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Development of a Computer Model for Domestic Rainwater Harvesting System

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***Abstract*—The major objective of this research is to develop a computer model named RAINMOD capable of performing comprehensive analysis for rooftop rainwater harvesting system. For this purpose village Saroona, Tehsil Allai, District Battagram was chosen as study area. Thirty houses were chosen at random on which complete system with two tanks of capacity 2250 Liters and 4500 Liters were installed. For comprehensive analysis of rooftop rainwater harvesting system, twenty five years of daily rainfall data for Balakot (1988-2012) was collected from Meteorological Stations of Peshawar and Lahore. For developing the generalized equations to determine adjusted performance parameters, twenty five years of daily rainfall data for Kakul (1988-2012) alongwith ten years of daily rainfall data for Saidu Sharif (2003-2012) was also collected from Meteorological Stations of Peshawar and Lahore. This model utilized the concept of two-state Markov chains and Gamma distribution for generating daily rainfall from historic daily, monthly and mean monthly rainfall data of Balakot Station which was then utilized for sizing of storage tank and prediction of performance parameters. Tank size was under-estimated for about 87 per cent of houses on which complete system was installed with respect to average tank size estimated from RAINMOD by utilizing different rainfall data. RAINMOD predicted average tank size within the range of 200 Liters and average adjusted performance parameters within 1 per cent by utilizing different rainfall data. Similarly, it predicted average tank size within 675 Liters and average adjusted performance parameters within the range of 4 per cent of observed daily data corresponding parameters. At 5 per cent significance level, storage tank size did not exhibit significant differences when it was estimated from RAINMOD by utilizing daily and mean monthly data, monthly and mean monthly data but exhibited significant differences when daily and monthly data was utilized by RAINMOD. Similarly, at 5 per cent significance level, all the adjusted performance parameters estimated at 2250 Liters and 4500 Liters tank from RAINMOD did not exhibit siginificant differences when monthly and mean monthly data was utilized but exhibited significant differences at 2250 Liters tank when daily and mean monthly data was utilized. Similarly, only adjusted storage efficiency and adjusted system efficiency estimated at tank size of 2250 Liters from RAINMOD exhibited significant differences at 5 per cent significance level when daily and monthly data was utilized. Majority of the parameters exhibited significant differences at 5 per cent significance level when they were estimated from observed daily data and RAINMOD utilizing daily data, observed daily data and RAINMOD utilizing monthly data, observed daily data and RAINMOD utilizing mean monthly data. Overall, the RAINMOD performed well for estimating different parameters by utilizing different rainfall data indicating that it is a reliable model for estimating different parameters under different rainfall data. This model will be a useful tool for various agencies since an effort is made to overcome the major issue of lack of long-term daily rainfall data.**

Keywords*—RAINMOD; Saroona; Balakot; Kakul; Saidu Sharif; Markov chains; Gamma distribution; performance parameters; tank size

I. INTRODUCTION

Fresh water is necessary for survival of life. Without it, there is no life. However, its availability remained a serious issue in both urban and rural areas in developing as well as in developed countries [14][4]. Under-investment, population growth and administrational failure as well as competition between irrigation, domestic water supply and industrial sectors are the major reasons for water scarcity. Groundwater has often been used as mainstay of domestic water supply as its quality is generally reliable. However, water table nowadays is depleting due to increase consumptive use and population growth.

Domestic Rooftop Rainwater Harvesting System (DRWH) technology is useful in hilly areas as it brings the source of water close to point of use. Hence, it eliminates the need for fetching water from far off places and reduces energy cost. Moreover, since boring for extracting ground water is extremely hard in hilly areas, it is the only source of water available in areas where streams and springs are far away. Hence, this technology was endorsed as the most suitable and viable approach for hilly areas of Pakistan [15].

For storage tank sizing, long-term daily rainfall data is required since catchment for rooftop rainwater harvesting system is small but since long-term daily rainfall data is expensive and seldom available for majority of locations in Pakistan, tanks are installed without in depth knowledge of behaviour of system. Moreover, estimation of performance parameters is not possible due to the same reason as mentioned above. Computer models commonly used for DRWH i.e. Storage and Reliability Estimation Tool (SARET), Rainwater Harvester and Rainwater harvesting Design and Costing tool are not suitable in Pakistan as these models also makes use of long-term daily rainfall data.

Hence, the present investigation aimed to develop a new computer model named RAINMOD for generating daily rainfall from historic daily, monthly and mean monthly data, sizing of storage tank and simulation of system performance under different rainfall data i.e. daily, monthly and mean monthly data and to compare the results of newly developed model under different rainfall data and with observed daily data.

II. MATERIALS AND METHODS

A. Study Area

Battagram District lies in Khyber Pakhtunkhwa province of Pakistan between 34º-35º N and 73º-74º E. It has an area of 1301 square kilometres [2]. Total population of Battagram District according to 2004-05 estimates was 361,000 [3]. It is at a distance of 58 kilometres from Mansehra.

The project of rooftop rainwater harvesting system has been implemented by Save the Children and Maqsood Welfare Foundation in Saroona village, Tehsil Allai, District Battagram. Allai is a valley which is at a distance of 60 kilometres from Battagram. Allai valley was badly destroyed by 08th October 2005 earthquake which also damaged the cable-way serving as facility for crossing Indus river [2]. The Saroona village is composed of 330 households with low income families living in majority of houses [3]. In pilot phase of project, 45 households in this village were provided with this facility [1]. Figure No. 01 shows the study area.

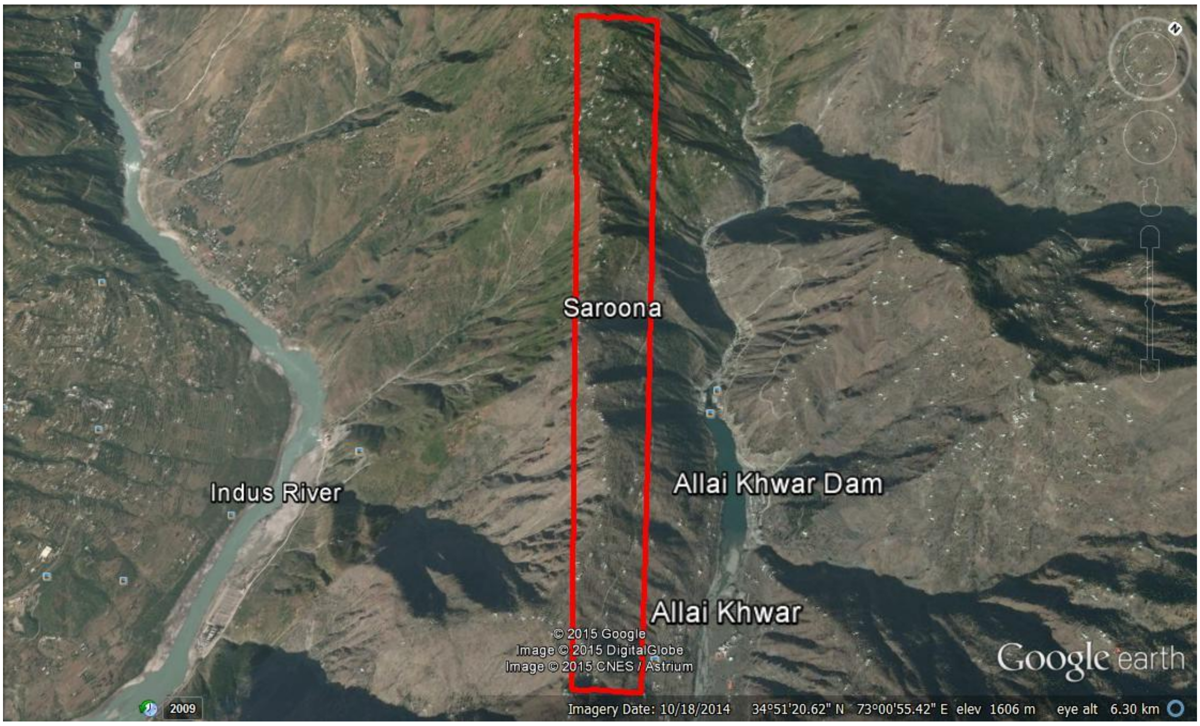

FIGURE NO. 01 Google Earth Map of Study Area

In Figure No.1 study area (Saroona) has been demarcated by red polygon. Location of Allai Khwar, Allai Khwar Dam and Indus River is also shown on this map. From the map it is cleared that the village Saroona is located at top up the hills.

B. Description of RAINMOD

A computer model named RAINMOD is developed which will be helpful for various Government and private agencies in planning, designing and implementation of rooftop rainwater harvesting system. This model is written in VB6 language and is compatible with operating system like Windows XP. This model supports saving of data, retrieval of data, updating of data, importing of data, printing of reports, graphs and summaries. Figure No. 02 shows generalized flow chart for RAINMOD.

