

Modeling Rainwater Harvesting Systems with Covered Storage Tank on A Smartphone

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1 Introduction

Harvesting rainwater and storing it in a covered tank for future use is an attractive way of meeting the water needs in many parts of the world¹. Such systems are often referred to as rainwater harvesting systems with covered storage tanks; for brevity, we will refer to them simply as RWHS. These systems are appealing on many counts: they are relatively simple to build, easy to integrate with other sources of water, and they minimize the use of energy for transporting the water from the source to the user. The role of RWHS is likely to increase with the increasing occurrence of drought, even in the regions which historically have not faced water scarcity [1].

An important concern while exploring the use of RWHS as a main or supplemental source of water is the variability in the rainfall. It is expected that due to global warming the variability in rainfall will increase in many parts of the world, and this will be reflected in frequent droughts interspersed with floods [2][3]. Therefore it is important to take into account these fluctuations in rainfall in designing and using RWHS. Specifically, we would like to take into account these fluctuations in finding the optimum tank size for meeting a given demand from a given catchment area. Similarly, while developing strategies for facing a drought we would like to take into account the fluctuations in rainfall in estimating the amount of water that will be available in the immediate future knowing the present amount of stored water.

Aim of this article is to document a model that attempts to answer the above questions². The model has been implemented as an app *SimTanka* for smartphones³. The

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¹For more details see the article Rainwater Harvesting in Wikipedia

²Precursor of the present model is described in [4]

³*SimTanka* is a free and open-source app for designing, maintaining and using a RWHS. More details of the app and its availability can be found here.

outline of the article is as follows: In the next section (2) we set up the water balance equation and describe the algorithm used to calculate the model probabilities for the reliability of a given RWHS in meeting the user's water needs. A critical look at the model and the manner in which the model probabilities are used in *SimTanka* is described in sec. (3). In sec. (4) we illustrate the use of *SimTanka*. We state our conclusions in the final section (5).

2 Water balance equation and the model probabilities

A RWHS with covered storage tank is characterized by three parameters: one, the size of the catchment area A , secondly, the so-called runoff coefficient k which determines the fraction of the rainwater that can be harvested from a given catchment area; and finally, by the volume V of the storage tank. The question that we are interested in answering is how well this system can meet a *given* water demand. If we could know in advance the daily rainfall, then one can use a simple water balance equation to answer this question. In the absence of such knowledge we would like to develop a model that uses past daily rainfall records together with the water balance equation to generate model probabilities for the likelihood of the system meeting a given demand.

With this in mind we first set up the water balance equation for a RWHS. Let R_i be the rainwater harvested on i^{th} day which is related to the daily rainfall r_i and the catchment area A through

$$R_i = k \times r_i \times A, \quad (1)$$

here k is the runoff coefficient which characterizes the surface area. Using R_i we can evolve W_i the water in the tank on i^{th} day from W_{i-1} in the following manner: if V is the volume of the storage tank and D_i is the daily water demand for the i^{th} day then we first calculate a variable M_i

$$M_i = \min(W_{i-1} + R_i, V) - D_i \quad (2)$$

then we evolve the variable W_i

$$W_i = \begin{cases} M_i & \text{if } M_i \geq 0 \\ 0 & \text{if } M_i < 0 \end{cases}. \quad (3)$$

Equation (2) implements the constraint that amount of water in the tank cannot be greater than the volume of the tank and (3) ensures that the water in the tank cannot be negative. Using these equation together with the given initial condition W_0 , the amount of water at the beginning of the simulation, we can evolve the amount of water in the tank. We will be interested in two scenarios, one in which $W_0 = 0$, that is we start with an empty tank, and other in which the user provides us with the initial amount of water in the tank.

