Improvement of Rainwater Harvesting Analysis Through an Hourly Timestep Model in Comparison with a Daily Timestep Model

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Abstract

For the analysis of rainwater tank outcomes, some researchers used monthly water balance model, which ignores an important factor such as overflow from the tank. Recently, to improve the accuracy of such analysis facilitated by the availability of daily rainfall data, many researchers started using daily timestep models. In the daily timestep models, the daily rainwater demand is deducted from the available storage, once in a day and there are debates on whether to apply that deduction at the beginning of the day or at the end of the day. Moreover, there is significant diurnal variation of water demand, which can not be accounted for in a daily timestep model. To overcome this, current study investigates an hourly timestep model considering hourly rainfall data and hourly variable rainwater demands. Hourly rainfall data was collected from the Australian Bureau of Meteorology for a raingauge station located in Melbourne. An earlier developed daily water balance model was converted to hourly scale incorporating hourly variable rainwater demands. Model simulated results for three distinct years (dry, average and wet) were compared with the results using a daily timestep model with the same data. Variations of water savings and overflow amounts are presented under four combinations of roof area and daily rainwater demand with tank sizes varying from 2500 L to 20,000 L. It is found that in all the selected years, the daily timestep model underestimated the annual water savings compared to the hourly timestep model and the highest difference was estimated to be 13,750 L for a smaller tank size connected with a bigger roof having higher rainwater demand.

Keywords Rainwater tank · Water balance model · Timestep · Water demand
1 Introduction

Rainwater tanks have been in use for many centuries, especially where rainfall magnitudes are reasonable to make it viable to be stored. Traditionally, for non-arid remote areas where other suitable water sources are not available, it is the salient source of water. Many remote and poor communities even use stored rainwater for potable purposes after some primary treatments of the harvested rainwater. In addition to mentioned remote areas, recently some urban authorities are also encouraging rainwater harvesting to offset current potable water demand, which has become unmanageable due to ever increasing demands driven by increase in population and water uses, as well as scarcity of water sources. Among alternative water sources, which can be used for the augmentation of potable water demand, rainwater harvesting is most fundamental, although some urban authorities are even implementing higher level systems such as greywater reuse and wastewater recycling. To minimise the pressure on centralised water supply system, contemporary urban authorities are encouraging decentralised water supply systems within smaller regions through waste water recycling and/or greywater reusing. Some authorities are also emphasizing communal rainwater tanks (Gurung and Sharma 2014), in addition to household rainwater tanks. To promote such augmented water supply, many authorities around the world have been offering different forms of incentives to the end-users (Imteaz and Moniruzzaman 2018).

As the uses of rainwater tanks are increasing, space optimisation and/or cost optimisation are becoming important. Matomela et al. (2020) investigated potential sites for rainwater harvesting in arid or semi-arid watersheds using GIS-based techniques. In an urban setup in many countries, space to be provided for a rainwater tank is limited. On top of that costs associated with rainwater tank installation and operation play an important role on the decision making of rainwater tank implementation (Karim et al. 2021; Bashar et al. 2018; Matos et al. 2015) and end-users are in general not convinced on ultimate monetary benefits through implementing rainwater tanks. Over the years, there have been several studies on water saving potentials or expected potable water savings through rainwater tanks, and some of those focused on ultimate monetary savings. Among some recent ones, Khan et al. (2021) presented details on rainwater harvesting potentials across several regions of Australia using rainfall data from 601 raingauge stations maintained by the Australian Bureaus of Meteorology. In a localised scale, Alim et al. (2020) presented a detailed feasibility study of a small-scale rainwater tank for potable water supply in an area within southeast Australia. In a household level, Hammes et al. (2020) through precise wateruse measurements using different appliances from a house in South Brazil, concluded that 46.5% water in a household level can be non-potable and a 2000 L rainwater tank would be able to supply that water. Nnaji and Aigbavboa (2020) presented an economic feasibility of rainwater harvesting using an optimized storage. With the impending impacts of climate change, some recent studies focused on evaluating rainwater savings potential under future climate scenario (Imteaz et al. 2021; Imteaz and Moniruzzaman 2020; Santos et al. 2020). Valdez et al. (2016) investigated potential energy and carbon savings through rainwater harvesting.