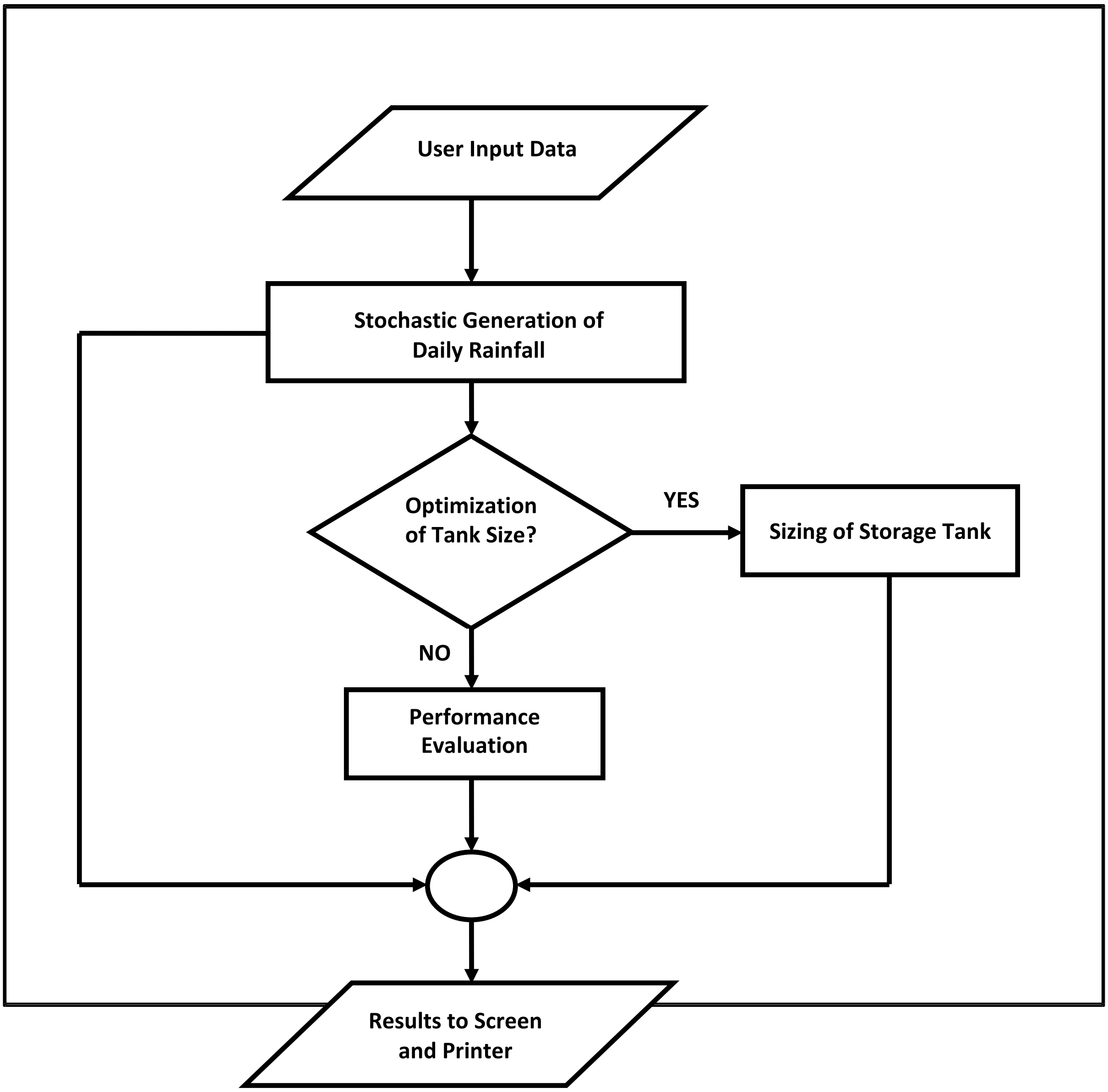

FIGURE NO. 02 Generalized Flow Chart for RAINMOD

First of all user will input data. Based on the data input by user, stochastic generation of daily rainfall will be done. Then the condition will be checked that whether user is interested in optimization of tank size, if interested, sizing of storage tank will be done otherwise performance evaluation of DRWH will be done. After stochastic generation of daily rainfall, sizing of storage tank and performance evaluation of DRWH, results will be displayed on screen and available to printer.

C. Data Collection

Thirty houses were chosen at random on which complete system with two tanks of capacity 2250 Liters and 4500 Liters were installed. The following data was collected from Meteorological Stations of Peshawar and Lahore:

- Twenty five years of daily rainfall data for Balakot (1988-2012)
- Twenty five years of daily rainfall data for Kakul (1988-2012)
- Ten years of daily rainfall data for Saidu Sharif (2003-2012)

In addition to it, the data regarding following was collected through personal interviews:

- Rooftop rainwater harvesting system
- Water sources
- Household

It was then incorporated in RAINMOD for stochastic generation of daily rainfall from historic daily, monthly and mean monthly data, sizing of storage tank and performance evaluation of system for thirty houses.

D. Water Demand Estimation

Since the user of system did not know water demand so daily demand per capita was assumed to be 45 Liters/day [9].

E. Stochastic Generation of Daily Rainfall

Stochastic generation of daily rainfall was done for daily, monthly and mean monthly rainfall data collected from Meteorological Department of Peshawar and Lahore for Balakot Station (being the nearest station from Allai for which rainfall data is available) from year 1988-2012. The following procedure was adopted for generating stochastic daily rainfall from daily, monthly and mean monthly rainfall data:

1). Procedure for generating daily rainfall from historic daily data:

a). Transition probabilities P_{WD} and P_{WW} alongwith P_W were estimated from historic daily rainfall data for each month over the entire rainfall record. These were estimated as follows:

$$P_{WD} = \left(\frac{N_{WD}}{N_D}\right) \quad ..(1)$$

$$P_{WW} = \left(\frac{N_{WW}}{N_W}\right) \quad ..(2)$$

$$P_W = \left(\frac{N_W}{N_T}\right) \quad ..(3)$$

Where, "P_W" is probability of a day being wet in a given month, "P_{WD}" is probability of a day being wet given that previous day is dry in a given month, "P_{WW}" is probability of a day being wet given that previous day is wet in a given month, "N_{WD}" is number of wet following dry days in a given month, "N_{WW}" is number of wet following wet days in a given month, "N_W" is number of wet days in a given month, "N_D" is number of dry days in a given month, "N_T" is total number of days in a given month.

b). Parameters for Gamma distribution were determined whose probability density function is given below:

$$f(x,\beta,\alpha) = \frac{x^{\alpha-1} \times e^{\frac{-x}{\beta}}}{\beta^{\alpha} \times \Gamma(\alpha)} \quad ..(4)$$

Where, "$\Gamma(\alpha)$" is Gamma function, "α" and "β" are shape and scale parameters respectively and were estimated for each month by using method of approximating maximum likelihood estimators [8]. Equations are as follows:

$$A = ln(X_o) - \left[\frac{1}{N} \times \sum_{i=1}^{N} ln(X_i)\right] \quad ..(5)$$

Where, "$\ln(X_o)$" is logarithm of the mean wet day rainfall in a given month, "$\ln(X_i)$" is logarithm of each observation having non-zero value in a given month, "N" is number of wet days in a given month. From this α and β were estimated as follows:

$For\ 0 \le A < 0.5772$

$$\hat{a} = \frac{1}{A} \times [0.50 + 0.16 \times A - 0.05 \times A^2]..(6)$$

$For\ 0.5772 \le A \le 17$

$$\hat{a} = \frac{(8.90 + 9.06 \times A + 0.98 \times A^2)}{[A \times (17.80 + 11.97 \times A + A^2)]}..(7)$$

$$B = \frac{X_0}{\hat{a}} \quad ..(8)$$

Where "â" and "B" are estimators for shape and scale parameter respectively. "B" was in mm.

2). Procedure for generating daily rainfall from historic monthly and mean monthly data:

a). Transition probabilities P_W, P_{WD} alongwith P_{WW} were estimated from historic monthly and mean monthly rainfall data for each month over the entire rainfall record. These were estimated as follows:

$$P_W = \sqrt{\frac{R_m}{A}} \quad ..(9)$$

$$P_{WD} = 0.75 \times P_W \quad ..(10)$$

$$P_{WW} = 0.25 + P_{WD} \quad ..(11)$$

Where, "R_m" is monthly/mean monthly rainfall in mm. Value of "A" used in (9), was 800 mm [13]. Equation (10) and (11) is derived by [7].

b). Mean wet day rainfall R_{wm} was determined from following equation:

$$R_{wm} = \frac{R_m}{N_{wm}} \quad ..(12)$$

Where, "R_{wm}" was in mm, "N_{wm}" is number of wet days in a given month and it was estimated from following equation:

$$N_{wm} = P_W \times N_t \quad ..(13)$$

Where, "N_t" is total number of days in a given month.

c). Parameters α and β for Gamma distribution were estimated for each month from following empirical formulas [7]:

$$\beta = (-2.16) + (1.83 \times R_{wm}) \quad ..(14)$$

$$\alpha = \frac{R_{wm}}{\beta} \quad ..(15)$$

A dry/wet day sequence was decided by generating a random number uniformly distributed between 0 and 1. For first day of each month, random number was compared with P_W so if it was less than P_W a day was considered wet else dry. For each subsequent day of each month, random number was compared with P_{WW} if previous day was wet and P_{WD} if previous day was dry. If random number came out to be less than appropriate probability, a day was considered wet else dry.

