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Defining reliability for rainwater harvesting systems

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Abstract: Rainwater harvesting systems such as roof-raintank water harvesting systems for internal domestic use, and artificial catchment rainfall-runoff harvesting systems connected to farm dams for agricultural purposes, have many advantages as sustainable water resources. Rainwater harvesting systems can provide adequate high quality water across significant areas of Western Australia (WA) that do not have access to the comprehensive water supply scheme. Declining rainfall trends in south-western Australia due to climate variability make rainwater harvesting systems more significant as a water resource for isolated farms and communities in arid and semi-arid areas (wheat-belt and pastoral areas) in WA.

The design of catchment-dam systems, especially size of dam and catchment, will impact the efficiency and cost of construction of the system, in arid and semi-arid areas of WA and they are generally determined to satisfy the targeted demand reliability of catchment-dam systems. The reliability of catchment-dam systems can be defined as the probability that the system will supply a required demand of water during a specified time. The result of water balance simulations for the design of harvesting system can be affected by time interval for the water balance simulation such as daily, weekly or monthly calculation. The practical reliability of catchment-dam systems can be defined using available water supply demand or period with water supply failure. Determination of the modelling time interval and the definition of reliability will therefore be a critical design factor for water supplies.

Evaporation from a farm dam will be affected not only by weather conditions (e.g. temperature, wind) but also by dam design characteristics such as surface area. Therefore, catchment-dam designs will return different water balance simulation results than those for roof-raintank systems, in arid and semi-arid climates. Farm dams undergo significant water loss through evaporation while roof-raintank systems (if capped) are unaffected by evaporative losses. The definition of the reliability of a rainwater harvesting system is a significant factor in determining the demand reliability that may result in the under-estimation or over-estimation of supply efficacy and reliability, particularly in dry climates.

Simulation process for the reliability of rainwater harvesting system has no great difference depending on which modeling time interval and the definition of reliability are applied. However, there is the variability in the calculated reliability considerably depending on regional conditions. This paper assesses this variability in the reliability of catchment-dam systems through an evaluation of the influence of the modelling time interval for the water balance simulations; and the definition of reliability. The reliability of catchment-dam systems for ten sites located in dryland agricultural areas of WA are evaluated using daily and weekly modelling time intervals and five definitions of reliability (volume-based estimation, daily, weekly, monthly, and annual period-based estimations).

Evaluation results indicate that using annual period-based estimation for reliability is not suitable for arid and semi-arid areas in WA due to the risk of under-estimation. When the cycle of agricultural activity and water demand in WA is considered, volume-based estimation, and daily and weekly period-based estimations have the risk of over-estimation. Therefore, the use of monthly period-based estimation is recommended for the design of artificial water harvesting systems in the dryland agricultural areas in south west WA.

Keywords: *Rainwater Harvesting System, Water Balance Simulation, Reliability.*

1. INTRODUCTION

Small scale agricultural reservoirs or water tanks are still the major water supply sources for almost all rural areas in Western Australia (WA), in spite of the fact that 90% of the population in WA are serviced by the comprehensive water supply scheme and local water supply schemes (Water Corporation, WA, 2005). Recharging these water storages by captured rainfall-runoff from natural catchments or carted water by using trucks is neither efficient, nor cost effective. Rainwater harvesting systems (RHS) such as artificial catchment-dam rainfall-runoff harvesting systems connected to farm dams have many advantages as sustainable water resources. RHS can provide sufficient high quality water across significant areas of WA that do not have access to the comprehensive water supply scheme. Declining rainfall trends in south-western Australia (Bureau of Meteorology, Australia, 2011) associated with climate change make catchment-dam systems and their designed reliability more significant as a water resource for isolated farms and communities in arid and semi-arid areas in WA (Baek and Coles, 2011).

