The stormwater retention performance of rainwater tanks at the land-parcel scale

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ABSTRACT

The use of tanks to harvest and store rainwater has the potential to simultaneously: 1) augment potable water supplies and 2) restore some aspects of pre-development flow regimes in receiving waters. However, the use of rainwater tanks to achieve these multiple objectives has not been well quantified. Such quantification is required to assist the development of computer models of urban water systems capable of up-scaling the effects of rainwater harvesting at the land-parcel scale to simulate catchment-scale responses. In this paper, we quantify how the use of rainwater tanks in a temperate climate (740 mm average annual rainfall) can achieve these multiple objectives at the land-parcel scale, based on water use measurement from houses with a range of tank volumes and demands. We use these new empirical data to model a range of typical rainwater tank scenarios. It is shown that tank yield can be substantial and is not significantly reduced when tanks are configured for passive irrigation, even though this design modification significantly improves the capacity of the tanks to retain rainfall events. We also find that the use of tanks alone cannot completely restore the natural retention capacity of typical land-parcels. Our results suggest that typical rainwater tank scenarios can concurrently *assist* in restoring pre-predevelopment flow regimes and reliably augment potable supply. If retention capacity is limited by tank volume or a lack of demands, tanks could be allowed to partly drain to the garden for passive irrigation or be configured to overflow to infiltration-based retention systems.

KEYWORDS

Hydrology; passive irrigation; rainwater tanks; streams; urbanization.

INTRODUCTION

The use of rainwater tanks can address a number of pertinent important environmental, social and economic issues. Rainwater harvesting can:

1. Reduce demand on potable water supplies by providing an alternative water source (Mikkelsen et al. 1999; Mitchell et al. 2007; Khastagir and Jayasuriya 2010);
2. Reduce flood risk (Burns et al. 2010);
3. Delay the need to augment existing potable water supplies using alternative options, which may have higher economic and environmental costs (e.g. desalination, wastewater recycling, etc.);
4. Retain runoff from small rainfall events to reduce the frequency of flow to waterways and thus assist in restoring natural flow regimes at larger scales downstream (Fletcher et al. 2011; Burns et al. in prep). This ability to retain runoff from impervious surfaces

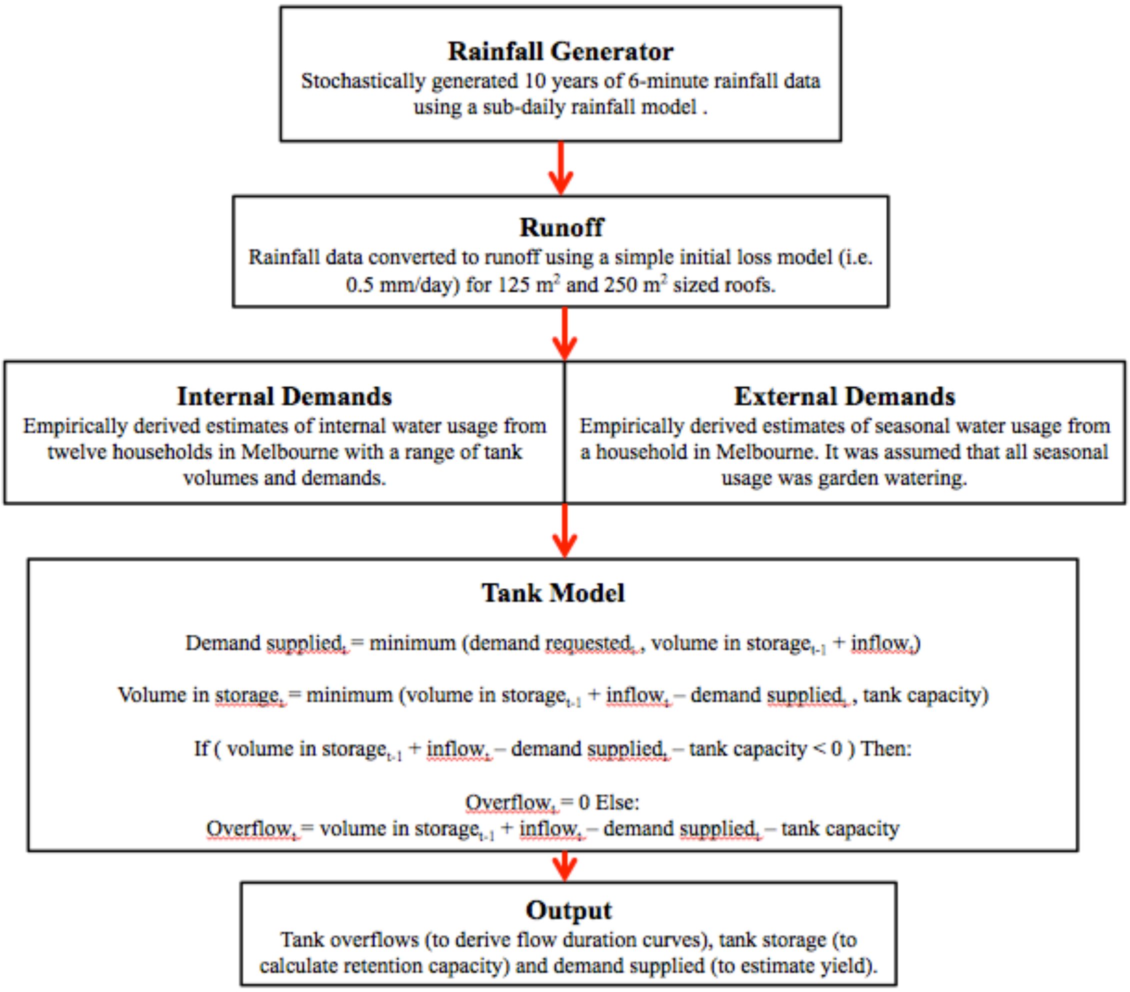
and in doing so to mimic the natural storage capacity of the pre-developed state (e.g. forest) has been defined as “retention capacity”, expressed in mm of rainfall retained before runoff is discharged from a site (Walsh et al. 2009);