Rainfall amount on wet day was determined by using inverse transform method i-e another random number uniformly distributed between 0 and 1 was generated, considering it equal to cumulative probability, the corresponding value of x was considered to be the rainfall amount on wet day. Cumulative probability for two parameters Gamma distribution is given below:

$$F(x,\beta,\alpha) = \int_0^x x^{\alpha-1} \times \frac{e^{\frac{-x}{\beta}}}{\beta^\alpha \times \Gamma(\alpha)} \times dx \quad ..(16)$$

F. Sizing of Storage Tank

After generation of stochastic daily rainfall from historic daily, monthly and mean monthly data, tank size was determined. For this purpose an initial tank size was assumed to be 1000 Liters and considered to be empty at start. The following procedure was then adopted for sizing of storage tank:

1). Inflow in Tank:

Inflow Q_t was determined from following procedure:

a). Effective rainfall RE_t in time t was determined from following equation [10]:

$$RE_t = max(R_t - IL_t, 0) \quad ..(17)$$

Where, "IL_t" is initial loss in time t and "R_t" is rainfall in time t. "IL_t" was determined on basis of roof material. Its value was taken equal to 0.25 mm [5] on wet day and 0 mm on dry day since roofs were made of corrugated galvanized iron. All parameters were in mm.

b). Effective runoff ER_t in time t was determined from following equation [10]:

$$ER_t = C \times RE_t \times RA \quad ..(18)$$

Where, "ER_t" was in liters, "RE_t" was in mm, "RA" is plan roof area and it was in m^2, "C" is the runoff coefficient and its value was taken to be 0.90 [11] as roofs were made of corrugated galvanized iron.

c). Inflow Q_t was finally determined from following equation [9]:

$$Q_t = max(ER_t - FF_{vol}, 0) \quad ..(19)$$

Where, "Q_t" was in Liters, "FF_{vol}" is first flush volume diverted and its value was taken to be 225 Liters as first flush diverter of this capacity was installed in houses.

2). Yield after Spillage algorithms:

Yield, volume of water in tank and overflow from tank was then determined by using following yield after spillage algorithms [6]:

$$Y_t = min(D_t, V_{t-1}) \quad ..(20)$$

$$V_t = min(V_{t-1} + Q_t - Y_t, S - Y_t) \quad ..(21)$$

$$O_t = max(V_{t-1} + Q_t - S, 0) \quad ..(22)$$

Where, "D_t" is water demand in time t, "V_{t-1}" is volume of water in time t-1, "Y_t" is yield in time t, "V_t" is volume of water in time t, "Q_t" is inflow in tank in time t, "S" is the storage tank size and "O_t" is overflow from tank in time t. All parameters were in Liters. Time interval so used was one day.

3). Determination of Satisfaction:

After simulating 25 years of stochastic daily rainfall, satisfaction was determined from following equation:

$$Sat\ (\%) = \frac{Total\ Yield}{Total\ Demand} \times 100 \quad ..(23)$$

Tank size was then increased at interval of 250 Liters and for each tank size, satisfaction was determined by adopting the above mentioned procedure. The above procedure was repeated until difference in satisfaction corresponding to two consecutive tank sizes became <=2%/m^3. When this occurred the first of the two consecutive tank sizes was considered to be the required tank size [12].

Since, stochastic daily rainfall pattern varies from realization to realization, so 20 realizations were performed i.e. the above procedure was repeated 20 times and maximum storage tank size among these 20 realizations was considered to be the required tank size.

Tank size was also estimated from observed daily data without utilization of Markov chains. Average tank size predicted from RAINMOD for different houses by utilizing different rainfall data was compared with capacity of tanks being installed on houses. Comparison was also made for tank sizes estimated by RAINMOD under different rainfall data and observed daily data. For this purpose, Two-way Analysis of Variance (ANOVA) alongwith Tukey's Honest Significant Difference (HSD) tests at 5 per cent significance level were conducted.

G. Performance Evaluation

Performance evaluation of system was conducted for 30 households on which two tanks of capacity 2250 Liters and 4500 Liters were installed. The same procedure as discussed earlier (in section, sizing of storage tank) was followed for determining satisfaction except here the tank size was known. Additional three parameters relating to performance of system were also determined from following equations:

$$Sys.Eff = 1 - \frac{Total\ Yield}{Total\ Inflow} \times 100 \quad ..(24)$$

$$Sto.Eff = 1 - \frac{Total\ Overflow}{Total\ Inflow} \times 100 \quad ..(25)$$

$$Reliability = \frac{n_d}{n_t} \times 100 \quad ..(26)$$

All the performance parameters were in % age. "n_d" is the number of days demand was fully met by system and "n_t" is the number of days over period of analysis.

Since, stochastic daily rainfall pattern varies from realization to realization, so 20 realizations were performed and performance parameters corresponding to minimum satisfaction among these 20 realizations were considered to be the required performance parameters.

In order to take into consideration seasonal variation of rainfall, adjusted satisfaction, adjusted reliability, adjusted storage and system efficiency were determined for corresponding non-adjusted performance parameters predicted through generated daily rainfall from historic monthly and mean monthly rainfall data by RAINMOD. For this purpose, simulation was done for predicting performance parameters from daily, monthly and mean monthly rainfall data for three rainfall regions i.e. Balakot (1988-2012), Kakul (1988-2012) and Saidu Sharif (2003-2012), range of roof areas from 20 to 100 m^2, average household demand of 360 Liters/day and at tank sizes of 2250 Liters and 4500 Liters. After determining performance parameters, generalized equations were developed in order to predict adjusted performance parameters for corresponding non-adjusted performance parameters predicted through generated daily rainfall from historic monthly and mean monthly rainfall data by RAINMOD. Generalized equations were based on best fitted line through the data points.

Performance parameters were also estimated from observed daily data without utilization of Markov chains. Comparison was then made of performance parameters predicted from RAINMOD at tank sizes of 2250 Liters and 4500 Liters under different rainfall data and observed daily data. For this purpose, Two-way Analysis of Variance (ANOVA) alongwith Tukey's Honest Significant Difference (HSD) tests at 5 per cent significance level were conducted.

III. RESULTS AND DISCUSSIONS

A. Rainfall Data Compilation Results

Mean annual rainfall for Balakot amounts to 1515.078 mm with a range from 1086.20 mm in 2009 to 2284.20 mm in 2006. Figure No.3 shows distribution of mean monthly rainfall data for Balakot Station based on 25 years of monthly rainfall data from 1988-2012. Mean annual rainfall for Kakul amounts to 1284.51 mm and that for Saidu Sharif amounts to 1068.25 mm.

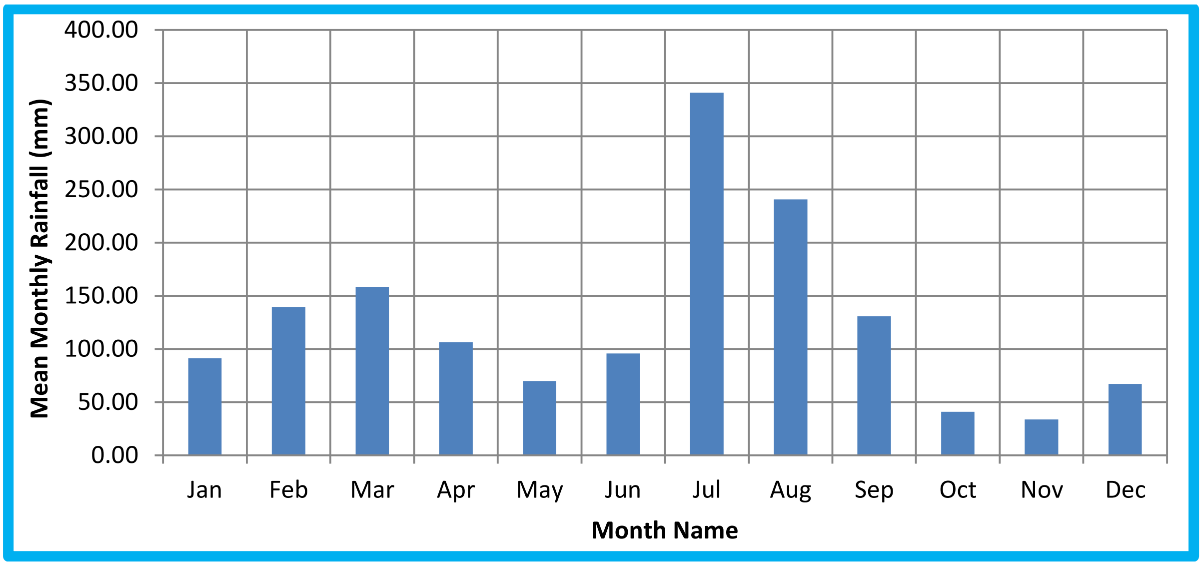

FIGURE NO. 03 Distribution of Mean Monthly Rainfall for Balakot Station

After observing the rainfall data, it is revealed that there is plenty of rainfall almost all the year around. The heaviest rainfall occurs in the monsoon season (July-August). Dry season is prevalent in only two months (October-November) receiving less than 50 mm of rainfall. The maximum rainfall occurs for the month of July with a value of 341.04 mm while the minimum rainfall occurs during the month of November with a value of 33.72 mm.

B. Stochastic Generation of Daily Rainfall

1). Estimation of Conditional Probabilities:

Table No. 01 shows average conditional probabilities estimated from observed daily, monthly and mean monthly rainfall data of Balakot Station for each month.