2.1 Estimating the reliability of the RWHS

We would like to estimate the likelihood of our RWHS meeting the given water demand. For this purpose we evolve the RWHS using eqs. (1-3) for the last five years with the initial condition $W_0 = 0$ and using the daily rainfall data from the historical time series of daily rainfall record for the past five years. Then we calculate the fraction of days for which M_i (2) is greater than or equal to zero while the demand D_i is not zero

$$\text{reliability} = \frac{\text{number of days when the system could meet the demand in past five years}}{\text{total number of days in five years with non-zero water demand}}. \quad (4)$$

A pseudo code that implements this calculation is show as Algorithm (1).

2.2 Model probability for the future performance of the RWHS

Similarly we can estimate the probability for meeting the daily demands for the next thirty days knowing the amount of water in the tank by evolving the system using last five years of daily rainfall record but now with the initial state of the system W_0 being provided by the user and evolving the system only for the next thirty days:

$$\begin{aligned} W_0 &= \text{Observed amount of water in the tank} \\ W_0 &\rightarrow W_{0+30} \quad \text{for each of the past years} \\ \text{probability} &= \frac{\text{number of successful days}}{\text{total number of non-zero water demand days}} \end{aligned} \quad (5)$$

The pseudo code for this is presented in Algorithm (2).

3 Motivation for the model and its use in *SimTanka*

The main purpose for developing this model was to facilitate the building, maintaining and using a RWHS. With this in mind the model has been implemented as an app called *SimTanka* for smartphones. There are various features of the model which are to an extent arbitrary. We comment on the rational behind these choices. The model assumes that the rainfall pattern at any location changes on a time scale which is greater than five years. The use of the past five years of daily rainfall records to estimate the future performance is an ad-hoc, but unfortunately, a necessary assumption in the absence of a dynamical model for predicting future rainfall with a useful precision. The choice of using past five years of daily rainfall records rather than say past ten years of rainfall records is a compromise between exposing the system to rare events and limiting the computation that can be done in real time on a smartphone.

Fortunately the ad-hoc nature of the model is to some degree mitigated by the manner in which the model is used. The model is used to answer two questions for the user:

1. Will the reliability of my system improve if I increase the volume of the storage tank?

Algorithm 1 A pseudo code for calculating the likely hood of the success in meeting the users demand based on the past rainfall records.

- N_{days} is the number of days in the past for which we have the daily rainfall record
- W is an array of $N_{\text{days}} + 1$ elements for storing the amount of water in the storage tank at the end of the i_{th} day.
- D is an array of N_{days} which contains the water demand for the i_{th} day. This array is provided by the user.
- N_d is a variable to store the number of days for which the RWHS is used.
- N_s is a variable to store the number of days for which the RWHS could meet the user's demand.
- H is an array of N_{days} for storing the amount of water harvested on the i_{th} day and is given by

$$H_i = k \times R_i \times A,$$

where k is a dimensionless constant characterizing the catchment area and it value ranges from 0 to 1, R_i is the rainfall on the i_{th} day and A is the area of the surface from which the rainwater is harvested.

```

W0 = 0 // we start with an empty tank
for i in 1...NDays {
    Wi = Wi-1 + Hi // Hi is the rainfall harvested on ith day
    Wi = min (Wi, V) // V is the volume of the storage tank

    if Di > 0 {
        // tank is used
        Nd = Nd + 1
        Wi = Wi - Di

        if Wi ≥ 0 {
            // RWHS is used and could meet the demand
            Ns = Ns + 1
        }
    } else {
        Wi = 0 // demand could not be met
    }
}
// Probabibility of success is calculated
// only if the water demand is non-zero
if Nd > 0 {
    Psucc = (Ns/Nd) × 100
}