5. Decrease pollutant loads to receiving waters (Fletcher et al. 2007); and
6. Increase the amount of water available in the landscape to help reduce the hot dry conditions that occur in urban areas in summer (Coutts et al. 2009).

Few studies have attempted to quantify the potential simultaneous benefits of tanks. Most previous studies have focussed on potable supply augmentation (Coombes and Kuczera 2003). A small number of studies have explored the flood mitigation benefits of using tanks (Coombes and Barry 2008) while even fewer have investigated the ability of tanks to restore retention capacity for flow-regime management (Walsh et al. 2009). In this paper, we quantify how the use of tanks at the land-parcel scale can simultaneously: 1) augment potable water supplies and 2) restore some aspects of pre-development flow regimes in receiving waters. We base our modelling on water use measurements from houses with a range of tank volumes and demands. This use of empirical tank water data is an advance on previous studies, which generally utilise total estimated demand for specific end uses demands (Coombes and Kuczera 2003; Mitchell et al. 2008). We use these new data to identify rainwater tank configurations that can restore retention capacity at the land-parcel scale. Such work is required for the development of models that represent the relationship between small-scale stormwater management and catchment-scale responses.

METHODS

To undertake this study, we constructed a model using the R software (R Development Core Team 2011). We firstly conjectured a range of typical rainwater tank scenarios (Table 1). The two roof areas considered (125 m^2 and 250 m^2) represented medium and high-density allotments, respectively. We modelled entire roofs connected to a variety of different sized tanks (2, 5, 10 and 15 kL). The occupancy for each allotment was assumed to be 2.67 persons per household which is consistent with other studies (Burns et al. 2010). The internal end-uses considered for each scenario were a combination of either: 1) clothes washing and toilet flushing or 2) clothes washing, hot water usage and toilet flushing. Most scenarios included watering of a large garden (Table 1). Some tanks were configured to allow for passive irrigation. A flow chart describing the modelling process is shown in Figure 1. Detailed information concerning the modelling is given below.



Stochastically generated 10 years of 6-minute rainfall data using a sub-daily rainfall model .

Rainfall data converted to runoff using a simple initial loss model (i.e. 0.5 mm/day) for 125 m^2 and 250 m^2 sized roofs.

Empirically derived estimates of internal water usage from twelve households in Melbourne with a range of tank volumes and demands.

Empirically derived estimates of seasonal water usage from a household in Melbourne. It was assumed that all seasonal usage was garden watering.

Demand supplied_t = minimum (demand requested_t , volume in storage_{t-1} + inflow_t)

Volume in storage_t = minimum (volume in storage_{t-1} + inflow_t – demand supplied_t , tank capacity)

If (volume in storage_{t-1} + inflow_t – demand supplied_t – tank capacity < 0) Then:

Overflow_t = 0 Else:
Overflow_t = volume in storage_{t-1} + inflow_t – demand supplied_t – tank capacity

Tank overflows (to derive flow duration curves), tank storage (to calculate retention capacity) and demand supplied (to estimate yield).