TABLE NO. 01 Average Conditional Probabilities Estimated from Observed Daily, Monthly and Mean Monthly Data

Month	Daily Data		Monthly Data		Mean Monthly Data	
	P_{WD}	P_{WW}	P_{WD}	P_{WW}	P_{WD}	P_{WW}
Jan	0.14	0.43	0.23	0.48	0.25	0.50
Feb	0.23	0.57	0.30	0.55	0.31	0.56
Mar	0.23	0.51	0.32	0.57	0.33	0.58
Apr	0.21	0.50	0.26	0.51	0.27	0.52
May	0.21	0.35	0.22	0.47	0.22	0.47
Jun	0.27	0.42	0.24	0.49	0.26	0.51
Jul	0.41	0.53	0.47	0.72	0.49	0.74
Aug	0.38	0.49	0.40	0.65	0.41	0.66
Sep	0.21	0.32	0.28	0.53	0.30	0.55
Oct	0.11	0.33	0.16	0.41	0.17	0.42
Nov	0.07	0.29	0.13	0.38	0.15	0.40
Dec	0.11	0.36	0.18	0.43	0.22	0.47

The above table indicates persistence of rainfall events. P_{WW} is always greater than P_{WD} for every month. For dry season (October-November), probability of wet day following a dry day and probability of wet day following a wet day is usually smaller than its values for wet season.

2). Estimation of Distribution Parameters:

Table No. 02 shows average distribution parameters estimated from observed daily, monthly and mean monthly rainfall data of Balakot Station for each month.

TABLE NO. 02 Average Distribution Parameters Estimated from Observed Daily, Monthly and Mean Monthly Data

Month	Daily Data		Monthly Data		Mean Monthly Data	
	Shape Parameter	Scale Parameter (mm)	Shape Parameter	Scale Parameter (mm)	Shape Parameter	Scale Parameter (mm)
Jan	1.77	13.67	0.92	12.29	0.63	13.79
Feb	1.12	14.83	0.63	18.29	0.61	18.92
Mar	1.00	15.38	0.63	17.94	0.61	18.85
Apr	1.08	12.52	0.64	14.91	0.62	15.63
May	1.66	11.34	0.66	11.38	0.65	11.78
Jun	1.25	11.67	0.61	13.76	0.63	14.73
Jul	0.91	30.89	0.60	27.66	0.59	28.67
Aug	0.82	23.16	0.60	23.09	0.60	23.74
Sep	0.94	24.71	0.64	16.19	0.61	17.57
Oct	3.48	7.12	0.83	7.61	0.69	8.50
Nov	3.69	7.35	0.79	6.66	0.70	7.86
Dec	1.91	9.80	0.58	9.60	0.65	11.53

The above table indicates that value of shape parameter varies from 0.82 (August) to 3.69 (November), 0.58 (December) to 0.92 (January) and 0.59 (July) to 0.70 (November) for daily, monthly and mean monthly data respectively. Value of scale parameter varies from 7.12 mm (October) to 30.89 mm (July), 6.66 mm (November) to 27.66 mm (July) and 7.86 mm (November) to 28.67 mm (July) for daily, monthly and mean monthly data respectively. Greater variation in value of scale parameter dictates a high variation in rainfall data.

C. Sizing of Storage Tank

Figure No. 04 shows comparison of average tank size estimated from RAINMOD by utilizing different rainfall data for Balakot Station with capacity of tanks being installed on thirty houses.

Figure No. 05 shows average tank size as estimated by RAINMOD under different rainfall data and observed daily data based on thirty households.

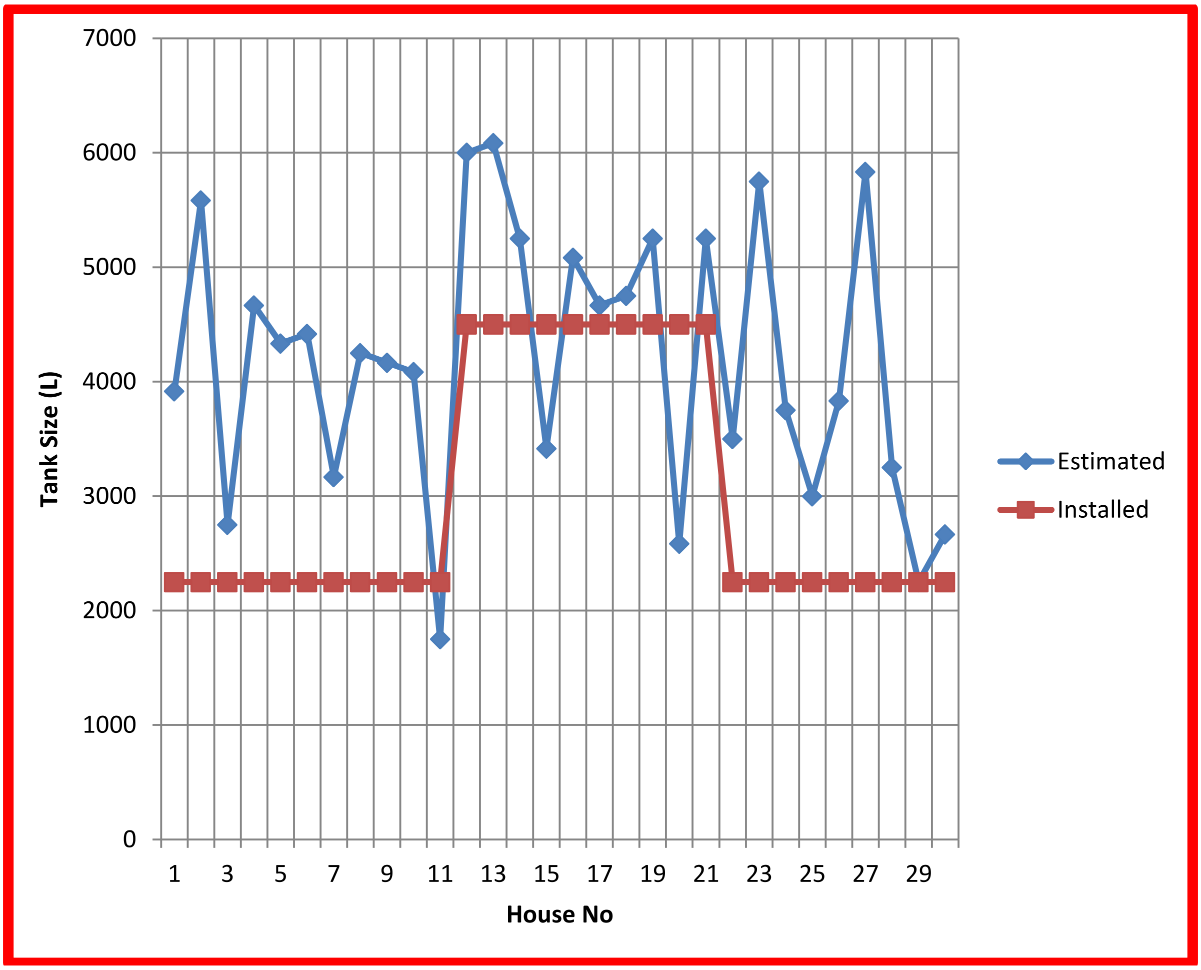

FIGURE NO. 04 Comparison of Average Tank Size Estimated from RAINMOD with Capacity of Tanks Installed on Houses

Tank size is under-estimated for about 87% of houses on which complete system is installed with respect to average tank size estimated from RAINMOD by utilizing different rainfall data.

