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A Model for Simulating Rainwater Harvesting Systems with Closed Tanks.

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ABSTRACT

A model for simulating the performance of rainwater harvesting systems that uses covered water storage tanks is presented. The model explicitly takes into account the fluctuations in the annual rainfall. The importance of such simulation is that they can provide an essential information for evaluating the possible role of rainwater harvesting in meeting the water needs of rural communities lying in arid and semi-arid regions.

1. Introduction

The idea of meeting the water and energy needs of a community by using local renewable resources is an attractive possibility, but for it to become a practical proposition will require, among other things, an intelligent integration of various resources. In this, the first of a series of papers, I will explore the role of computer simulation in achieving this aim, starting with the case of rainwater harvesting.

It has long been realized that the rainwater harvesting is an important means of meeting the water demand of a community in the water scarce regions, see Refs [1-3]. Its main attraction is that by harvesting rainwater one is using the water cycle in a way that is both sustainable and efficient. It has further advantage that its continual working is not dependent on external human agencies. In spite of these advantages the use of rainwater harvesting has been declining even in the areas where it was traditionally the main source of water, like the western parts of the state of Rajasthan in India[3]. Correspondingly there has been an increased reliance on the underground water provided by hand-pumps and on centralized piped water systems*. Some of the reasons for this decline can be traced to the differences in the expectations of the water users from a system based on rainwater harvesting as compared with that of a piped water system. In the mind of a user there is a definite advantage of having a piped water system for it (can) provide clean water in any desired quantity in a completely dependent manner, while a system based on rainwater harvesting is unreliable (the amount of rainfall is extremely erratic in Rajasthan), it can only provide a finite amount of water and that too has to be carefully stored. Further more there is a feeling that the piped water system is "free" while the development of rainwater harvesting systems requires an investment by the individual or by the community.

*By centralized piped water systems I mean the schemes in which the water is piped from a <u>distant source</u> at great expenditure of energy, in contrast to the case when water is delivered by means of pipe from local sources to a household.

