton
2006	Ganangara Rd Madeley, Infiltration Basin Design	Watson Engineering Pty Ltd	J3807	City of Wanneroo
2006	Lot 22 Smirk Rd, Baldivis	Urban Endeavour	J3784	City of Rockingham
2006	Fremantle Ports Authority: Kwinana Bulk Terminal infiltration basin	Fremantle Ports	J3762	City of Fremantle
2004-2006	Iluka Sump Monitoring	Cossill & Webley	J3466	City of Joondalup
2005	River Gums Estate - Baldivis	TABEC	J3710	City of Rockingham
2005	Brookland Grove Canning Vale Basin C2 Hydrological Investigation	TABEC	J3708	City of Canning
2005	Burns Beach Infiltration Basins	TABEC	J3703	City of Joondalup
2005	Geraldton - Southern Bypass	Bruechle, Gilchrist &	J3624	City of

		Evans		Geraldton
2005	Yanchep Infiltration Testing	Cossill & Webley	J3614	City of Wanneroo
2005	Meadow Springs, Mandurah	Wood & Grieve	J3595	City of Mandurah
2004	Carramar Park Infiltration Testing	Maunsell Australia Pty Ltd	J3448	City of Wanneroo
2004	Ashton Heights, Pinjar	TABEC	J3444	City of Wanneroo
2004	Annie St & O'Hara St Sumps, Beaconsfield	City of Fremantle	J3416	City of Fremantle
2004	Ocean Lagoon Sump Testing	Maunsell Australia Pty Ltd	J3390	City of Wanneroo
2004	Investigation and Recommendation On-Site Stormwater Disposal Standard	City of Stirling	J3373	City of Stirling
2004	Archer and Kemp St, Pearsall Development	Ewing Consulting Engineers Pty Ltd	J3359	City of Wanneroo
2004	Lots 45-49 Wanneroo Road, Madeley Investigation	Watson Engineering Pty Ltd	J3358	City of Wanneroo
2004	Fremantle Sump Permeability	City of Fremantle	J3289	City of Fremantle
2003	Seascapes, Mandurah	Cossill & Webley	J3318	City of Mandurah
2003	Infiltration Basin, City of Joondalup	Cossill & Webley	J3305	City of Joondalup
2003	Secret Harbour-Australand Land	Australand Holdings Ltd	J3287	City of Rockingham
2003	Lots 9 & 10 Backshall Place, Wanneroo	Ewing Consulting Engineers Pty Ltd	J3279	City of Wanneroo
2003	Cook Avenue Primary School, Hillarys	Ewing Consulting Engineers Pty Ltd	J3183	City of Joondalup
2003	Geraldton Southern Transport Corridor	Main Roads WA	J3133	City of Geraldton
2003	Lakelands, Mandurah	Sinclair Knight Merz	J3129	City of Mandurah
2002-2003	Iluka Sump	Cossill & Webley	J3087	City of Joondalup
2002-2003	Panorama Gardens Subdivision, Beeliar	Cossill & Webley	J3078	City of Cockburn
2003	Ray Counsel Sump, Victoria St, Mosman Park	Town of Mosman Park	J3075	Town of Mosman Park

2002-2003	Brighton Sizing of Infiltration Basins	Cossill & Webley	J3069	City of Wanneroo
2002-2003	Retirement Village, Erskine Mandurah: MODRET modelling	Dennis Price & Miller	J2952	City of Mandurah
1996-2003	Gordon Rd, Mandurah	Cossill & Webley	J2287	City of Mandurah
2002	Anchorage, Rockingham	Cossill & Webley	J3080	City of Rockingham
2002	Review of City of Wanneroo Infiltration Basin Guidelines	Stockland	J3073	City of Wanneroo
2002	Barfield Road, Banjup	Peet & Company Ltd	J2959	City of Cockburn
2001	Merriwa/Seagrove Sump	Dennis Price & Miller	J2886	City of Wanneroo
2001	Baldivis Development Basin Sizing	EGIS Consulting	J2809	City of Rockingham
2001	College Grove Subdivision: Bunbury, Infiltration Analysis	Thompson McRobert Edgeloe (TME) (Bunbury)	J2801	City of Bunbury
1999-2000	UWA Land Shenton Park	Cossill & Webley	J2653	City of Subiaco
2000	Kwinana Freeway Basins	GHD Pty Ltd	J2640	Town of Kwinana
2000	Nedland's Drainage Issues	City of Nedlands	J2599	City of Nedlands
1999-2000	Lot 402 Rae Road, Rockingham	Cossill & Webley	J2590	City of Rockingham
2000	Sump Redesign: Mosman Park	Town of Mosman Park	J2566	Town of Mosman Park
1999	Lots 1, 2, 3 Wanneroo Rd, Wangara	Cossill & Webley	J2594	City of Wanneroo
1999	The Avenues, Canning Vale	Cossill & Webley	J2565	City of Gosnells
1999	Inglewood Urban Infill	Water Corporation	J2557	City of Stirling
1999	Westminster Street Sump	Town of Victoria Park	J2543	Town of Victoria Park
1999	Windsor Hills	Cossill & Webley	J2527	Town of Kwinana
1999	Annois Road, Cockburn	Cossill & Webley	J2517	City of Cockburn
1999	Regent Waters Infiltration Basin	Cossill & Webley	J2499	City of Wanneroo
1997-1999	Seascapes, Mandurah	Cossill & Webley	J2283	City of Mandurah

1998	MODRET: Mt Henry Como	Cossill & Webley	J2489	City of South Perth
1998	Subiaco Redevelopment: Soakwell Infiltration Rates	Soil & Rock Engineering (Coffey Geosciences)	J2390	City of Subiaco
1998	Preliminary Sizing of Sump at Mandurah	Bruechle, Gilchrist & Evans	J2382	City of Mandurah
1998	Stormwater Basin cnr Westminster St & Albany Hwy, Victoria Park	Purely Entertainment Pty Ltd	J2373	Town of Victoria Park
1998	Infiltration Basin, Ecclesbourne St, Mosman Park	Town of Mosman Park	J2354	Town of Mosman Park
1998	INFIL Program, Copy of	SHAWMAC Pty Ltd	J2350	N/A
1997-1998	Review Design of Channel 9 Studio Sump	Channel Nine	J2344	City of Stirling
1997	Atlantis Drainage Cell Infiltration Test	DS Agencies	J2310	N/A
1996	INFIL Retention Basin (Sump) Design	JDA Consultant Hydrologists	J2235	N/A
1995	McGregor Road Sump Redesign	City of Melville	J2232	City of Melville
1992	ECU Bunbury	Hydro-Plan Pty Ltd	J2113	City of Bunbury
1992	Falcon Drainage	GHD Pty Ltd	J2108	N/A

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