Figure 1 – Modelling flow chart. All components of the model are run at 6-minute time-steps.

Rainfall and Runoff

We stochastically generated ten years of 6-minute rainfall data using a sub-daily rainfall model (DRIP) (Heneker et al. 2001). The data generated was statistically comparable to that of data recorded at a Bureau of Meteorology gauge located to the east of Melbourne (Mitcham; station number 086074; period of record: 01/05/1939 to 31/12/1948). More information concerning DRIP can be found in Heneker et al. (2001) and Srikanthan (2007). A simple initial loss model (i.e. 0.5 mm/day) was used to convert the stochastically generated rainfall data to runoff data (and therefore tank inflow). The same inflow estimates (in units of mm) were used for each scenario.

Demands

Internal and external end-use demands for each scenario were derived using empirical data.

Internal Demands

Internal end-use demands were based on measured rainwater tank usage (Burns et al. in prep) from 12 households with a range of tank volumes and demands. Because not all the tanks were connected to the same demands, the data for each household was standardized and grouped together to form a data set representative of tank usage for all households. The data was standardized using Equation 1:

$$SU_{(h)} = \frac{TU_{(h)}}{\left(O_{(h)}\right)^{0.64} * P_{(h)}} \qquad (1)$$

Where: SU is the standardized usage for household h in litres/day/person, TU is the data set of measured tank usage for household h in litres/day/household, O is the reported occupancy for household h and P is the fraction of total water usage that was rainwater for household h. This fraction (P) was calculated using Equation 2:

$$P_{(h)} = \frac{\overline{TU_{(h)}}}{\overline{TU_{(h)}} + \overline{TW_{(h)}}} \qquad (2)$$

Where: $\overline{TU_{(h)}}$ is the mean measured tank usage for household h in litres/day/household and $\overline{TW_{(h)}}$ is the mean potable water demand for household h (obtained from the local water authority; Yarra Valley Water) in litres/day/household.

The data set representative of tank usage for all households was used to derive internal end-use demands for each scenario. For the first internal demand type (i.e. *clothes washing and toilet flushing*), each estimate of total water usage per person per day was multiplied by 0.36, which is the fraction of total water usage such demands typically account for (Wilkenfeld 2006). These demand-specific estimates of water usage were then multiplied by an occupancy factor (1.87) in order to obtain allotment scale demands. This factor was calculated as allotment occupancy (2.67) to the power of 0.64 and is based on a study conducted by Roberts (2005), who showed that a non-linear relationship exists between household water usage and occupancy. This process was repeated for the second internal demand type (i.e. *clothes washing, hot water usage and toilet flushing*) although the relevant fraction used was 0.76 (Wilkenfeld 2006). These estimates of daily usage were then used to derive short time-step, long-term demand time series(s). To do this, we sampled (with replacement) 3,653 values (i.e. the number of days in ten years) of usage from the distributions of daily usage. An in-house diurnal pattern from Roberts (2005) was used to disaggregate daily usage into 240 six-minute values. The mean daily usage for the first demand type was 101 litres/day whereas for the second type it was 219 litres/day.

External Demands

External end-use demands were based on estimates of seasonal potable water usage (i.e. primarily garden watering) from a household in Melbourne. We assessed this household as typical of the region, based on our analysis of the area. Six years of quarterly billing data (prior to the installation of a rainwater tank) were obtained for this household. We then calculated the average daily usage for each quarter and found that usage was lowest in the July-September quarter. By assuming that usage in this quarter represented base usage, we calculated the seasonal usage for the other quarters as average daily usage minus base usage. The resultant seasonal usage for the January-March, April-June, July-September and October-December quarters was 307, 176, 0 and 95 litres/day, respectively.

To derive a long-term series of seasonal demand, we assumed that the monthly seasonal usage for each month was distributed uniformly on non-rain days only. For example, if the monthly seasonal usage for January was 10 kL/month and there were 20 non-rain days in that month, then the seasonal usage on each non-rain day would be 500 litres/day. Each value of daily seasonal usage over the modelling period was disaggregated into 240 six-minute values using a diurnal pattern for seasonal demand from Roberts (2005).