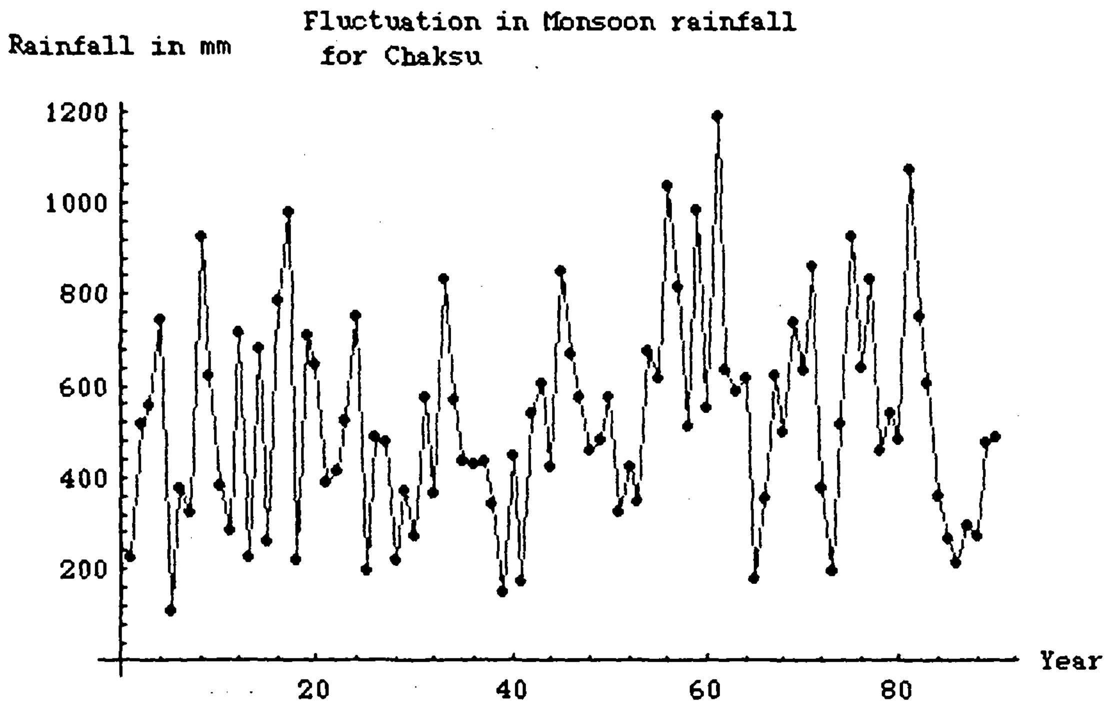

Figure 1

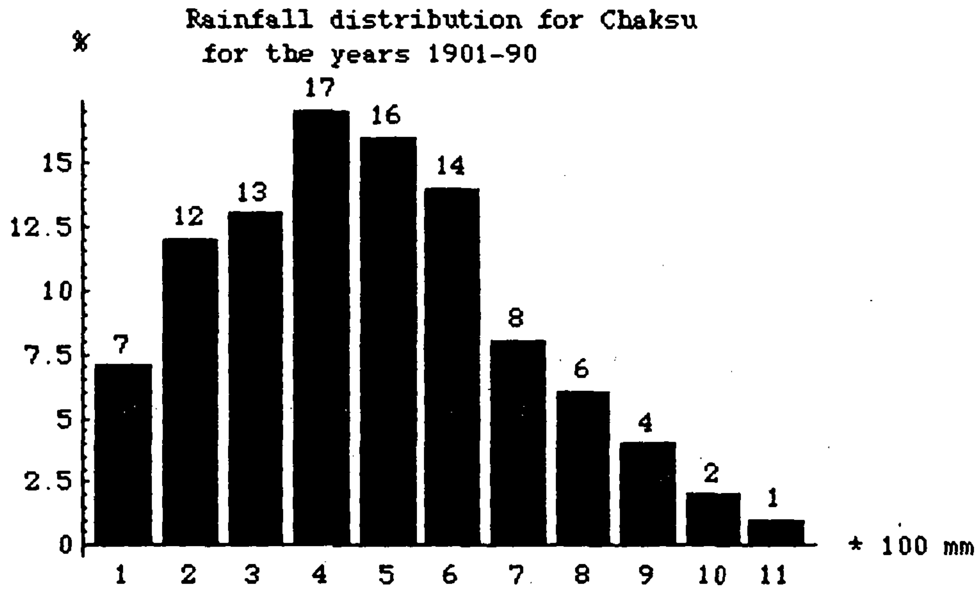

Figure 2 Histogram of the monsoon rainfall. Vertical axes represents the probability of the rainfall, while the horizontal axis represents the amount of rainfall in intervals of 100 mm.

This suggests that for the rain water harvesting to play its appropriate role will require that not only the advantages of using local renewable sources of water should be made explicit to a user and to a community, but also it will require the integration of local water and energy resources in a manner that they can compete with a centralized piped water schemes on the ground of ease of use and reliability. First step in such an integration of resources is to make an estimate of the potentiality of each individual source. In this paper I will develop a model for estimating the performance of a rainwater harvesting system, restricting to cases where the water is stored in a closed tank.

The outline of the paper is following: in the next section I will give my reasons for the need and advantage of computer simulation in developing rainwater harvesting systems for a community. The details of the method used for the simulation will be described in the third section. In the fourth section of the paper I will present the results of simulations of rainwater harvesting system located in the villages that are near Chaksu town in Rajasthan. In the last section of the paper I will state my conclusions.

II. The Need for Computer Simulation

One can consider two extreme limits as to the role of the rainwater harvesting. In one limit the entire water needs of a community are meet by rain water harvesting. The other limit being that rainwater harvesting is of no importance to the community. Some where between these two extremes lies the appropriate role of rainwater harvesting. One important piece of information that can help in determining this role is our estimate of the extent to which the rainwater harvesting can meet the water demands. More specifically, one would like to know that for a given demand of water what should be the size of rainwater harvesting system which can meet this demand with the desired degree of reliability. Alternatively, one would like to know, that to what extent and with what degree of reliability can a given system meet a fixed demand.

Further more we would like to answer these questions before building a rainwater harvesting system, since it is the answer to these questions that will determine the advisability of building such systems in the first place. Often such estimates are made on the basis of some simple characteristics of the rainfall data, like its mean (see Refs [1, 2]), but such characterization are inadequate when the rainfall shows a large degree of annual fluctuation. This is true for the much of the state of Rajasthan, see for example Figure 1.