Among the analysis methods used for the rainwater tank outcomes analysis, a water balance model is widely used and reasonably acceptable both in regard to accuracy and easy but comprehensive presentability of the outcomes to a general audience. Some researchers used monthly-scale water balance models (Shadeed and Alawna 2021; Lizárraga-Mendiola et al. 2015; Aladenola and Adeboye 2010) for analysing rainwater harvesting potential. Monthly-scale model is unable to consider overflow from the system, which may occur during some consecutive heavy rainy days. In the monthly-scale model, a bulk amount of
rainfall is considered as inflow and a bulk amount of monthly demand is considered as outflow. Such gross analysis can be adopted when it is know that there will be no overflow from the system (i.e. the storage capacity is very high) or the required accuracy from such analysis is not high (Aladenola and Adeboye 2010). In some cases, researchers were compelled to adopt a monthly-scale due to lack of daily rainfall data (Shadeed and Alawna 2021; Lizárraga-Mendiola et al. 2015). Imteaz et al. (2012a, b) elaborated inaccuracies of using monthly timestep model compared to a daily timestep model presenting a case study in Nigeria. With the advancement of scientific instrumentations as well as with the fact that rainfall measurement does not require sophisticated devices, vast majority of the studies on rainwater harvesting used daily timestep models with the aim of achieving more accurate results. However, there are two major drawbacks with the daily timestep models. Firstly, a constant water demand is considered for the whole day, whereas water demands significantly vary throughout the day. Secondly, a bulk demand is deducted from the stored water either at the end of the day (after adding rainfall, named ‘yield after storage’, YAS) or at the beginning of the day (before adding the rainfall, named ‘yield before storage’, YBS). Lade et al. (2012) reported that the YAS algorithm underestimates water savings, whereas the YBS algorithm has a tendency to overestimate the water savings. A daily timestep model will have to assume either of the two above-mentioned algorithms, which will cause inaccurate results. To overcome the above-mentioned issues, this paper presents rainwater tank outcomes using an hourly timestep model, eventually presenting comparisons of the calculated results with a daily timestep model. Also, as the results of the two different timestep models are likely to be significantly influenced by the weather and other tank conditions, comparisons are presented for different weather conditions as well as for different demands, roof and tank sizes. This is a pioneer attempt of presenting such comparisons under variety of conditions.

2 Methodology and Data

Many studies elaborated the mathematical equations, logical sequence and algorithm of daily water balance model (Karim et al. 2015; Imteaz et al. 2012a, b; Eroksuz and Rahman 2010). Algorithm used in Imteaz et al. (2012a, b) has been modified to incorporate hourly rainfall data, as well as hourly variable demands. The brief summary of the algorithm is that from the incoming rainfall amount, a certain percentage is deducted as losses. The remaining amount is multiplied with the roof area to convert it to runoff from the roof, which is then diverted to the rainwater tank having a certain volume. This calculation proceeds in an hourly basis and runoff from a certain hour is added with the cumulative stored water in the tank accumulated from the runoffs during preceding hours (if any). In every hour, the assigned rainwater demand amount is deducted from the stored water (if available). If at any stage the tank becomes full, the subsequent runoff amount is diverted as overflow. In the contrary if there is no water in the tank, it is assumed that the rainwater demand will be fulfilled from normal townwater (potable) supply and model calculates total such water needed in a year for the selected scenario. Hourly demand distribution (as % if total daily demand) in an Australian context as provided by Beal (2011) is presented in Fig. 1.

As the hourly rainfall data for several years (2003 – 2020) was available through Australian Bureau of Meteorology for a raingauge in Melbourne, the hourly water demands pattern for the Melbourne was collected from the local water authority,
Melbourne Water. The selected raingauge station is located at Essendon Airport, about 10 km north-west of Melbourne CBD. As one objective was to investigate the difference between daily-scale model and hourly-scale model in different weather conditions, from the collected rainfall data, three years’ data were selected for further analysis. Based on methodology of defining the dry, average and wet years as the years having close to 10 percentile, 50 percentile and 90 percentile annual rainfall amount respectively, three years were selected as dry, average and wet years. For the selected location, based on historical annual rainfall data, the 10 percentile, 50 percentile and 90 percentile rainfall amounts are 422.7 mm, 603.8 mm and 758.8 mm, respectively. The selected years and the corresponding annual rainfall amounts are presented in the Table 1. For use in the daily timestep model, hourly rainfall data for the selected years were converted to daily rainfall data.

Both the hourly-scale and daily-scale models were separately used with the corresponding rainfall data for the selected years, along with other rainwater tank related data such as roof area, tank volume, rainwater demand and percentage loss from the rainfall. Models were simulated for a range of tank volumes from 2,500 L to 20,000 L, for roof areas (200 and 300 m²) and rainwater demands (300 and 600 L/day). As per Imteaz et al. (2012a, b), a runoff loss of 10% was considered for all the simulations.