Passive Irrigation

Some tanks were configured for passive irrigation, by providing an elevated trickle outlet directed to nearby garden, to 1) improve retention capacity, by reducing the probability that the tank is full at the start of a rainfall event, and 2) augment local soil moisture with the aim of restoring baseflows. For relevant scenarios, passive irrigation only occurred when tank storage was at least 75 percent of capacity. The rate at which passive irrigation occurred was 6.9 litres per hour per 100 m^2 of roof area. This rate is a nominal estimate of the baseflow for a nearby undeveloped, forested catchment.

Tank Model

The inflows and demands for each scenario were input to a rainwater tank behaviour model (Mitchell 2007). The behaviour of each tank was simulated on a 6-minute time-step over a relatively long simulation period (ten years). We assumed that all calculations were carried out within the same time-step (i.e. demands were supplied before overflow occurred).

Output

For each scenario, the following time series of outputs were extracted: tank storage, tank overflow, demand requested and supplied. We used the storage time series to calculate tank retention capacity. This variable represented the amount of rainfall a tank could retain before overflow to the stormwater system occurred. Overflow duration curves were derived for some scenarios using the time series of tank overflows. Tank yield was calculated from the time series of demand supplied.

RESULTS AND DISCUSSION

Tank Yield

Mean annual yield for each rainwater tank scenario is shown in Table 1, which shows that rainwater is able to supply a substantial proportion of the demands. Tanks connected only to indoor demands supplied the majority of the requested demand (i.e. had high reliability). For illustration, the 5-kL tank (Scenario 6) draining the small (125 m^2) roof, supplied 81% of the requested demand (Table 1). Tanks connected to external demands could only supply the bulk of demand requested when they were large and drained the large roof (e.g. Scenario 24). Importantly, configuring tanks for passive irrigation resulted in practically no detriment to yield (Table 1). For example configuring the tank in Scenario 4a for passive irrigation (Scenario 4b) only decreased yield by around 2 kL/year. The yields in this paper are substantial and consistent with other studies (Coombes and Kuczera 2003; Mitchell et al. 2005). While the reliability of some tanks was not high, this is not of great importance where potable backup is available. Our results indicate that it might be desirable to increase the rate of passive irrigation (i.e. to improve retention capacity), given the flood and stream protection benefits and the small loss of yield. That said, it is important to ensure that any increased rate of passive irrigation does not undesirably saturate local soils.

Table 1 – Tank modelling scenarios. Internal demands include: clothes washing (C), toilet flushing (T) and hot water usage (H). Some scenarios feature garden watering (G) as an external demand. Also shown is the mean annual yield for each rainwater tank configuration. The proportion of total water usage that was supplied by rainwater is shown in parentheses.

Scenario number (with, without passive irrigation)	Tank capacity (kL)	Internal demands	External demands	Mean annual yield (kL/year) with passive irrigation	Mean annual yield (kL/year) without passive irrigation
125 m^2 roof					
1a, 1b	2	C + T	G	47 (52%)	44 (50%)
2a, 2b		C + H + T	G	57 (43%)	54 (41%)
3		C + H + T	None	53 (66%)	NA
4a, 4b	5	C + T	G	59 (67%)	57 (64%)
5a, 5b		C + H + T	G	72 (54%)	70 (53%)
6		C + H + T	None	65 (81%)	NA
7a, 7b	10	C + T	G	67 (75%)	65 (73%)
8a, 8b		C + H + T	G	79 (60%)	78 (59%)
9		C + H + T	None	71 (89%)	NA
10a, 10b	15	C + T	G	71 (80%)	70 (78%)
11a, 11b		C + H + T	G	82 (62%)	81 (61%)
12		C + H + T	None	74 (93%)	NA
250 m^2 roof					
13a, 13b	2	C + T	G	54 (61%)	50 (56%)
14a, 14b		C + H + T	G	70 (53%)	64 (49%)
15		C + H + T	None	63 (78%)	NA
16a, 16b	5	C + T	G	73 (82%)	70 (78%)
17a, 17b		C + H + T	G	96 (73%)	92 (69%)
18		C + H + T	None	76 (95%)	NA
19a 19b	10	C + T	G	81 (90%)	79 (88%)
20a, 20b		C + H + T	G	110 (83%)	107 (81%)
21		C + H + T	None	80 (100%)	NA
22a, 22b	15	C + T	G	84 (95%)	83 (93%)
23a, 23b		C + H + T	G	117 (88%)	114 (86%)
24		C + H + T	None	80 (100%)	NA

Retention Capacity

We found that all tanks draining the small roof (125 m^2) and connected to garden watering restored retention capacity closer to natural conditions when tanks were sized to around 40 litres per m^2 of roof area (Figure 2A). Natural conditions were estimated using the MUSIC software (eWater 2009), assuming that the field capacity of the forest parcel was 30 mm; the resultant median retention capacity is the available soil storage volume at each timestep, extracted from MUSIC's flux file.