Under such circumstances a reliable estimate of the performance of a rainwater harvesting system must take into account these large variations in the annual rainfall. There exists a way of simulating a fluctuating variable on a computer when it takes its value according to a known probability distribution. This, under certain assumptions that I will discuss in the next section, allows one to simulate the performance of a rainwater harvesting system which is dependent on a fluctuating annual rainfall for its functioning.

III. Monte-Carlo Simulation of Rainwater Harvesting Systems

The key element that goes in the simulation of a rainwater harvesting system is the estimate of the rainfall. In the present simulations I have assumed that the monsoon rainfall, at a given place, is distributed over the years according to a pattern that can be approximated by the known rainfall data of last hundred years or so. For example for Chaksu[**] the probability distribution of the monsoon rainfall is given by Figure 2. The key assumption that I am making is that the time scale over which the monsoon pattern **may** be changing is much larger than the order of few hundred years. I have chosen to make this assumption for two reasons. Firstly lacking a true dynamical understanding of the monsoon our best guide for the future estimate is the past experience. Secondly, from the presently available rainfall data, there in no **unambiguous** evidence for a change in the **statistical distribution** of the rainfall.

With these assumptions in mind the amount of rainfall in a given year at a given place can be simulated by following procedure: if L is the number of years for which the rainfall data for the given place is available then a random integer between one and L, with a uniform probability distribution, is generated. If that integer is y then the rainfall is assumed to be that which was observed in the y_{th} year of the time series of the annual monsoon rainfall for that place. By repeating this procedure a large number of times, say for few hundred times, one samples the entire probability distribution, Figure 2. In particular if one simulates the water harvesting system for the total period of hundred years using the time series data of Figure 1, then roughly for seven out these hundred years that rainfall will be between 100 and 200 mm, as expected from Figure 2. In this manner the rainwater harvesting system is subjected to, during the course of the simulation, to the entire spectrum of the fluctuation in rainfall. This procedure of simulating a stochastic variable, in our case rainfall, according to a known probability distribution is called the "Monte-Carlo" simulation.

The next step in modeling the rainwater harvesting system is to calculate the

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**Chaksu is a small town in the semi-arid region of the state of Rajasthan, India.

amount of rainwater collected by the system, which is a function of the catchment area and the nature of the collecting surface. In the model the nature of the collecting surface, like the type of the roof or the treated ground, is characterized by a parameter called the *runoff coefficient*. The runoff coefficient is defined as the fraction of the rainfall falling on the catchment area that is available for harvesting. Hence its value ranges between one and zero. In Table 1, which is taken from Ref [1], indicative values of the runoff coefficient are given for the various surfaces. The amount of water collected by the system in the i_{th} year of the simulation is

$$<W_i> = <r_i> * k * A$$

where $<W_i>$ is the amount of water collected in the i_{th} year; $<r_i>$ is the amount of (monsoon) rainfall in the i_{th} year simulated by the above mentioned Monte-Carlo procedure, k is the runoff coefficient, and A is the catchment area. The angular bracket around a quantity reflects its stochastic nature.

The above two steps are common to any Monte-Carlo simulation of rainwater harvesting system. In this paper I will restrict to the case when the collected water is stored in a container for which the loss of water due to evaporation or seepage is very small. The next step is to model the water usage. I have modeled the water usage in terms of two variables, n, the number of people (or the number of livestocks, or the number of trees/plants) that will be using the system, and d , the average daily water need per person. Thus, the annual demand made on the rainwater harvesting system is:

$$D = n * d * 365 .$$

The rainwater harvesting system is simulated in cycles of c years. In the beginning of the cycle the tank is assumed to be empty. The number of years in a cycle may be taken to be the interval before a major maintenance of the tank is required. The amount of water at the beginning and the end of the year is given by:

$$<T_1^b> \;=\; < W_1>,$$

$$<T_i^b> \;=\; <T_{i-1}^e> + < W_i>,$$

$$<T_i^e> \;=\; <T_i^b> - D.$$

$<T_i^b>$ is the amount of water at the beginning of the i_{th} year, and $<T_i^e>$ is the amount of water at the end of the year***. For the purpose of the simulation the year is taken to be the interval between two monsoons, and it is assumed that the water is collected only from the monsoon rains, for it is only during the monsoon that the conditions are suitable for rainwater harvesting. The size of the tank, *S*, appears as a constrain that the amount of water at the beginning of the year is always less than or equal to *S*.