![Diurnal distribution of typical household water demand](image)

**Table 1** Selected years and corresponding annual rainfall amounts

| Weather | Year | Annual Rainfall (mm) |
|---------|------|----------------------|
| Dry     | 2019 | 406.0                |
| Average | 2017 | 551.6                |
| Wet     | 2011 | 731.0                |
3 Results

Simulated results from the hourly timestep model and daily timestep model are compared in regard to annual water savings and annual overflow losses from the tank. Comparisons are shown for different simulations comprising different combinations of roof areas and total rainwater demand for varying tank sizes under three weather conditions (dry, average and wet).

Figure 2a–c show the comparisons of simulated annual water savings and annual overflow amounts under different weather conditions (a: dry, b: average and c: wet) and varying tank sizes for a roof area of 200 m² and rainwater demand of 300 L/day. From the figure, it is clear that expected annual water savings through daily timestep model can be underestimated by 3500~7400 L depending on weather condition. In a dry year, as the total amounts of rain (hence the amount of water savings) are less compared to an average/wet year, the variation is also the least, i.e. 3500 L. In the contrary Accordingly, in a wet year, as the amounts of rain (hence the amount of water savings) are more compared to a dry/average year, the variation is also the highest, i.e. 7400 L. These variations decrease with the increase in tank size. As with the bigger tank sizes, amount of overflow losses reduce, the differences between daily timestep model and hourly timestep model results also decrease. In a dry year, with lesser amount of rainfall, with a bigger tank (> 10,000 L) as overflow loss becomes zero, there is no difference between the results of daily timestep model and the hourly timestep model. For this particular scenario (i.e. demand and roof size), overflow does not become zero in an average and wet years, even with a very big tank size (i.e. 20,000 L). This pattern changes for a higher demand scenario (i.e. 600 L/day) as shown in the Fig. 3a–c, which show the comparisons of simulated annual water savings and annual overflow amounts under different weather conditions (a: dry, b: average and c: wet) for a roof area of 200 m² and rainwater demand of 600 L/day. With this higher consumption scenario (with the same roof size), overflow gets to zero even in average and wet years, and whenever the overflows are zero in both the simulations, there is no difference between daily timestep model and hourly timestep model. However, with smaller tank sizes, simulation results between the daily timestep model and hourly timestep significantly vary. However, these variations get narrower compared to a lower consumption scenario; expected annual water savings vary 4500~7000 L with the a smallest tank size (2,500 L).

Figure 4a–c show the comparisons of simulated annual water savings and annual overflow amounts under different weather conditions (a: dry, b: average and c: wet) for a roof area of 200 m² and rainwater demand of 300 L/day. From the figures, it is clear that with the increased roof area, as the captures of rainfall were more, significant overflows are observed under all the weather conditions and any tank size. As such, there are always significant differences between the results of the daily timestep model and hourly timestep model. Under this scenario, the underestimations through daily timestep model become higher compared to a smaller roof size scenario; with the a smallest tank size (i.e. 2,500 L), underestimations through daily timestep model vary by 8,500~12,000 L depending on the weather condition. Under this scenario, the magnitudes of the differences between the daily timestep model and hourly timestep model remain almost same irrespective of the tank size, whereas in the earlier two scenarios, these differences become narrower with the increase in tank size. The overflow pattern changes with the increase in consumption (i.e. 600 L/day) as shown in Fig. 5a–c, where it is found that with the increased consumption, the overflow in dry year becomes zero for a bigger tank size. Hence, under these conditions, there is no difference between the daily timestep model
Fig. 2  Annual water savings and overflows for a roof of 200 m² and demand of 300 L/day (a: dry year, b: average year, c: wet year)
Fig. 3 Annual water savings and overflows for a roof of 200 m² and demand of 600 L/day (a: dry year, b: average year, c: wet year)
Fig. 4 Annual water savings and overflows for a roof of 300 m² and demand of 300 L/day (a: dry year, b: average year, c: wet year)
Fig. 5  Annual water savings and overflows for a roof of 300 m² and demand of 600 L/day (a: dry year, b: average year, c: wet year)
and hourly timestep model (Fig. 5a). However, in most cases (including all the cases under average and wet years), there are significant differences between the simulation results of daily timestep model and hourly timestep model. With the a smallest tank size (i.e. 2,500 L), the differences vary from 5,300 to 13,750 L depending on weather condition.