The design of the key components of RHSs such as the artificial catchment, storage dam, and the connecting channel impacts the efficiency and the cost of these systems. In south-western Australia rainfall is delivered as banded frontal patterns during the winter season or through intense summer thunderstorm activity (Baek and Coles, 2011). Artificial catchments and storage dam design combinations are generally determined to satisfy a targeted demand reliability. Reliability is defined as the probability that the dam-catchment combination will supply a required demand for water during a specified time. Available water supply can be calculated by water balance simulation based on catchment size, dam volume, rainfall, water demand, and evaporation losses. The resultant water balance simulation will be applied to estimate the reliability.

The result of water balance simulation for the design of a RHS can be affected by the modelling time interval for the water balance simulation such as daily, weekly or monthly calculation intervals (Cowden et al., 2008; Basinger et al., 2010; and Baek, 2010). Practical reliability of the system can be defined using available water supply amount (volume-based estimation, VE) or the time period with water supply failure (period-based estimation, PE) (Baek and Coles, 2011). Determination of the modelling time interval and definition of reliability won't make great difference in simulation process for the design of RHS such as computational time. But they will be critical factors for water supply design. For example, variation of reliability caused by variation in modelling time intervals has been reported by previous studies (Basinger et al., 2010; and Kahinda et al., 2010) but these studies mainly focused on roof-raintank systems. Evaporation from a farm dam will be affected not only by climatic conditions (temperature, wind, etc) but also by dam characteristics such as size, volume and exposure (Farmer and Coles, 2003). Farm dams also undergo significant water loss through evaporation while roof-raintank systems (if capped) are unaffected by evaporative losses (Khastagir and Jayasuriya, 2010). Therefore, farm dams will demonstrate a different pattern of variance for water balance simulations than roof-raintank systems. The definition of the reliability of a water supply (VE or PE) will also generate a wide range of the reliability of the system. Therefore, appropriate definition of the reliability of a catchment-dam system must be the first critical design factor evaluated and defined.

Suitable modeling time interval or definition of reliability for a specific region must be determined not only by calculated reliability but also by regional condition considered by decision maker. This paper assesses the variability in the reliability of catchment-dam systems through an evaluation of the influence of the modelling time interval for the water balance simulations and the definition of reliability. The reliability of catchment-dam systems for ten sites located in dryland agricultural areas of WA is evaluated using daily and weekly modelling time intervals and five definitions of reliability.

2. ROADED CATCHMENTS

A roaded catchment (Figure 1) will be used to represent the artificial catchment in the simulation study. Roaded catchments in various forms have been utilised for harvesting rainfall-runoff in WA since the 1960s (Coles et al., 2004) to improve the reliability and efficiency of natural catchments by grading, compacting and sealing the surface of the catchment. The roaded catchment is suited to the low and moderate intensity rainfall patterns in WA and it is presumed that between 2,000~3,000 roaded catchments have been constructed and used in WA for agricultural purposes. Figure 2 shows the structure of a typical farm dam used for water storage (Dept. of Agriculture, WA, 2005). A maximum dam depth of 5.0 m and batter slope of 1:3 are generally applied to the design of a farm dam in the dryland agricultural areas of Western Australia (Stanton, 2005).

In the dryland agricultural areas of WA, defined as areas receiving less than 600 mm of rainfall per annum (Coles et al., 2000), summer evaporation rates range around 300 mm/month, and dam depth will decline by up to 70 mm, by evaporation through one week without rainfall. This change in dam depth will also cause reduced water surface area (Famer and Coles, 2004). For a farm dam, which has maximum storage volume of 3,000 m^3, maximum dam depth of 5.0 m and batter slope of 1:3, weekly evaporation loss simulations calculated using water surface area of 1st day of a week for the whole week; are greater than using water surface areas considering only daily change of dam depth by as much as 0.2~1.5 m[3]. Therefore, calculated reliability using weekly modelling time interval can be lower than that using a daily interval. However, as mentioned above, because extra rainfall can cover some proportion of water deficiencies during the week, calculated reliability using weekly interval will be greater than that using daily interval. The variation in deficiency patterns between daily and weekly intervals will be described later, and this analysis will be utilised to assess demand reliability.