***The details of the computer program used for the simulations can be obtained from the author.

Table 1. Runoff coefficients

Roof catchments	
- tiles	0.8 - 0.9
- corrugated metal sheet	0.7 - 0.9
Ground surface coverings	
- concrete	0.6 - 0.8
- plastic sheeting (gravel covered)	0.7 - 0.8
- butyl rubber	0.8 - 0.9
- brick pavement	0.5 - 0.6
Treated ground catchments	
- compacted and smoothed soil	0.3 - 0.5
- clay/cow-dung threshing floors	0.5 - 0.6
- silicone-treated soil	0.5 - 0.8
- soil treated with sodium salts	0.4 - 0.7
- soil treated with paraffin wax	0.6 - 0.9
Untreated ground catchments	
- soil on slopes less than 10 percent	0.0 - 0.3
- rocky natural catchments	0.2 - 0.5

Based on Ref[1].

IV. Results

The computer simulation of rainwater harvesting system can be used to answer two specific questions. One, what fraction of the water demand can be met by a given system. Here the catchment area, the nature of the collecting surface and the volume of the tank is assumed to be fixed, they may reflect the local constrains like the size of a typical house, number of people in a household and the size of the tank they can afford to build. The other question is to find the optimum size of the rainwater harvesting system for a given demand.

To illustrate this, consider the question of meeting the drinking water needs of a household living near Chaksu. In many villages near Chaksu the underground water is very high in fluoride content, and is therefore unfit for drinking. Hence it is natural to ask, that to what extent can one meet the drinking water needs by harvesting rainwater. The results of the simulation for answering this question are presented in Table 2. The parameters chosen for the simulation, particularly the demand, are more for the purpose of illustration than to reflect the actual water needs of the user. This can be rectified by consultation with the user, which as has been emphasized in Refs[1-3], is the single most important ingredient for a successful implementation of rainwater harvesting.

Some comments need to be made in interpreting the results of the simulation. A simulation based on a stochastic or fluctuating input will correspondingly reflect this in the end results, thus the simulation can give only probability distributions. In Table 2 these distributions are represented by their mean values, and the fluctuation about these mean values is given by the standard deviation (S.D.), thus all the results are presented in the form of "mean value +/- S.D.." The simulation where done as if rainwater harvesting system had been operating for five-hundred years, the reason for what may appear to be an artificially long time is to give the system enough time to experience all possible fluctuation in the rainfall. Also the simulations where done in cycles of five years, this is particularly useful in simulating large systems where there is a possibility of storing surplus water due to occasional above average rainfalls, in these cases the cycle length can be interpreted as the interval between the major maintenance of the tank which requires its emptying.

The results are presented in terms of number of months in a year for which a given rainwater harvesting system can meet the assumed demand. Only the mean values and their standard deviations have been shown in Table 2, even though the simulation gives the entire distribution, this is shown in Figures 3 and 4. Using these results we can answer the question posed at the beginning of this section. Firstly for a given catchment area and tank size we can find the extent to which the system can meet the assumed demands. For example a system consisting of a catchment area of 36 m^2 and a tank size of 20 m^3 can meet assumed demand for an interval ranging between 6-12 months period with 88% reliability, see Figure 3. From this we see that in order to meet the drinking water need with say 95% reliability will require an access to other sources that are capable of meeting the demand for eight months. Figure 4 shows the performance a system for various tank sizes, this figure also allows us to find the optimum tank size for a given catchment area. Finally one can also see from Table 2 that the minimum configuration for meeting the entire drinking water demand by harvesting rainwater alone is: Catchment area of 64 m^2 and a tank with a capacity of 50 m^3. As mentioned above the particular assumption about the usage of water is merely to illustrate, for example if after consultation with the potential user, and from past experience, it is realized that the rainwater collected is used not merely for drinking but also for other purposes then one can do the simulation with this in mind by changing the daily water requirement.