4 Discussions

From the studied scenarios, it is found that with a higher roof area and higher demand, as potentials of water savings become higher, the difference between the results of daily timestep model and hourly timestep model is highest, which can vary up to 13,750 L. Also, it is found that under all the scenarios, daily timestep model always provided lower water savings compared to a hourly timestep model, and it is to be noted that the hourly timestep model is supposed to be more accurate. This finding matches with the findings of Zhang et al. (2020) and Lade et al. (2012), who concluded that YAS technique provides underestimated water savings. It is to be noted that the daily timestep model used in the current study also employed YAS technique. Overall, with a 5 kL tank underestimations varied from 1.8% to 15.6% depending on weather and tank conditions. Zhang et al. (2020) reported that use of daily timestep model with YAS algorithm can result in up to 0.3% underestimations in ‘water savings efficiency (WSE)’ for a tank size of 5 kL. WSE is the ratio of the total amount of water saved to the total rainwater demand. Whereas, as per the current study, with the same tank size the use of daily timestep model (with YAS algorithm) yields underestimations in WSE varying from 1.8% to 15.6% depending on weather and tank conditions. In general, in dry years or with a bigger tank size when overflow becomes nil, there is no difference between the daily timestep model and hourly timestep model in regards to annual water savings.

5 Conclusions

In the past, simulations with smaller timestep was hindered by lack of appropriate data, as well as lack of computer capacity. In the case of rainwater harvesting analysis, the lack of shorter timestep data has been the real issue, which affected the accuracy of conducted analyses using longer timestep data. Recently, with the advent of faster computers, as well as the availability of shorter timestep data, researchers adopted using shorter timestep simulation models. For rainwater harvesting analysis, as currently many countries/regions are having daily rainfall data, current widely adopted analysis practice is to use daily timestep model, while daily rainfall data is fed into the model as input. In the daily timestep model, a single amount is considered as daily rainwater demand, which is deducted either at the end or beginning of the day and there are debates on which method is appropriate, i.e. to deduct rainwater demand at the beginning or at the end of the day. In reality, both the methods will not provide very accurate results, as the water demand significantly varies during a day and consideration of such diurnal variation is not possible without adopting a sub-daily timestep model. To overcome this issue, this paper presented development of an hourly timestep model for the analysis of rainwater harvesting considering variable hourly demands within a day. Hourly rainfall data for several years for a rainfall station near Melbourne city was collected from Australian Bureau of Meteorology. Also, hourly demand pattern was collected from the local water authority study. An earlier developed
daily water balance model was modified to accommodate hourly rainfall and demand data. To assess the variation of results in different weather conditions, from the available data, three years were selected as dry, average and wet years. The modified model was simulated with hourly rainfall and demand data. The model was simulated with varying roof sizes, total rainwater demands and tank sizes for the selected three years’ rainfall. Same rainfall and demand data was converted to daily scale and the daily timestep model was simulated with the same tank parameters and daily rainfall data for the same years. Results from the hourly timestep model were compared with the results from the daily timestep model. From the comparisons it is found that hourly timestep model provide higher annual water savings compared to daily timestep model under all the weather and tank scenarios. This is due to the fact that the used daily water balance model applied the concept of YAS, which at times caused excess water in the tank at the beginning of the day (i.e. before use) prompting more frequent overflows from the tank than a realistic scenario. The hourly timestep model overcomes this issue, as it considers smaller additions (i.e. inflow) and subtractions (i.e. demand) of water at every hour, which causes less likelihood of tank being filled. As such, for accurate analysis of rainwater harvesting, it is recommended that a hourly timestep model be used if data is available. However, as hourly data is rarely available, analysts are compelled to use daily time step model. In such case, another daily time-step algorithm, YBS can be explored in conjunction with the YAS algorithm. It is recommended to have a future study with conjunctive use of YAS and YBS algorithms.

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Availability of Data and Materials Data used in this study will be made available upon request.

Declarations

Ethical Approval Not required as the study did not involve human or animal.

Consent to Participate Authors have consent to participate any offer by the journal.

Consent to Publish Authors are giving consent to publish the article in the submitted journal.

Competing Interests There is no competing or conflict of interest.