```

Algorithm 2 Pseudo code for estimating the future performance

```
initialAmount = amount of water in the storage tank on the start date
// provided by the user

for year in PastYears {
// start with the amount of water measured by the user
waterInTankYesterday = initialAmount

for i in start Date ... start Date + 30{

    waterInTankToday = waterInTankYesterday +  $H_i$ 
    //  $H_i$  is the rainfall harvested on  $i_{th}$  day

    waterInTankToday = min(waterInTank,  $V$ )
    //  $V$  is the volume of the storage tank

    if  $D_i > 0$  {
        // tank is used
         $N_d = N_d + 1$ 
         $W_i = W_i - D_i$ 

        if  $W_i \geq 0$ {
            // RWHS is used and could meet the demand
             $N_s = N_s + 1$ 
        }

    } else {
         $W_i = 0$  // demand could not be met
    }
    // prepare for tomorrow
    waterInTankYesterday = waterInTankToday
}
// append the water in the tank on the last day to an array
waterAtTheEndOfSimArray.append(waterInTankToday)
}
// Probabibility of success is calculated
// only if the water demand is non-zero
if  $N_d > 0$  {
     $P_{succ} = \left(\frac{N_s}{N_d}\right) \times 100$ 
}
// estimate of the minimum amount of wate in the tank
likelyWaterInTheTankAtTheEnd = min (waterAtTheEndOfSimArray)
```

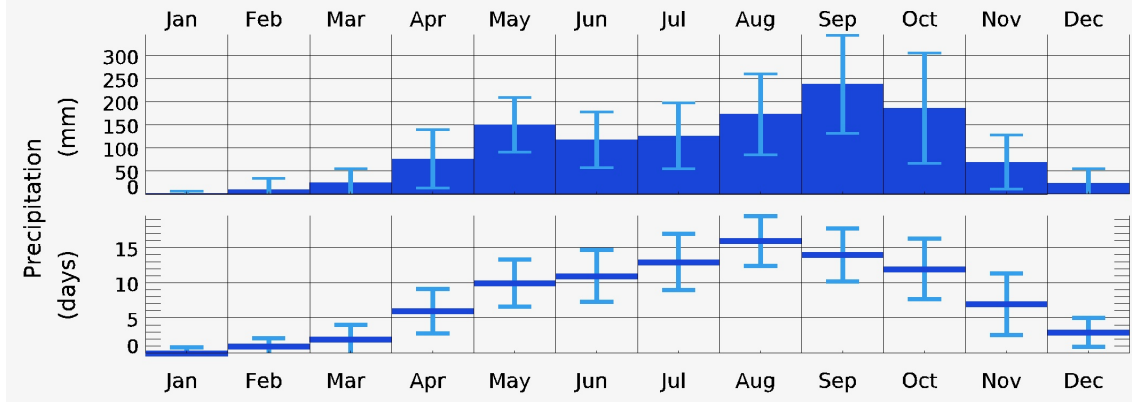


Figure 1: Rainfall pattern for Bangalore, India bars represent the standard deviation from the average value (obtained from metoblue.com)

- Will the system be able to meet my water needs for the next thirty days and how much water will be there in the tank after that?

The model is used to answer these questions by using the following heuristic metric,

$$\text{Reliability} = \begin{cases} \text{if } P \leq 0.5 & \text{Unlikely} \\ \text{if } 0.5 < P \leq 0.6 & \text{Occasionally} \\ \text{if } 0.6 < P \leq 0.8 & \text{Fair} \\ \text{if } 0.8 < P \leq 0.9 & \text{Good} \\ \text{if } 0.9 < P \leq 1.0 & \text{Very Good} \end{cases} \quad (6)$$

where P is the model probability calculated using the above described algorithm.

4 Illustrative use of *SimTanka*

We present the results for the use of model probabilities for two different scenarios.