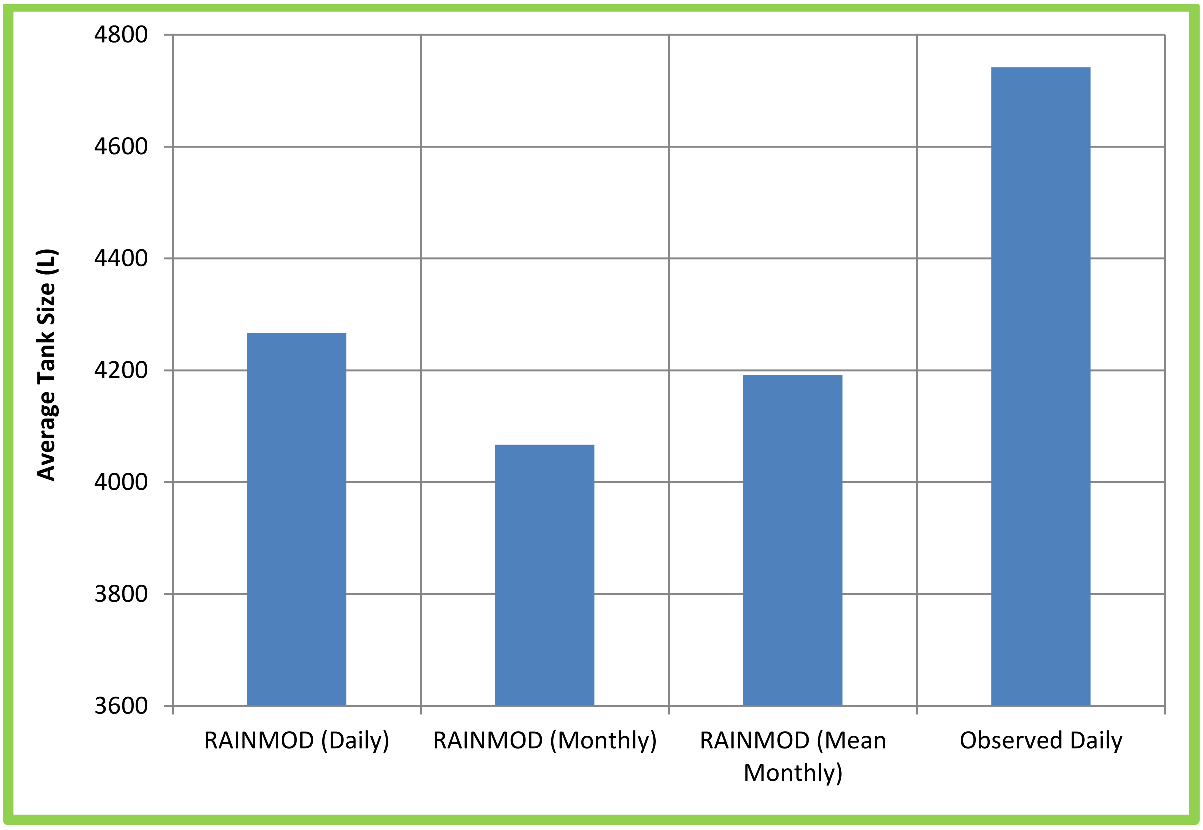

FIGURE NO. 05 Average Tank Size Estimated from RAINMOD and Observed Daily Data

Average tank size ranges from 4067 Liters for RAINMOD utilizing monthly rainfall data to 4742 Liters for observed daily data. RAINMOD predicts average tank size as 4267 Liters, 4067 Liters and 4192 Liters from daily, monthly and mean monthly data respectively. Variation in results of average tank size estimated by RAINMOD under different rainfall data and observed daily data is due to different methodology adopted. RAINMOD makes use of Markov chains with Gamma distribution and 20 realizations for predicting tank size. Observed daily data makes use of past record with only one realization without utilization of Markov chains and Gamma distribution for predicting tank size. Variation in average tank size predicted from RAINMOD by utilizing monthly and mean monthly data is 200 Liters and 75 Liters respectively with respect to that predicted from daily data by RAINMOD. Similarly, RAINMOD predicts average tank size within 675 Liters of observed daily data predicted average tank size.

D. Performance Evaluation

Figure No. 06 to Figure No. 11 shows generalized equations for predicting adjusted performance parameters at tank size of 2250 Liters by RAINMOD whereas Figure No. 12 to Figure No. 17 shows generalized equations for predicting adjusted performance parameters at tank size of 4500 Liters by RAINMOD. For developing the generalized equations, daily, monthly and mean monthly rainfall data for all the three Stations i.e. Balakot (from 1988-2012), Kakul (from 1988-2012) and Saidu Sharif (from 2003-2012) was utilized.

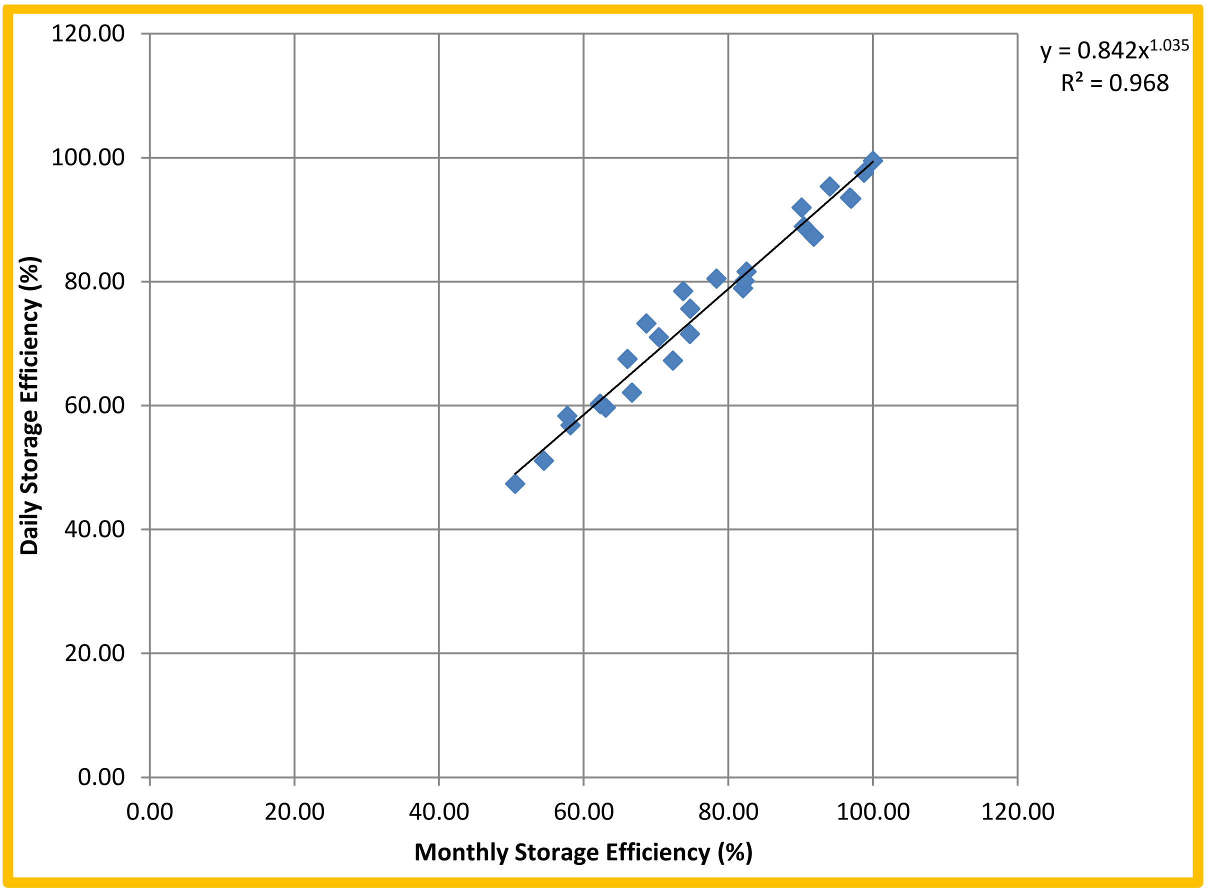

FIGURE NO. 06 Relation between Storage Efficiency Predicted from Monthly and Daily Data (for 2250 L Tank)

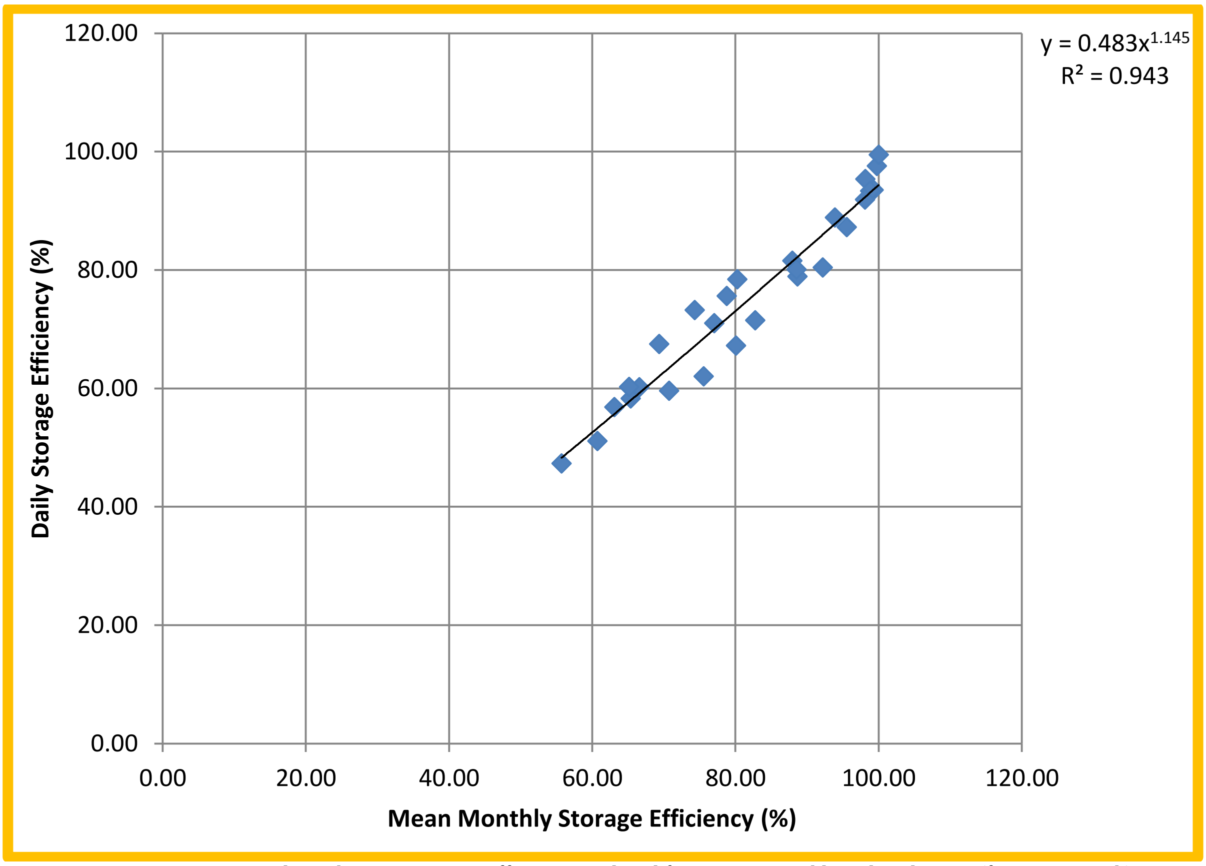

FIGURE NO. 07 Relation between Storage Efficiency Predicted from Mean Monthly and Daily Data (for 2250 L Tank)