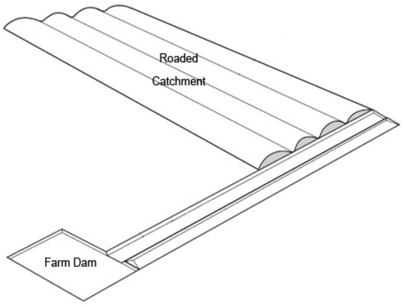


Figure 1. Catchment-dam system using a roaded catchment

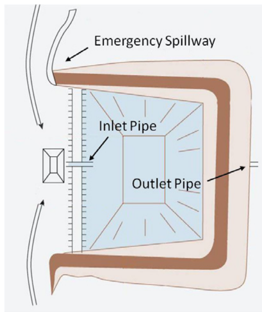


Figure 2. Structure of typical farm dam

3. WATER BALANCE SIMULATION AND RELIABILITY

3.1. Water Balance Simulation

Water balance simulations for the design of catchment-dam systems generally use a simple equation. The volume of rainwater maintained in the farm dam mainly depends on the runoff from a roaded catchment, the demand met from the rainwater, and the evaporation from the farm dam. To maintain reliability, enough water in the dam is required to supply the demand with minimum risk of the storage failing (i.e. being empty). The equation for water balance simulation used in this study is given in Eq. (1).

$$S_t = S_{t-1} + Q_t^{rc} + Q_t^{d} - D_t - E_t\ , \quad 0 \le S_t \le S^{\max} \tag{1}$$

where, S_t is the storage (dam) volume at the time period (t) for a given simulation, Q_t^{rc} is the runoff from the roaded catchment, Q_t^{d} is the direct rainfall amount to the dam, D_t is the total demand for water, E_t is the total evaporation from the dam and S^{max} is the maximum dam volume..

3.2. Definition of Reliability

Volume-based and period based estimations (VE and PE) are used to define the reliability for catchment-dam systems. VE (Eq. (2)) assesses the system reliability using available water supply and required water demand during the simulation period. PE (Eq. (3)) evaluates the system reliability using the total number of simulations and number of simulations in which water supply failure occurs.

$$R^{RHS} = \frac{\sum (D_t - De_t)}{\sum D_t} \tag{2}$$

$$R^{RHS} = \frac{(N^T - N^{failure})}{N^T} \tag{3}$$

where, R^{RHS} is the reliability of the catchment-dam system, D_t is the total demand for water on the t^{th} time period, De_t is the total deficiency for water, N^T is the total number of water balance simulations, and $N^{failure}$ is the total number of water balance simulations where the water supply has failed.

3.3. Variability in Reliability

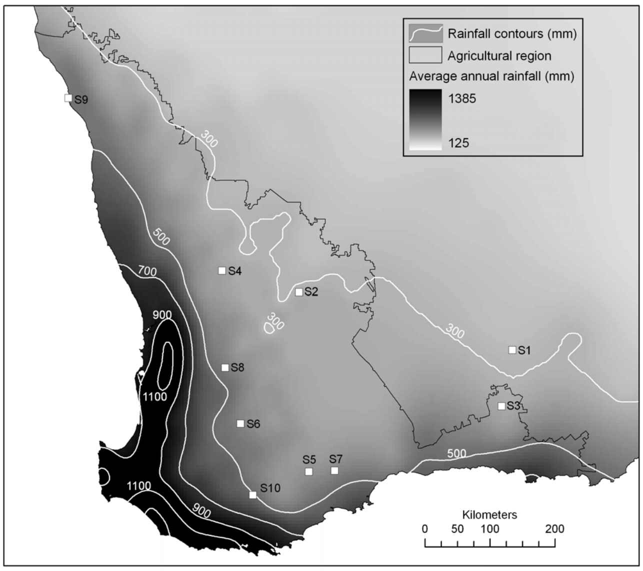
As mentioned, the result of water balance simulation for the design of catchment-dam systems can be affected by the modelling time interval (i.e. daily, weekly or monthly). The reliability calculated using longer intervals for the simulation is generally better(greater) than that of using shorter time frames intervals because additional stored rainfall can be carried forward during longer time simulations, and cover some proportion of water deficiencies for the extended simulation period. This is not possible during short time simulation runs. In addition, since agricultural activities generally have an annual cycle, the DAMCAT5 model (Baek, 2010), originally developed to assess demand-design reliability for livestock water supplies in dryland agricultural areas of south-western Australia by the Department of Agriculture, WA, adopts an annual PE for reliability estimation. For example, one week failure and ten weeks failures in one year will give the same reliabilities with DAMCAT5. However, the most critical issue resulting for annual based reliability estimation (annual PE) is the increased potential for the under-estimation of reliability. However, reliability using VE and daily or weekly PE may risk over-estimation of reliability based on the random characteristics of rainfall patterns (Baek and Coles, 2011). For example, a single day failure of water supply for every 12 months in a year, and 12 days failure for one month in one year will have a significantly different simulated reliability. Rainfall, evaporation and water demand patterns will influence this failure pattern and appropriate definition of the reliability is required to be determined depending on local consumption and climatic conditions.