The retention capacity of tanks draining the large roof (250 m^2) was poorer than those draining the small roof (125 m^2) (Figure 2B). The only tank draining the larger roof that resulted in near natural retention capacity performance was large (sized to 60 litres per m^2 of roof area), configured for passive irrigation and connected to all possible demands considered in this paper. This result shows the challenge in restoring runoff frequency and volume towards natural levels at the land-parcel scale, but also shows that it is possible. The retention capacity of tanks draining the small roof was high because the demands for these scenarios were large relative to tank inflows. When tanks were sized larger than 40 litres per m^2, it could be argued that too much runoff was retained (Figure 2A). However, it should be noted that for most land-parcels impervious area often exceeds 125 m^2. As such, a large tank (i.e. sized to greater than 40 litres per m^2) might only *partially* restore the retention capacity of a typical land-parcel – other retention systems (e.g. vegetated infiltration systems) will be required to drain additional impervious surfaces (e.g. paving). These results suggest that the overflows from tanks draining large roof areas will need further retention — for instance, by downslope infiltration systems.

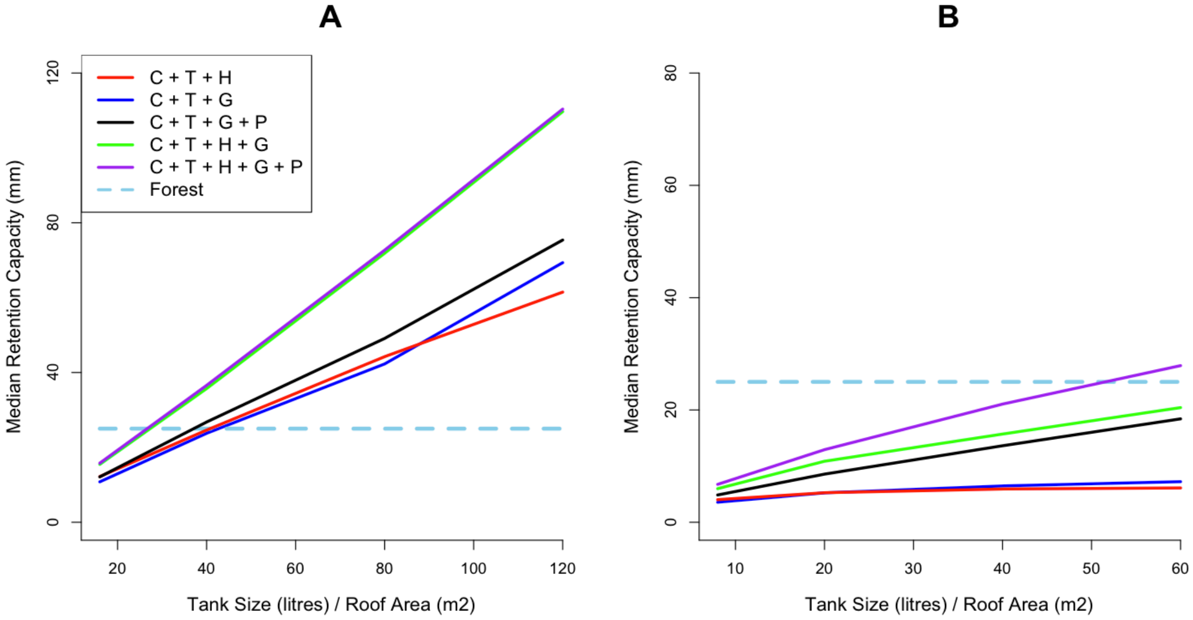


Figure 2 – A) Median retention capacity of tanks draining the small roof (125 m^2). B) Equivalent curves for tanks draining the large roof (250 m^2). Abbreviations in the legend refer to: clothes washing (C), toilet flushing (T), hot water usage (H), garden watering (G) and passive irrigation (P). The dashed light blue line is an estimate of the median retention capacity of the roof had it been a parcel of forest.