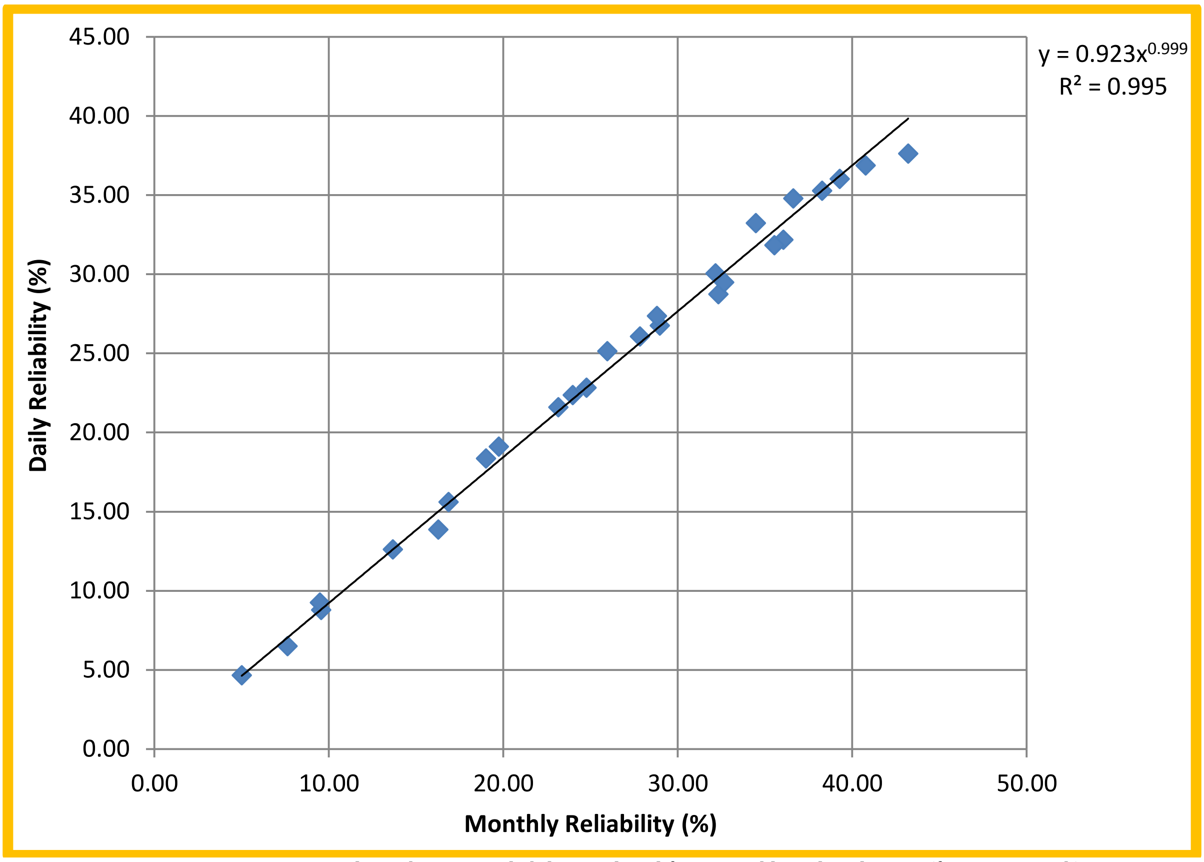

FIGURE NO. 08 Relation between Reliability Predicted from Monthly and Daily Data (for 2250 L Tank)

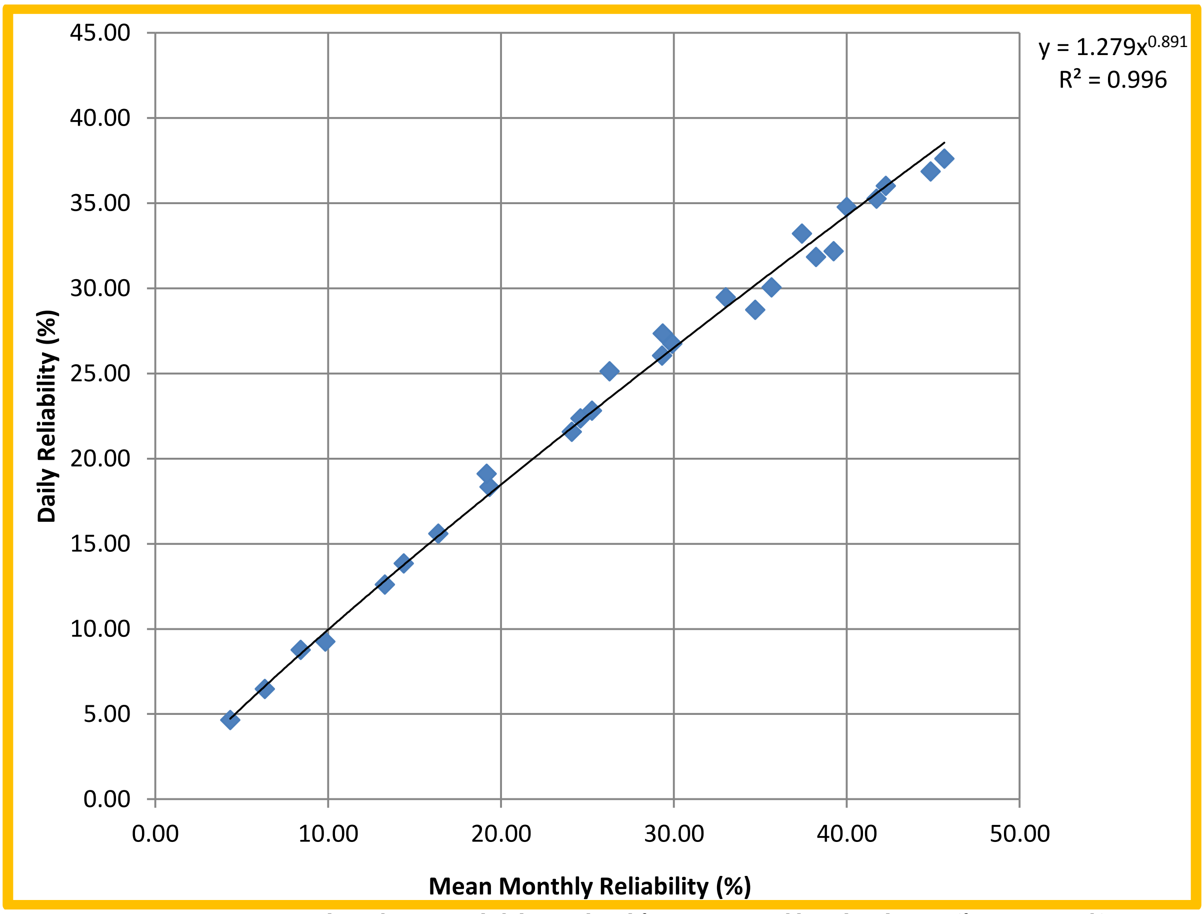

FIGURE NO. 09 Relation between Reliability Predicted from Mean Monthly and Daily Data (for 2250 L Tank)

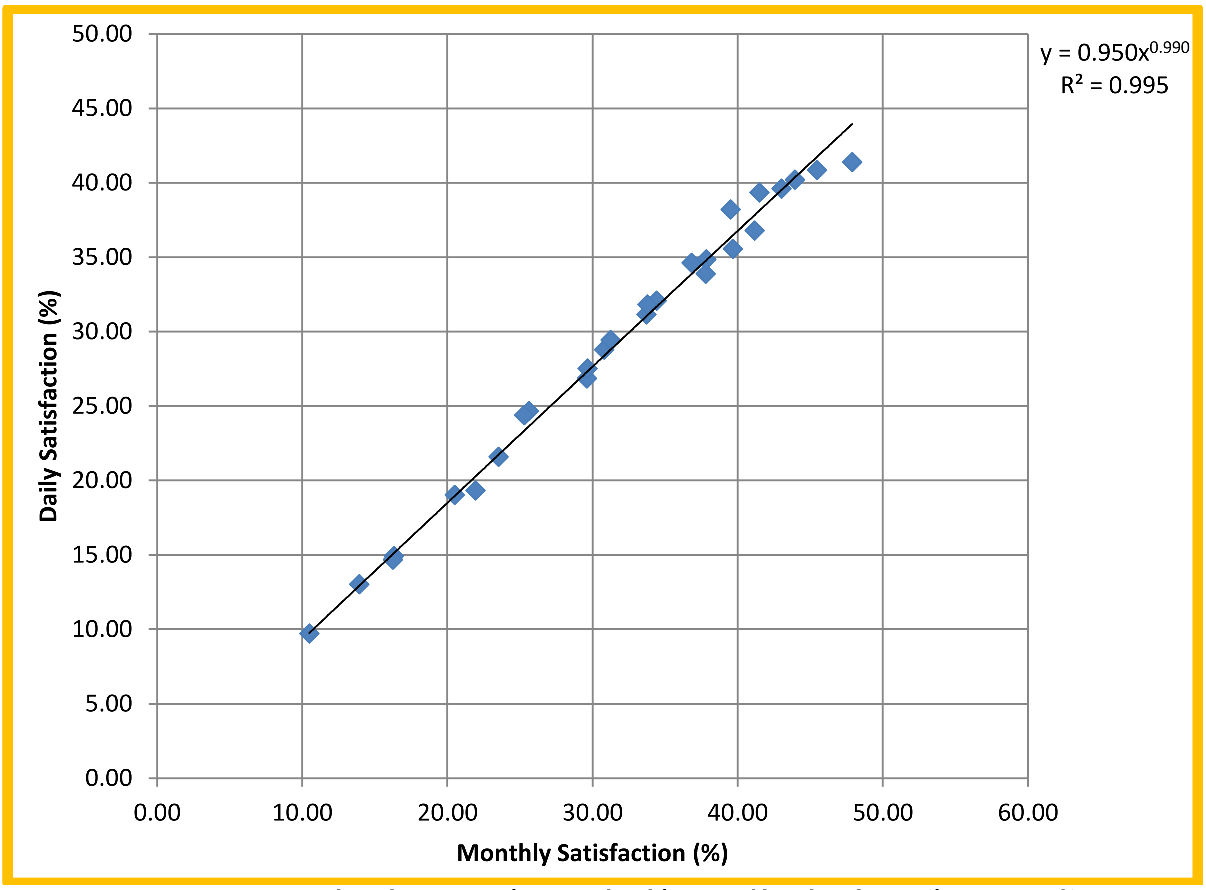

FIGURE NO. 10 Relation between Satisfaction Predicted from Monthly and Daily Data (for 2250 L Tank)

