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Monte-Carlo Simulation of Rainwater Harvesting Systems

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Abstract

A model for simulating the performance of rainwater harvesting systems is presented. The model explicitly takes into account the fluctuations in the rainfall. This is done using the techniques of Monte Carlo simulation. The model has found use in developing sustainable water resources for rural communities living in the arid and semi arid regions of the world.

Keywords

Rainwater, fluctuations, Monte-Carlo

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1 INTRODUCTION

It is being increasingly realized that a growing fraction of the human population will face scarcity of water in the coming decades and this will be felt most acutely by rural communities of the arid and semi-arid (ASA) regions of the world. In this context the role of rainwater harvesting systems (RWHS), by which we mean the collection, concentration and storage of rainwater that runs off a natural or man-made catchment surface (Lee, 1992) has greatly increased. For in the ASA regions the RWHS offers unique advantages over the alternative means of meeting the water needs of the rural communities. These advantages stem from the fact that the rainwater harvesting makes use of the natural water cycle in a sustainable way, further more by bringing the source of water closer to the users it minimizes the amount of energy needed to transport water. Contrasting these advantages of RWHS is its unreliability as a source of water, for these systems are dependent on a very meager and erratic rainfall. This is particularly true for the RWHS located in ASA regions.

Thus one is faced with the task of designing a RWHS that can meet, in spite of the erratic rainfall, the water demands of a community with a desired degree of reliability. The task of designing such a RWHS will be greatly facilitated if one has an access to a computer model for simulating RWHS that explicitly takes into account the fluctuation in the rainfall. In this paper we will describe one possible such model. The model uses the method of Monte-Carlo simulation to simulate the effect of fluctuating rainfall on the performance of a given RWHS. The outline of the paper is as follows: in the next section the basic assumptions underlying the use of the Monte-Carlo simulation and the resulting procedure for implementing it are described. In the third section of the paper use of Monte-Carlo simulations in designing RWHS is illustrated. The conclusions are stated in the final section of the paper.

2 MONTE CARLO SIMULATIONS

The RWHS, especially those located in the ASA regions, are dependent on an extremely erratic and meager rainfall. Further more, in general, the fluctuation in the rainfall is characterized by the simultaneous presence of many time scales, and thus cannot be easily characterized by means of few statistical indicators like the average value or the moments about the average value. Therefore a realistic simulation of RWHS must explicitly take into account all possible fluctuations in the rainfall pattern. One possible way of simulating the RWHS under such conditions is to assume that the rainfall pattern at the given place is given by some probability distribution and then use the method of Monte-Carlo simulation (Binder, 1984) to simulate this probability distribution.

The difficult and delicate question that one faces then is, what is this probability distribution. In this paper I have taken the approach that the probability distribution of the future rainfall pattern at a given place can be approximated by the known past rainfall record at that place. There are two reasons for making this assumption. Firstly, lacking a true dynamical understanding of the rainfall pattern, our best guide for the future estimate is the past experience. Secondly, this assumption allows for the possible changes in the weather pattern of a given place, say due to global warming, but only assumes that the rate at which this may be occurring, i.e. the time scale of the change of the entire probability distribution, is more than the order of few decades. As our dynamical understanding of weather increases one will have a more precise measure of this time scale. For the moment, according to our assumption one can use the rainfall data of the last few decades to simulate the behavior of a given RWHS for the next few decades.

With these assumptions in mind the pattern of rainfall can be simulated by the following procedure. Let Y_i to Y_f be the time period for which the monthly rainfall data is available, and we would like to use this rainfall data to define a probability distribution of the future rainfall. Then generate a (pseudo)random integer, with uniform probability, lying in the closed interval (Y_i,Y_f). If the integer is, say Y_j, then in the simulation the rainfall experienced is taken to be that which was recorded in the Y_j^{th} year. By repeating this procedure for sufficiently large number of times one can simulate the entire probability distribution. This procedure of simulating a stochastic variable, in our case rainfall, according to a given probability distribution is called the "Monte-Carlo" simulation (Binder, 1984). It is important to note that while this procedure does simulate the probability distribution it does not simulate any correlation that might be their in the rainfall of the successive years.