Selection of the best option for the design of water harvesting systems is difficult as each method has both advantages and disadvantages. This is due to uncertainty inherent in the rainfall delivery to the water supply associated with inter-annual variability and drying trends induced by climate variability in the last two decades. Selection of the most appropriate simulation method such as VE or PE, and period (daily, weekly, monthly or annual) for PE is critical to determining the target demand reliability. In this study, the reliability of a catchment-dam system is defined using five different scenarios. Scenario 1 uses VE and Scenarios 2~5 are based on daily, weekly, monthly and annual PE, respectively. In addition, two modelling time intervals (i.e. daily and weekly) are used for the evaluation of reliability because monthly interval is not suitable for the water balance simulation for catchment-dam systems in arid and semi-arid areas due to the error caused by the difference in evaporation losses. DAMCAT5 model was modified to calculate these scenarios. Calculated results are compared to suggest suitable definition for the reliability for use in arid and semi-arid areas at WA.

4. APPLICATION AND DISCUSSION

4.1. Research Sites and Climate

Except for the northern region above Broome and some regions along the south-western coastline, almost all parts of WA are classed as arid or semi-arid areas whose annual average rainfall is less than 600 mm (Figure 3). However, there are many farms, vineyards and pastures in south-west parts in WA (named the Wheatbelt division and South West Division by Institution of Engineers, Australia (2001)) that are supplied with water from small to large on-farm dams, that have a wide range of rainwater harvesting (or contributing) catchments. Although farm dams are the major water source, an increasing number of dam or water supply failures or water shortages have occurred in recent years due to changes in climate, an associated decline in annual rainfall and/or a variation in rainfall delivery patterns. Ten sites, whose annual average rainfall ranges from 300 to 500 mm, have been selected from arid and semi-arid areas in WA (Figure 1), and the reliability of catchment-dam systems are evaluated using two modelling time intervals, daily and weekly and five reliability scenarios (previously described).



S1. Norseman
S2. Merredin
S3. Salmon Gums
S4. Dowerin
S5. Ongerup
S6. Wagin
S7. Jerramungup
S8. Pingelly
S9. Geraldton
S10. Cranbrook

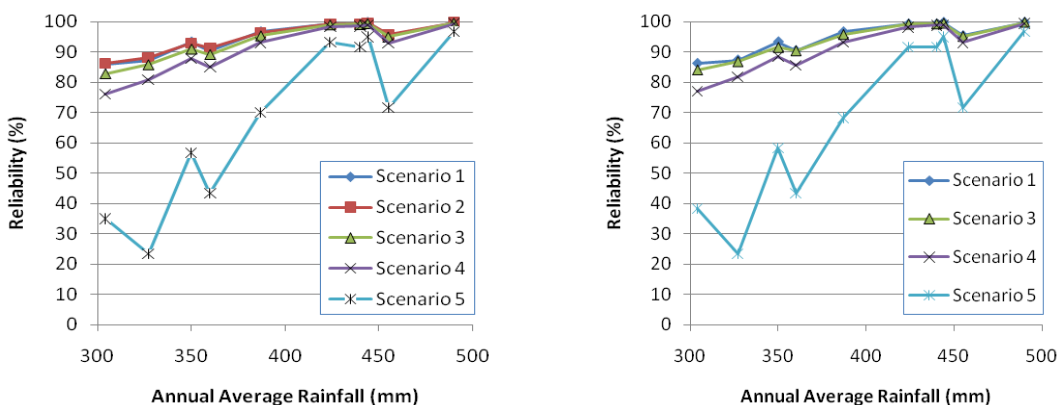
Figure 3. Annual average rainfall of WA and Research sites