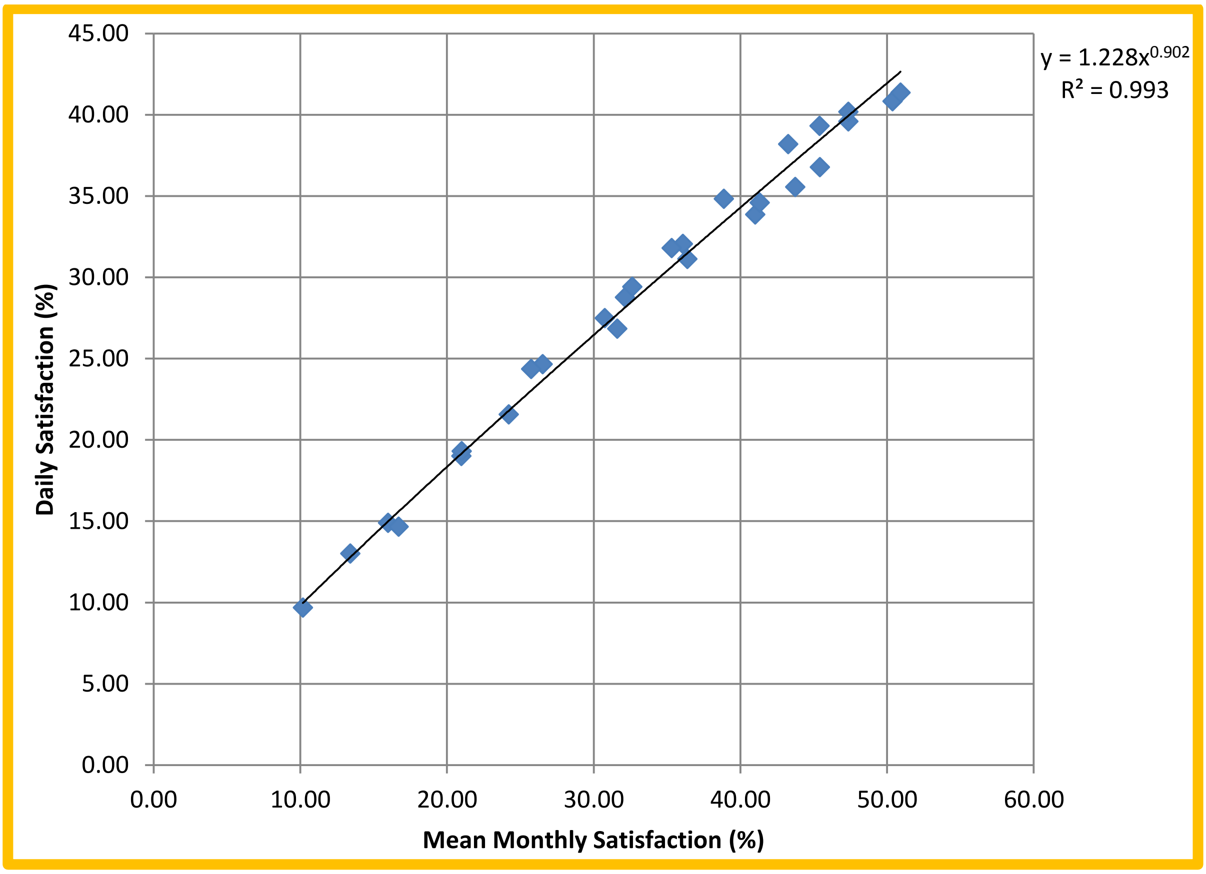

FIGURE NO. 11 Relation between Satisfaction Predicted from Mean Monthly and Daily Data (for 2250 L Tank)

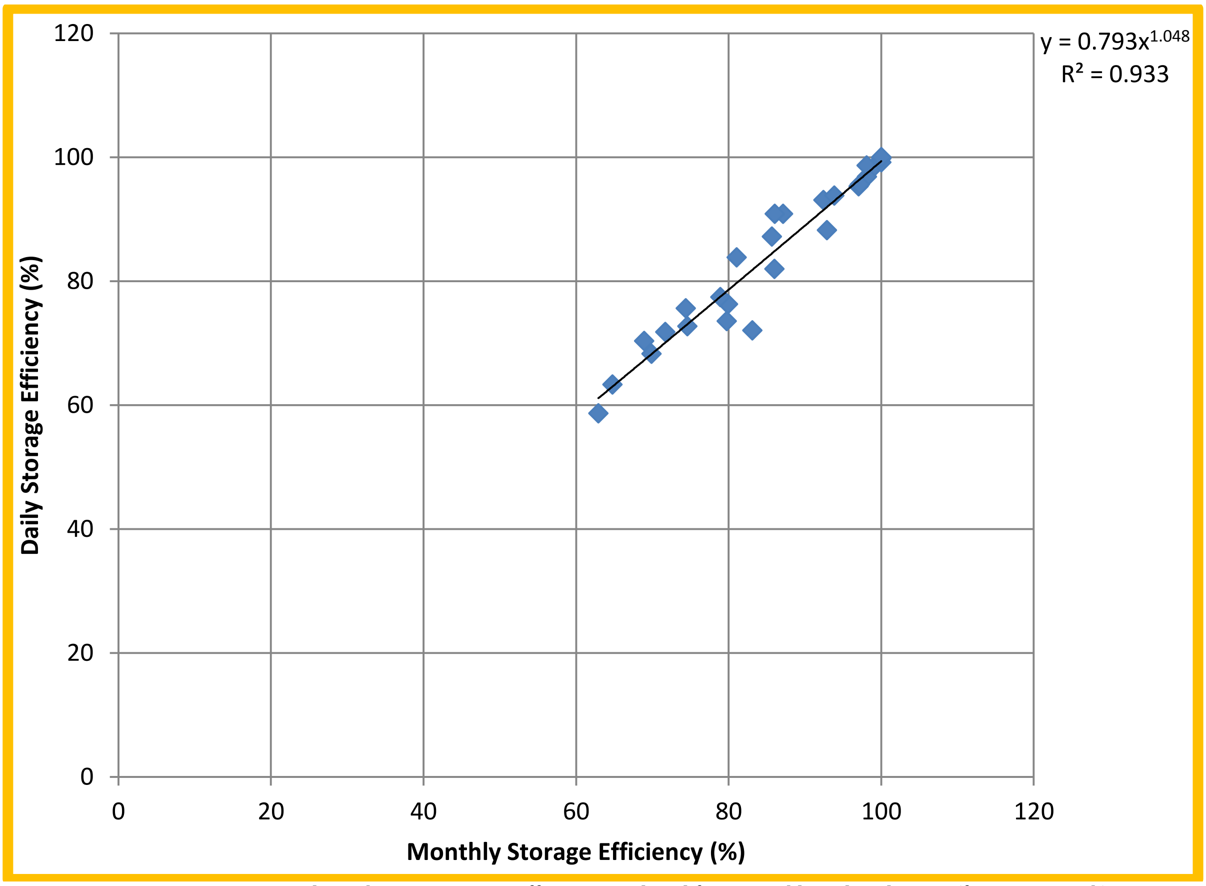

FIGURE NO. 12 Relation between Storage Efficiency Predicted from Monthly and Daily Data (for 4500 L Tank)