4.1 Domestic rainwater harvesting system in Bangalore, India

Bangalore, like many other metropolitan cities is facing water shortage. For city like Bangalore, which has roughly six rainy months in an year (see Fig. (1)) rainwater harvesting can be a very attractive supplemental source of water. This has been recognized by the state government by requiring that all buildings with area larger than 100 m² must construct a rainwater harvesting system⁴. We consider a RWHS which is used throughout the year for watering a garden in a residential house. The house has a catchment area of 150 m² and for illustrative purpose daily water requirement of 100 Liter/Day was assumed. The existing system has a tank size of 1.2 m³. A natural question for a user to ask is “Is it worth increasing the tank size?” Such questions can be easily addressed using

⁴See the article: Harvesting and using rainwater, a must in Bengaluru

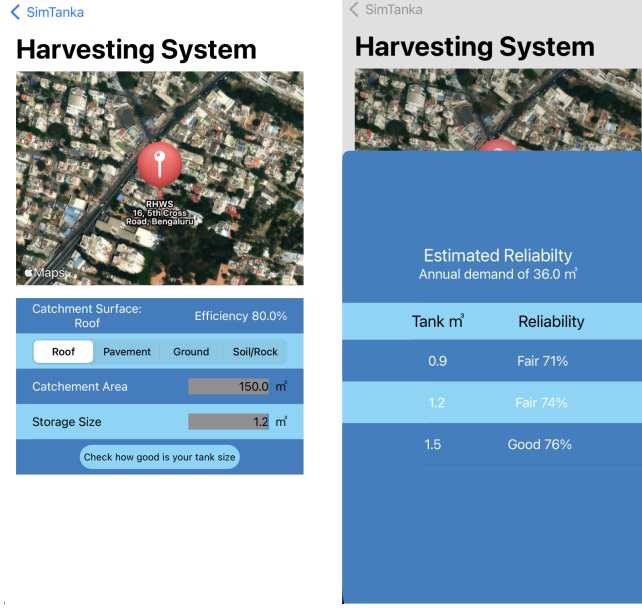


Figure 2: Estimating the reliability of a RWHS with the user provided tank size

SimTanka. In Fig. (2) we show the screen shots of *SimTanka* exhibiting the performance for the original tank size of 1.2 m³ along with tank sizes which are 25% smaller and 25% larger. These simulations were done using daily rainfall data for Bangalore for the years 2018-22 [5]. We see that the estimated reliability of the users existing system is 74% with not significant changes in reliability for the smaller and the larger tanks. In Fig. (3) we exhibit the performance for a scenario in which the user doubles the size of the storage tank to 2.4 m³. With a tank size of 2.4 m³ the reliability of the original system increases from 74% to 80%. For a RWHS which is used as a supplemental system this modest increase in reliability may not be worth the expense of an additional tank. But we can imagine a situation where the same RWHS is used as a main source of water and we may want to find the “optimum” tank size, namely the tank size which provides maximum reliability for the minimum storage size. Using *SimTanka* repeatedly one can answer such a question. The results from such repeated use of *SimTanka* are exhibited as a graph between the size of the storage tank and the reliability in Fig. (4). For the scenario under consideration the optimum tank size is approximately 11 m³ with a reliability of 96%. It is important to emphasize that this optimum tank size is based on the user provided fixed daily water budget, and in real life situation adherence of a user to a fixed water budget may not always be possible.

4.2 Rainwater harvesting systems in Thar Desert, India

Traditional rainwater harvesting systems called *Tanka*⁵, like the one shown in Fig. (5)), have played an important role for the communities living in Thar Desert of India (see