4.2. Reliability Calculation

The reliability of catchment-dam systems for a simulation period of 60 years is calculated using daily rainfall data from 1950 to 2010. Water balance simulation for the first year (1950) was excluded in the reliability calculation. For the purpose of these simulations a maximum dam volume of 2,000 m^3 and the roaded catchment (artificial catchment) area of 1.5 ha are assumed. (In this study, it was accepted that dam and catchment designs will vary with site conditions, rainfall, evaporation and demand. The sizes given are for consistency in design performance evaluation rather than adaptation to local conditions and demand) The rainfall-runoff threshold value, which is for calculation of rainfall loss prior to runoff generation was set at 10 mm/day based on Laing (1981), and Baek (2010). DAMCAT5 model (Baek, 2010) provides regional daily livestock drinking rate (L/day) and monthly dam evaporation rate (mm/month) based on the results of Luke (1988) and they are used to calculate water demand and evaporation. Number of livestock was assumed as 1,000. To include the variation of evaporation associated with variable dam surface area, it is also assumed that the farm dam has rectangular plan shape, batter slope of 1:3, and initial storage of 30% to maximum dam volume. Table 1 and Figure 4 display the simulated results.

Table 1. Comparisons of reliability depending on the different reliability scenario

Site (ID)	Ave. Rain (mm)	Time step	Volume-based estimation (Sc. 1)			Period-based estimations											
						Daily (Sc. 2)			Weekly (Sc. 3)			Monthly (Sc. 4)			Annual (Sc. 5)		
			$\sum D_t$	$\sum De_t$	R	N^T	$N^{failure}$	R	N^T	$N^{failure}$	R	N^T	$N^{failure}$	R	N^T	$N^{failure}$	R
Norseman	304	Daily	51,991	7,291	86.0	21,915	3,026	86.2	3130	538	82.8	720	172	76.1	60	39	35.0
(S1)		Weekly	51,967	7,191	86.2	-	-	-	3130	497	84.1	720	165	77.1	60	37	38.3
Merredin	327	Daily	53,799	6,844	87.3	21,915	2,584	88.2	3130	445	85.8	720	138	80.8	60	46	23.3
(S2)		Weekly	53,775	6,835	87.3	-	-	-	3130	412	86.8	720	132	81.7	60	46	23.3
Salmon	357	Daily	49,085	3,302	93.3	21,915	1,556	92.9	3130	281	91.0	720	88	87.8	60	26	56.7
Gums (S3)		Weekly	49,066	3,303	93.3	-	-	-	3130	266	91.5	720	82	88.6	60	25	58.3
Dowerin	357	Daily	55,242	5,301	90.4	21,915	1,896	91.3	3130	337	89.2	720	107	85.1	60	34	43.3
(S4)		Weekly	55,217	5,290	90.4	-	-	-	3130	301	90.4	720	104	85.6	60	34	43.3
Ongerup	387	Daily	47,621	1,634	96.6	21,915	786	96.4	3130	144	95.4	720	50	93.1	60	18	70.0
(S5)		Weekly	47,601	1,638	96.6	-	-	-	3130	135	95.7	720	49	93.2	60	19	68.3
Wagin	424	Daily	49,279	399	99.2	21,915	179	99.2	3130	32	99.0	720	12	98.3	60	4	93.3
(S6)		Weekly	49,257	413	99.2	-	-	-	3130	29	99.1	720	13	98.2	60	5	91.7
Jerramungup	440	Daily	47,435	402	99.2	21,915	165	99.2	3130	28	99.1	720	11	98.5	60	5	91.7
(S7)		Weekly	47,415	390	99.2	-	-	-	3130	25	99.2	720	9	98.8	60	5	91.7
Pingelly	444	Daily	43,830	416	99.7	21,915	84	99.6	3130	20	99.4	720	7	99.0	60	3	95.0
(S8)		Weekly	43,818	151	99.7	-	-	-	3130	20	99.4	720	7	99.0	60	3	95.0
Geraldton	455	Daily	52,696	2,461	95.3	21,915	958	95.6	3130	158	95.0	720	51	92.9	60	17	71.7
(S9)		Weekly	52,673	2,488	95.3	-	-	-	3130	152	95.1	720	50	93.1	60	17	71.7
Cranbrook	490	Daily	44,371	126	99.7	21,915	63	99.7	3130	11	99.6	720	4	99.4	60	2	96.7
(S10)		Weekly	44,358	125	99.7	-	-	-	3130	9	99.7	720	4	99.4	60	2	96.7