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References

Aladenola OO, Adeboye OB (2010) Assessing the potential or rainwater harvesting. Water Resour Manag 24:2129–2137
Alim MA, Rahman A, Tao Z, Samali B, Khan MM, Shirin S (2020) Feasibility analysis of a small-scale rainwater harvesting system for drinking water production at Werrington, New South Wales, Australia. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.122437
Bashar MZI, Karim MR, Imteaz MA (2018) Reliability and economic analysis of urban rainwater harvesting: A comparative study within Six Major Cities of Bangladesh. Resour Conserv Recycl 133:146–154. https://doi.org/10.1016/j.resconrec.2018.01.025
Beal C (2011) South east Queensland residential end use study: Final report. Urban Water Secur Res Alliance Tech Rep 47. http://www.urbanwateralliance.org.au/publications/UWSRA-tr47.pdf
Eroksuz E, Rahman A (2010) Rainwater tanks in multi-unit buildings: A case study for three Australian cities. Resour Conserv Recycl 54:1449–1452
Gurung TR, Sharma A (2014) Communal rainwater tank systems design and economics of scale. J Clean Prod 67:26–36. https://doi.org/10.1016/j.jclepro.2013.12.020
Hammes G, Ghisi E, Thives LP (2020) Water end-uses and rainwater harvesting: A case study in Brazil. Urban Water J 17(2):177–183. https://doi.org/10.1080/1573062X.2020.1748663
Imteaz MA, Adeboye O, Rayburg S, Shanableh A (2012a) Rainwater harvesting potential for southwest Nigeria using daily water balance model. Resour Conserv Recycl 62:51–55. https://doi.org/10.1016/j.resconrec.2012.02.007
Imteaz MA, Moniruzzaman M (2020) Potential impacts of climate change on future rainwater tank outcomes: A case study for Sydney. J Clean Prod 273:123095. https://doi.org/10.1016/j.jclepro.2020.123095
Imteaz MA, Moniruzzaman M (2018) Spatial variability of reasonable government rebates for rainwater tank installations: A case study for Sydney. Resour Conserv Recycl 133:112–119
Imteaz MA, Rahman A, Alsan (2012b) Reliability analysis of rainwater tanks: A comparison between South East and Central Melbourne. Resour Conserv Recycl 66:1–7. https://doi.org/10.1016/j.resconrec.2012.05.009
Imteaz MA, Paudel U, Santos C (2021) Impacts of climate change on weather and spatial variabilities of potential water savings from rainwater tanks. J Clean Prod 311(127491). https://doi.org/10.1016/j.jclepro.2021.127491
Karim MR, Bashar MZI, Imteaz MA (2015) Reliability and economic analysis of urban rainwater harvesting in a megacity in Bangladesh. Resour Conserv Recycl 104:61–67. https://doi.org/10.1016/j.resconrec.2015.09.010
Karim MR, Sakib BMS, Sakib SS, Imteaz MA (2021) Rainwater harvesting potentials in commercial buildings in Dhaka: reliability and economic analysis. Hydrology 8(9). https://doi.org/10.3390/hydrology8010009
Khan Z, Alim MA, Rahman MM, Rahman A (2021) A continental scale evaluation of rainwater harvesting in Australia. Resour Conserv Recycl 167(105378). https://doi.org/10.1016/j.resconrec.2020.105378
Lade O, Oloke D, Chinyio E and Fullen M (2012) Use of multi-criteria decision analysis methods for water supply problems: A framework for improved rainwater harvesting. J Environ Sci Eng A 1(7):909–917
Lizárraga-Mendiola L, Vázquez-Rodríguez G, Blanco-Piñón A, Rangel-Martínez Y, González-Sandoval M (2015) Estimating the rainwater potential per household in an urban area: Case study in Central Mexico. Water 7:4622–4637. https://doi.org/10.1016/j.watres.2015.02.007
Matomela N, Li T, Ikhumhen HO (2020) Siting of rainwater harvesting potential sites in arid or semi-arid watersheds using GIS-based techniques. Environ Process 7:631–652
Matos C, Santos C, Bentes I, Imteaz MA, Pereira S (2015) Economic analysis of a rainwater harvesting system in a commercial building. Water Resour Manag 29(11):3971–3986. https://doi.org/10.1007/s11269-015-1040-9
Mnaji CC, Aigbavboa C (2020) A scenario-driven assessment of the economic feasibility of rainwater harvesting using optimized storage. Water Resour Manag 34:393–408
Santos C, Imteaz MA, Ghisi E, Matos C (2020) The effect of climate change on domestic rainwater harvesting. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138967
Shadeed S, Alawna S (2021) Optimal sizing of rooftop rainwater harvesting tanks for sustainable domestic water use in the West Bank, Palestine. Water 13(573). https://doi.org/10.3390/w13040573
Valdez MC, Adler I, Barrett M, Ochoa R, Pérez A (2016) The water-energy-carbon nexus: Optimising rainwater harvesting in Mexico City. Environ Process 3:307–323
Zhang S, Jing X, Yue T, Wang J (2020) Performance assessment of rainwater harvesting systems: Influence of operating algorithm, length and temporal scale of rainfall time series. J Clean Prod 253(120044). https://doi.org/10.1016/j.jclepro.2020.120044

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