⁵For more details see the wikipedia article Tanka

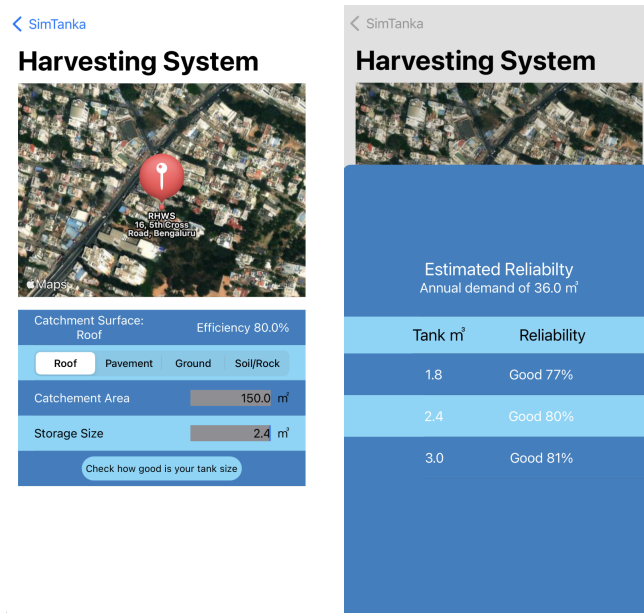


Figure 3: Exploring the doubling of the tank size using *SimTanka*

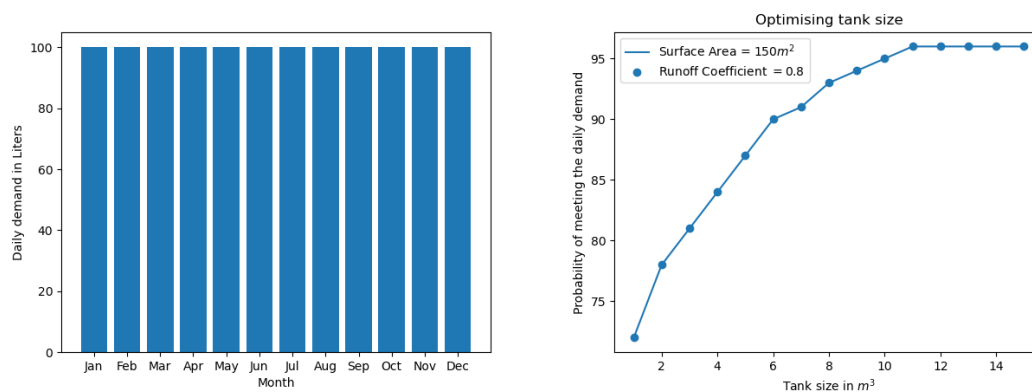


Figure 4: Reliability of a RWHS in Bangalore as a function of the tank size for the given daily water demand.



Figure 5: A traditional rainwater harvesting system in Thar desert of Rajasthan, India. (Public Domain, Wikipedia)

for e.g. [6] and references there.) The rainfall pattern for Jodhpur which lies in Thar Desert is shown in Fig. (6). As is typical of a location in arid or semi-arid region, the rainfall is concentrated in two to three months in a year, further the rainfall is meager and erratic often leading to a drought like situation. We use *SimTanka* to explore two aspects of using RWHS in arid and semi-arid regions.

4.2.1 Estimating the effect of improving runoff coefficient

Tanka's typically have a large catchment area, for the example we will consider the catchment area is 166 m^2 , and their efficiency can be improved by treating the catchment area by making the surface more impervious and thus increasing the runoff coefficient. Such treatments are expensive, thus it is useful to estimate before hand the increase in the efficiency of the system and see if the extra investment is a worthwhile. We illustrate this for a RWHS located in a remote village of *Bhaloo Rajwan* (latitude: 26.56757, longitude: 72.46754) in Jodhpur district [6]. We consider a situation in which the user has a water budget of 100 Liter/day all through the year and exhibit the effect of improving the runoff coefficient from 0.3 to 0.6 in Fig. (7). One can see a dramatic increasing the reliability of the system from 51% to 85% for the optimum tank size. Indicating that it might be worth while to make an investment in treating the catchment area. Simulations were done using daily rainfall records for the period of (2018-2022) [5]⁶.

4.2.2 Devising strategies to meet water shortage

Often a user of RWHS will have to face water shortage, either because of more than planned use of water or because of draught like situation leading to inadequate harvesting of rainwater. In response to such a situation, the user can either try and reduce the daily

⁶For details of how Visual Crossing Weather supplements the observation weather data with data derived from remote sources, such as satellites and radar see their website.