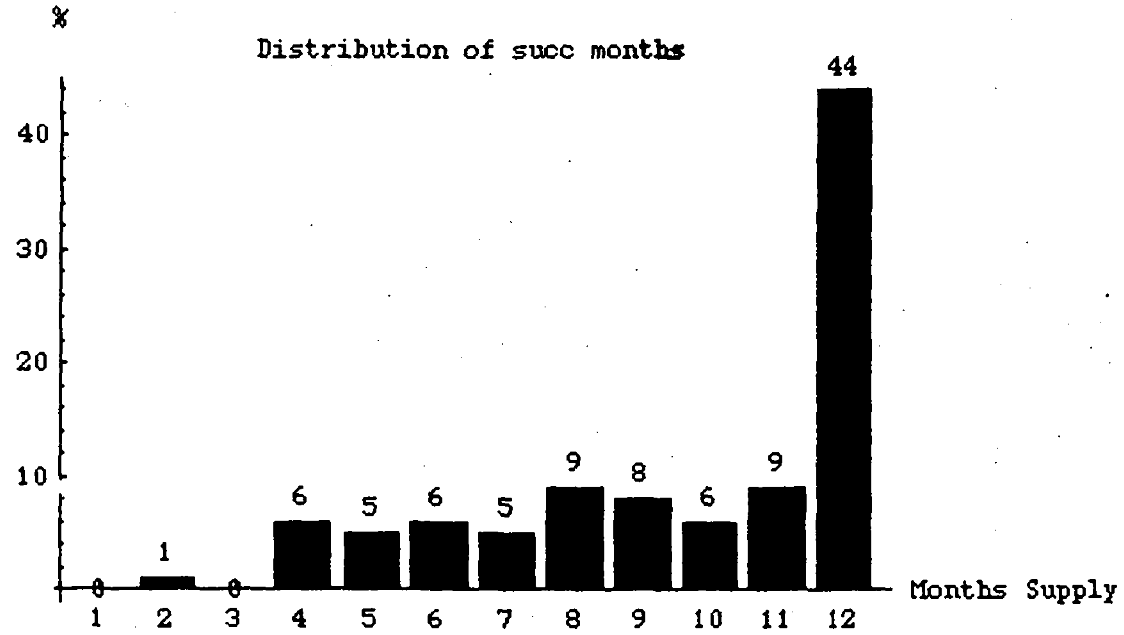

Figure 3 : Performance of a system with Catchment Area of 36 m^2 and Tank size of 20 m^3