Overflow Duration

Configuring tanks for passive irrigation resulted in the frequency and magnitude of overflows being closer to natural conditions (Figure 3). For example, overflows occurred half as often in Scenario 4b, with passive irrigation than in Scenario 4a, without (Figure 3A). This effect was maintained for tanks draining the larger roof (Figure 3B). These results suggest that configuring tanks for passive irrigation could be a simple, yet effective means of reducing the frequency of particularly low-magnitude tank overflows

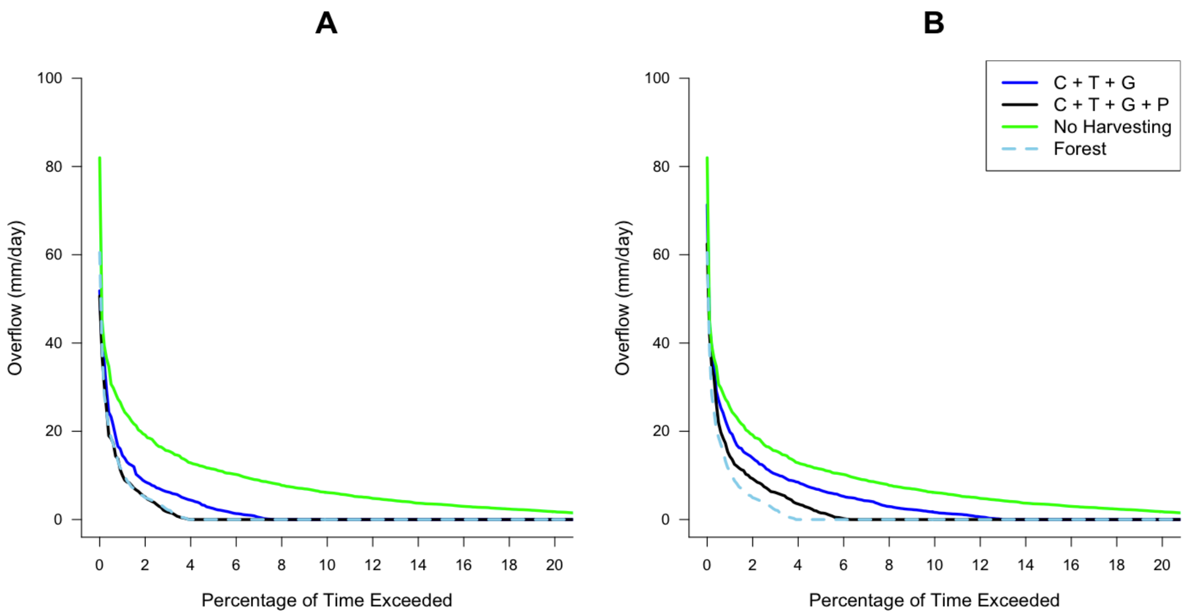


Figure 3 – A) Overflow duration curves for Scenarios 4a and 4b (125 m^2 roof). B) Equivalent such curves for Scenarios 19a and 19b (250 m^2 roof). Abbreviations in the legend refer to: clothes washing (C), toilet flushing (T), garden watering (G) and passive irrigation (P). Overflow duration curves are also shown for the conditions: 1) no harvesting (green line) and 2) the roof been a parcel of forest (dashed light blue line).

CONCLUSIONS

Harvesting stormwater using tanks can restore retention capacity at small scales and augment potable water supplies. We reveal (using modelling) rainwater tank scenarios which can achieve these multiple objectives at the land-parcel scale. It was shown that tank yields can be substantial and reliable. We also showed that the use of tanks alone cannot completely restore the retention capacity of typical land-parcels. Finally, configuring rainwater tanks for passive irrigation was shown to improve retention capacity performance with practically no detriment to supply yield.

While this preliminary study does reveal optimal tank scenarios for a region east of Melbourne, a number of pertinent research questions still remain. For example, research is required to explore how the retention capacity of tanks varies with different climates. It is likely that the results of this paper would have been different had climate data from the west of Melbourne been used, since rainfall there is significantly lower. Further work is also needed to derive estimates of external end-use demands based on more sophisticated and realistic assumptions. Lastly, it is currently unknown how the use of small-scale retention systems impacts catchment scale flow regimes. Optimal scales and arrangements of retention systems might exist, but no studies exist on this question. We envisage that any attempt to investigate such hydrologic scaling questions will depend on the accurate modelling of retention systems at the land-parcel scale.

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