3 ILLUSTRATIVE EXAMPLE

To illustrate one possible use of Monte-Carlo simulations in designing of RWHS, consider a hypothetical system. For the purpose of illustration let us assume that a family would like to use a RWHS to meet its water needs during the dry months, March to June, when their main source of water, the well, fails to meet their needs. For this hypothetical case let us assume that the daily water demand of the family is 300 Liters. Let us also assume that the RWHS that family is planning to build will use a catchment surface that is made of compacted and smooth soil, characterized by a runoff coefficient value of 0.6. We will use simulations to find the size of the catchment area, and the volume of the storage tank so that the resulting RWHS can meet the family's water demands with a probability of at least 95%.

To test the assumptions made, in particularly of disregarding the possible correlation in the rainfall record, the simulations will be done using monthly rainfall data from the years 1901 to 1959 and this will be compared with the performance of the RWHS under the known time series of rainfall record for the years 1960 - 1990, and therefore maintaining any possible correlation that may be present in the rainfall pattern.

The parameters of the desired RWHS will be obtained by doing a rather coarse search in a two-parameter space of the catchment area, and the tank size. To start the search we use the value of the catchment area and the tank size based on the average value of the rainfall. The result of this search are shown in Table-1, and the results of the performance of the RWHS under the time-series of the rainfall for the period 1960 - 90 are presented in Table-2. The simulations clearly show that a RWHS designed on the basis of the average rainfall, in general, fails to meet its objective. Comparing Table 1. and 2, we see that the optimum tank size and the catchment area, bold faces in both tables, as obtained by our simulation using the rainfall data for the period 1901 - 59, does performs with the desired degree of reliability in the years 1960 - 90.

Table. 1

Simulation of a RWHS located at Chaksu, Rajasthan, India.

Using the rainfall record from 1901-59 Runoff - Coefficient = 0.6

Simulation was done for 200 cycles, each cycle consisting of 5 years.

Catch Area M^2	*Volume of the Storage Tank*	*Results of the Simulations as Probability, in percentage, of meeting the demand*			
		March	***April***	***May***	***June***
128	37	96	79	65	-
Based on the average value of the rainfall					
220	60	100	99	97	91
250	60	100	99	98	94
280	60	100	99	98	96
310	60	100	100	100	99
280	40	100	98	94	89
280	**50**	**100**	**99**	**99**	**95**
280	70	100	99	98	96

Table. 2

The performance of RWHS subjected to the time series of rainfall from year 1960-90

Catchment Area M^2	*Volume of the Storage Tank*	*Results of the Simulations as Probability, in percentage, of meeting the demand*			
		March	*April*	*May*	*June*
128	37	100	87	70	60
220	60	100	100	90	83
250	60	100	100	97	90
280	60	100	100	100	97
310	60	100	100	100	97
280	40	100	100	100	94
280	**50**	**100**	**100**	**100**	**97**
280	70	100	100	100	97

4 CONCLUSIONS

This illustration shows one of the ways in which the computer modeling allows one to enhance an environmentally attractive but unreliable technique of rainwater harvesting into a reliable source of water. The key reason that makes Monte-Carlo simulation useful is the existence of fluctuations with many time scales in the time-series data of the rainfall. There are many other problems of interest, both to environmental scientist and to physicist, where one is forced to model fluctuations on many scales simultaneously. It is not unreasonable to hope that the interactions between environmental scientists and computational physicists will bring new insights and techniques in modeling such complex systems.

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BIOGRAPHY

Vikram Vyas obtained his undergraduate degrees from Delhi University and Indian Institute of Technology, Bombay. In 1990 he obtained his Ph. D in theoretical physics from Boston University, USA. He has done research and taught at the University of Wuppertal, Germany and at the University of Utah, Salt Lake City, USA. His research interests have been focused on various aspects of numerical solution of Quantum field theories. At present he is working with the Ajit Foundation, Jaipur, India, as a scientist and Executive Director. His current research interests are in theoretical particle physics and on the application of methods of computational physics for modeling water and energy resources.