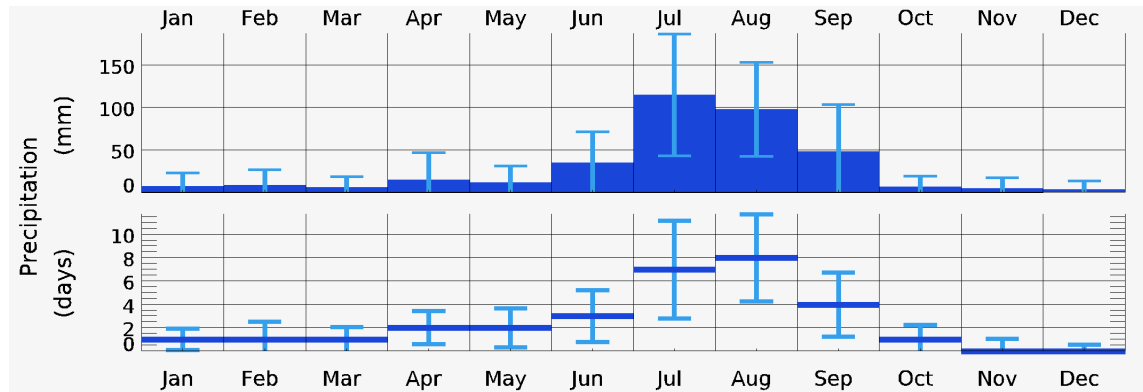


Figure 6: Rainfall pattern for Jodhpur, India based on last ten years of rainfall. Bar represents standard deviation from the average value (obtained from meto-blue.com)

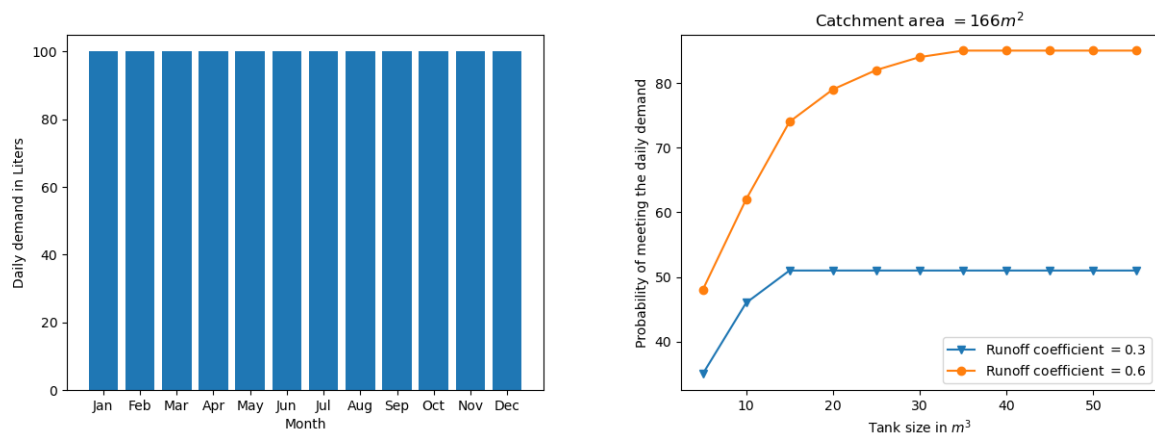


Figure 7: Estimating the improvement in the reliability of a RWHS in Thar Desert by increasing the runoff coefficient