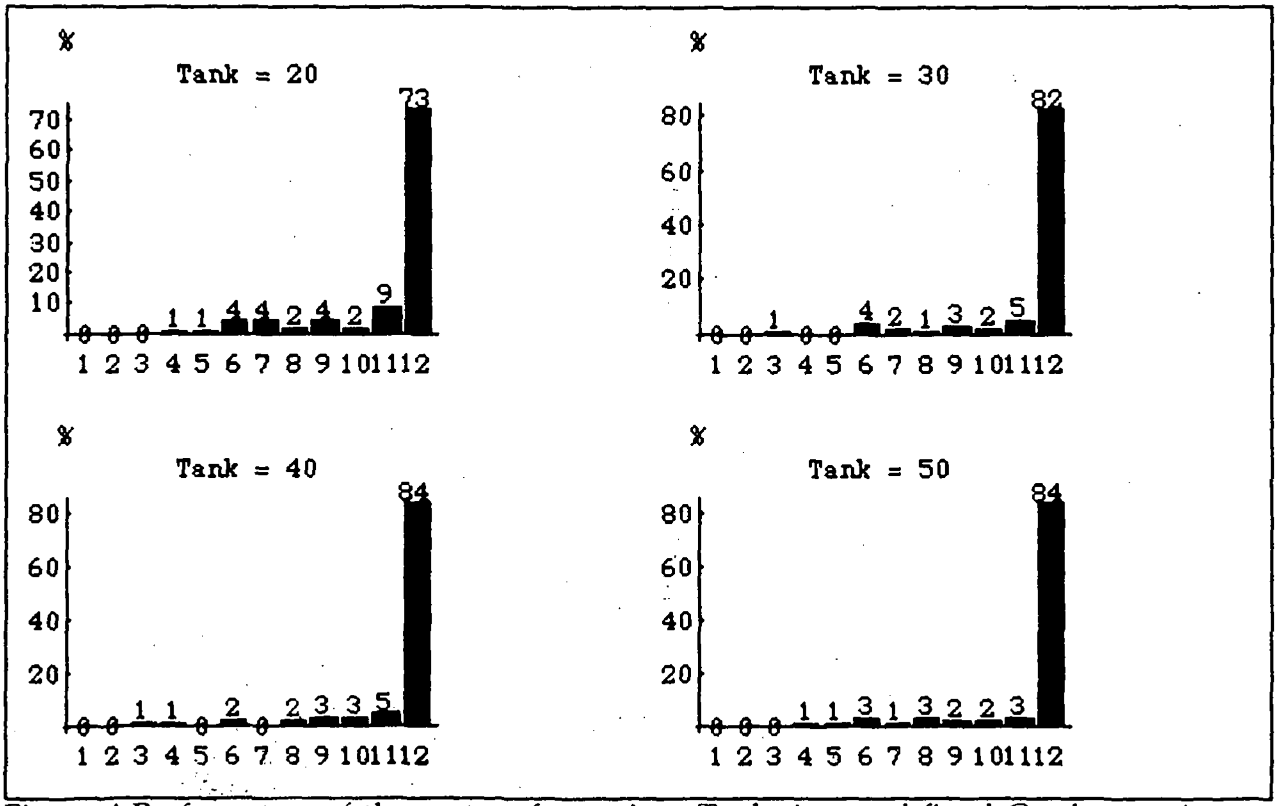

Figure 4 Performance of the system for various Tank sizes and fixed Catchment Area = 49 M2

Table 2: Simulation of a rainwater harvesting system in Chaksu using the rainfall data for the years 1901-1984

The simulation is done for 500 years in the cycles of 5 years

Number of people in household = 7
Daily drinking water need per person = 7.0 Liters
The runoff coefficient = 0.8

Catchment Area (m^2)	Tank Volume (m^3)	Number of months for which the system can meet the demand.
36	20	9 +/- 2.9
	30	10 +/- 2.8
	40	10 +/- 2.9
	50	10 +/- 2.8
49	20	11 +/- 2.1
	30	11 +/- 1.8
	40	11 +/- 1.8
	50	11 +/- 1.8
64	20	11 +/- 1.7
	30	12 +/- 1.2
	40	12 +/- 1.1
	50	12 +/- 0.73
81	20	12 +/- 1.2
	30	12 +/- 0.92
	40	12 +/- 0.87
	50	12 +/- 0.78

V. Conclusions

The main aim of this paper was to present a model for simulating the performance of rainwater harvesting systems that uses covered water storage tanks. The importance of such simulation is that they can provide an essential information for evaluating the importance of rainwater harvesting. This was illustrated by simulating the performances of the rainwater harvesting systems located in Chaksu (Rajasthan).

In case of Chaksu, even with the simplified assumptions made for the water demand, few conclusions are clear. The rainwater harvesting system by itself cannot, except in the rare cases of very large systems, meet the entire water demand of a household or a community, but it can meet a significant fraction of it and therefore should be considered as a viable source of drinking water.

These conclusions naturally suggest that the next step should be an integration of the present model for rainwater harvesting with other local sources like underground water. It is unlikely that any one single source by itself can meet the water needs of a small rural community in arid or semi-arid zone, therefore one will have to look for a combination of various sources, each in itself unreliable and inadequate but combined in a manner so that together they can provide an adequate amount of water for the community. It is in designing such networks that computer simulation will play an essential role.

Acknowledgments

The initial impetus for the present work was the availability of the detailed rainfall records of Rajasthan at the Institute of Development Studies (IDS) Jaipur, I am grateful to Dr. M. S. Rathor, coordinator of water management program and his colleagues at IDS for giving me the access to this data. I have also taken advantage of the generosity of the various members of IDS faculty in trying to rectify my ignorance about the different aspects of the water situation in Rajasthan. The present work would not have been possible but for the help of the members of three organizations: CECOEDDECON, Jaipur Rural Health & Development Trust, and Kumarappa Institute; they introduced me to the different villages in Chaksu, and explained me the various constrains and difficulties involved in solving the problem of providing water in rural communities. For that I would like to thank Dr. Sharad Joshi at CECOEDDECON, Dr D. K. Jagdev at Jaipur Rural Health & Development Trust, and Dr. Awadh Prasad at Kumarappa Institute.

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