(a) using daily modelling time inteval

(b) using weekly modelling time inteval

Figure 4. Comparisons of reliability depending on different reliability scenarios

Results depending on the Reliability Scenarios

As shown in Table 1 and Figure 4, Scenario 1 and Scenario 2 show similar reliability values for given conditions. The majority of rainfall in the south-west Australia is delivered in winter, with a generally long dry summer season, where rainfall can be delivered from post sub-tropical cyclonic events or localised thunder storms. In the majority of cases there is a water deficit prior to the winter rains. Note that Scenario 5 treats water supply failure of 1 week in a year, as water supply failure of the whole year, therefore the calculated reliability of Scenario 5 is lower than all other cases. This highlights the risk of under-estimation using an annual PE. This pattern is displayed in Figure 5, which shows percentile of monthly failures calculated using a daily modelling time interval. Monthly water supply failures are comparatively distributed from Jan to May (dry season) and rarely happen in the winter rainy season. Therefore, it is demonstrated that Scenario 5 is not suitable for reliability estimation for arid and semi-arid areas in WA because of the risk of under-estimation (or increased failure rates associated with single events within a year).

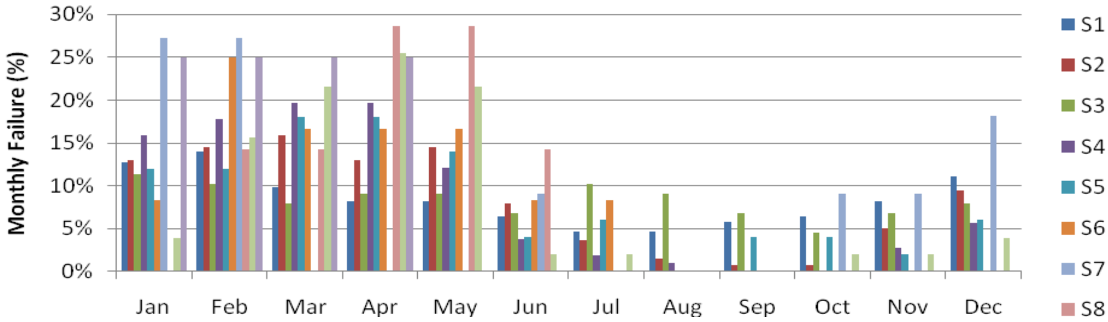


Figure 5. Percentile of monthly failure using daily modelling time interval

Results depending on Annual Average Rainfall

As shown in Table 1 and Figure 4, the reliability of Scenario 5 is lower than other scenarios as the annual average rainfall for these regions is low and less reliable relative to distance in-land from the coastal regions as rainfall declines from 600 mm to 300 mm per annum. This result can be also explained by the seasonal rainfall pattern of WA. Figure 6 compares monthly average rainfall of Norseman (S1, 304 mm), Merredin (S2, 307 mm), Geraldton (S9, 455 mm) and Cranbrook (S10, 490mm) regions. The difference in monthly average rainfall during winter (May~Aug) and summer (Sep~Apr) becomes greater as average annual rainfall increases. Geraldton (S9) and Cranbrook (S10), which has more rainfall in the winter season than Norseman (S1) and Merredin (S2), have greater opportunities to harvest rainwater during this period. Therefore the roaded catchments in the higher average annual rainfall areas have the potential to generate significantly more runoff, thus improving reliability. Note that not only does rainfall decline from the South-West to the North-East but evaporation increases. The combination of these two trends significantly impacts the reliability of the dam-catchment designs evaluated in this simulation.