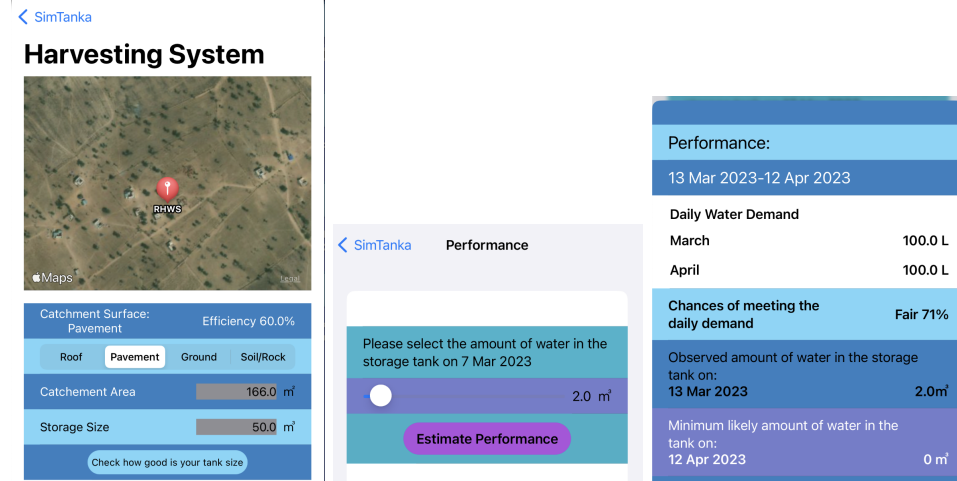


Figure 8: Estimating future performance of a RWHS in Thar Desert, India

water demand and or supplement harvested rainwater with water from other sources, including purchasing water from private suppliers. We can use *SimTanka* to estimate the efficacy of such strategies. We again consider a *Tanka* located in Thar Desert which is described in Fig. (8), and explore a hypothetical situation in which the user observes that the water in storage tank is 2.0 m^3 , and then uses *SimTanka* to estimate if the system will be able to meet the water needs for the next thirty days. The result of this estimation are also shown in Fig. (8) and we see that there is a significant chance that the RWHS may not be able to meet the water needs of the user. In Fig. (9) we show the effect of various combinations of reducing water demand from 100 Liter/Day to 75 Liter/Day and of purchasing 1000 Liters of water. Not surprisingly the greatest water security is obtained by purchasing 1000 Liters of water and reducing the daily demand to 75 Liter/Day.

5 Conclusion

RWHS are useful means of meeting the water needs in water scarce regions of the world. Their attractiveness is tempered by their potential unreliability as they depend on the vagaries of the daily rainfall. The aim of the model described here is to try and mitigate these uncertainties by using past daily rainfall records to estimate future reliability. The model has been implemented as an app *SimTanka* for smart phones. In the planning stage it can inform the user the extent to which the planned RWHS system will be able to meet the user's water budget. Once the RWHS is build, or for existing RWHS, the app can be useful in developing strategies for meeting drought like situation. The app also allows the user to maintain monthly records that includes the amount of water in the storage tank at the beginning of the month and the potability of the water.

A natural question to ask is wether the probabilistic models described here can be replaced, or supplemented, by machine learning models. The present view of the experts

Performance:	Performance:	Performance:
13 Mar 2023-12 Apr 2023	13 Mar 2023-12 Apr 2023	13 Mar 2023-12 Apr 2023
Daily Water Demand	Daily Water Demand	Daily Water Demand
March 75.0 L	March 100.0 L	March 75.0 L
April 75.0 L	April 100.0 L	April 75.0 L
Chances of meeting the daily demand Good 87%	Chances of meeting the daily demand Very Good 96%	Chances of meeting the daily demand Very Good 100%
Observed amount of water in the storage tank on: 13 Mar 2023 2.0m ³	Observed amount of water in the storage tank on: 13 Mar 2023 3.0m ³	Observed amount of water in the storage tank on: 13 Mar 2023 3.0m ³
Minimum likely amount of water in the tank on: 12 Apr 2023 0 m ³	Minimum likely amount of water in the tank on: 12 Apr 2023 0 m ³	Minimum likely amount of water in the tank on: 12 Apr 2023 0.7 m ³

(a) Reducing Demand (b) Purchasing water (c) Purchasing water and reducing demand

Figure 9: Using *SimTanka* to explore strategies to meet water shortage

seems to be less than sanguine on this possibility [7] but it is an attractive possibility particularly in conjunction with local automated rainfall measuring instruments and automated measurement of water in the storage tank. These two sets of information providing the necessary data for machine learning models.

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