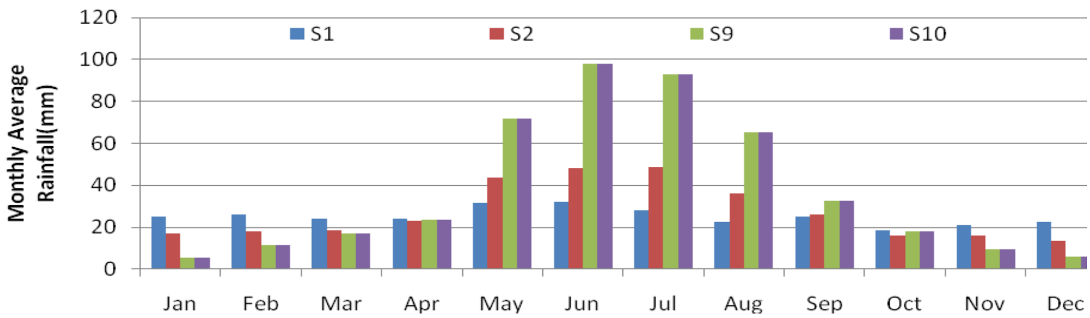


Figure 6. Monthly average rainfall for S1, S2, S9 and S10 sites

Simulation Results

Figure 7 shows the difference in calculated reliability between daily and weekly modelling time intervals. Apart from S6 (scenario 4 and 5) and S5 (scenario 5), all the calculated reliabilities using weekly interval are higher than those using daily interval. Reliability using the weekly interval is comparatively higher than that of using daily intervals for dry regions. However these differences are not as significant as those described by Cowden et al. (2008) and Basinger et al. (2010) for the roof-raintank systems. The difference in the reliability pattern between daily and weekly simulations is caused by the additional winter rainfall (positive effect) and the variation of dam surface area (negative effect), which influences the water balance simulation.

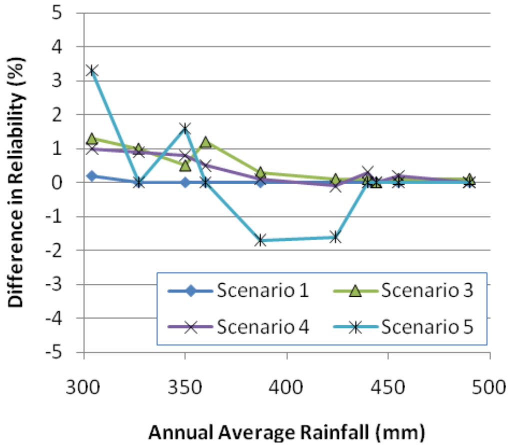


Figure 7. Difference in reliability between daily and weekly modelling time intervals

5. CONCLUSIONS

In this study, the variability of the reliability of catchment-dam systems is evaluated using a water balance simulation model DAMCAT5. The water supply reliability for ten sites located in the arid and semi-arid areas in WA has been estimated using two modelling time intervals and five scenarios to assess reliability, including: volume-based, and daily, weekly, monthly, and annual period-based estimations. The research has suggested that using annual period-based estimation (Scenario 5) is not suitable for arid and semi-arid areas in WA due to the elevated risk of under-estimation. When the cycle of agricultural activity is considered, Scenarios 1~3 risk over-estimation of water supply reliability. The evaluations have demonstrated that monthly period-based estimation (Scenario 4) for the design of roaded catchment-dam water harvesting systems provide the best results in arid and semi-arid areas of WA.

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