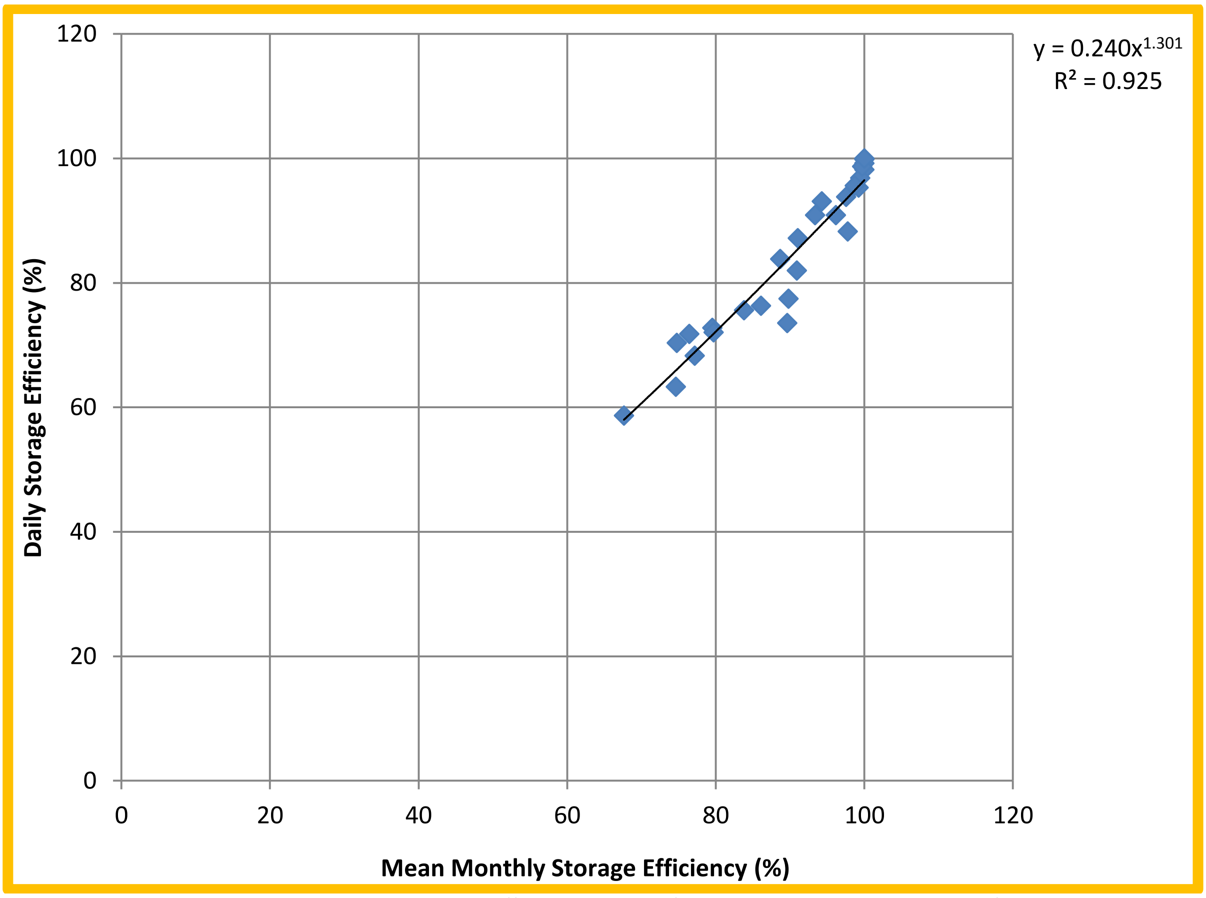

FIGURE NO. 13 Relation between Storage Efficiency Predicted from Mean Monthly and Daily Data (for 4500 L Tank)

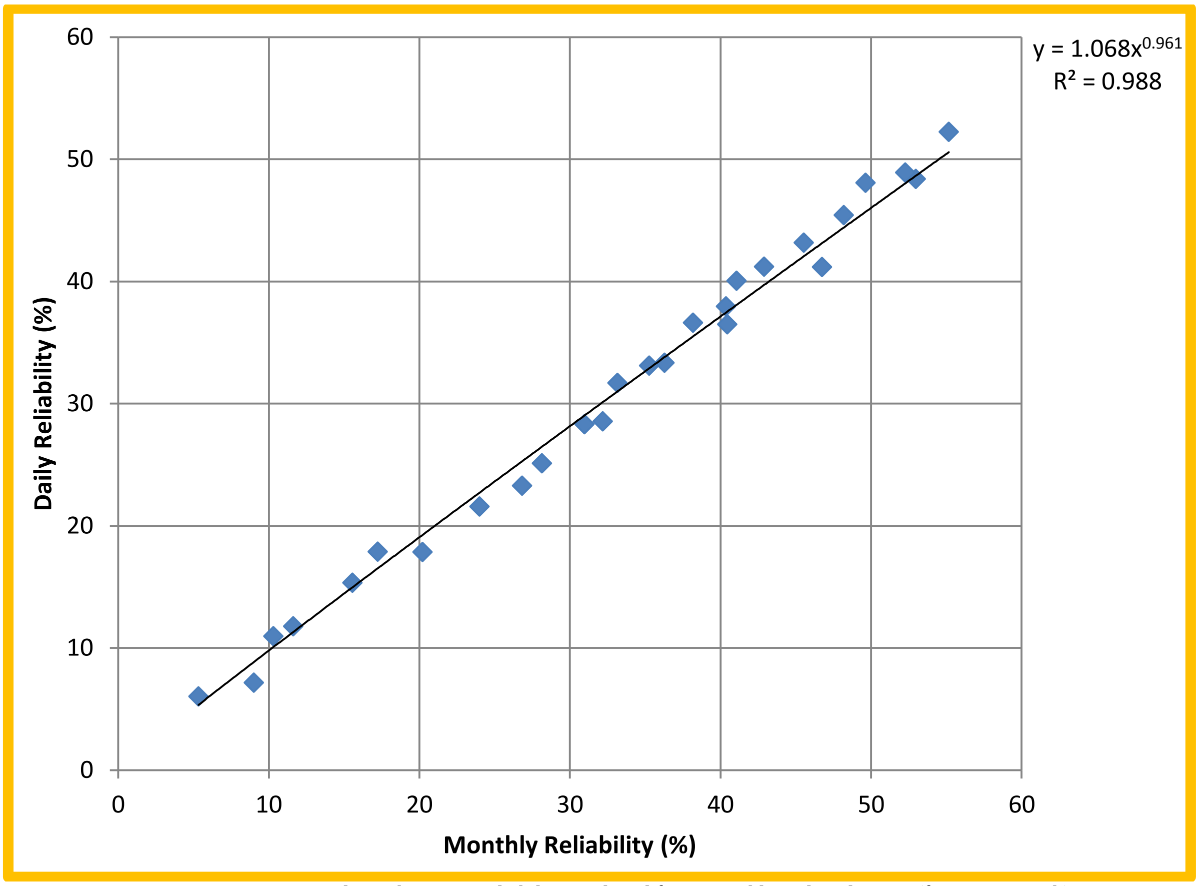

FIGURE NO. 14 Relation between Reliability Predicted from Monthly and Daily Data (for 4500 L Tank)

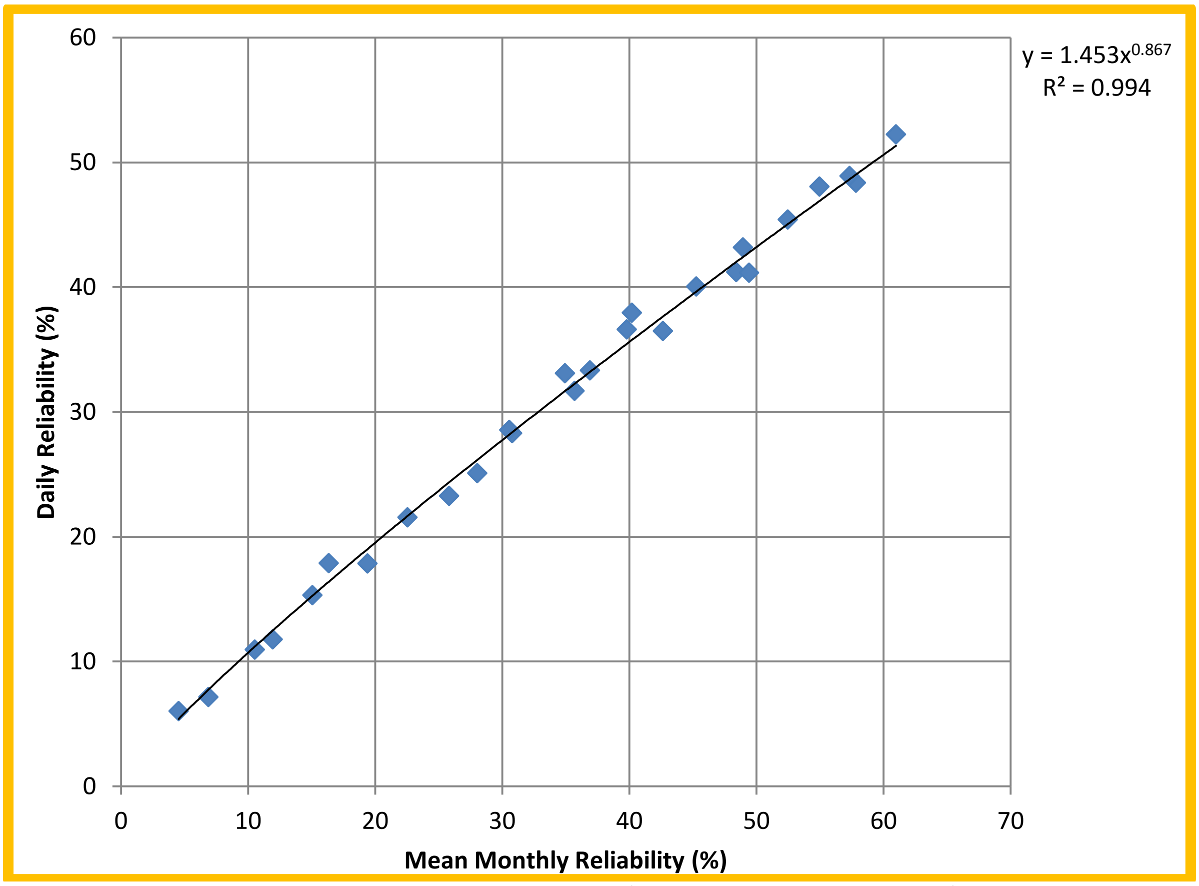

FIGURE NO. 15 Relation between Reliability Predicted from Mean Monthly and Daily Data (for 4500 L Tank)

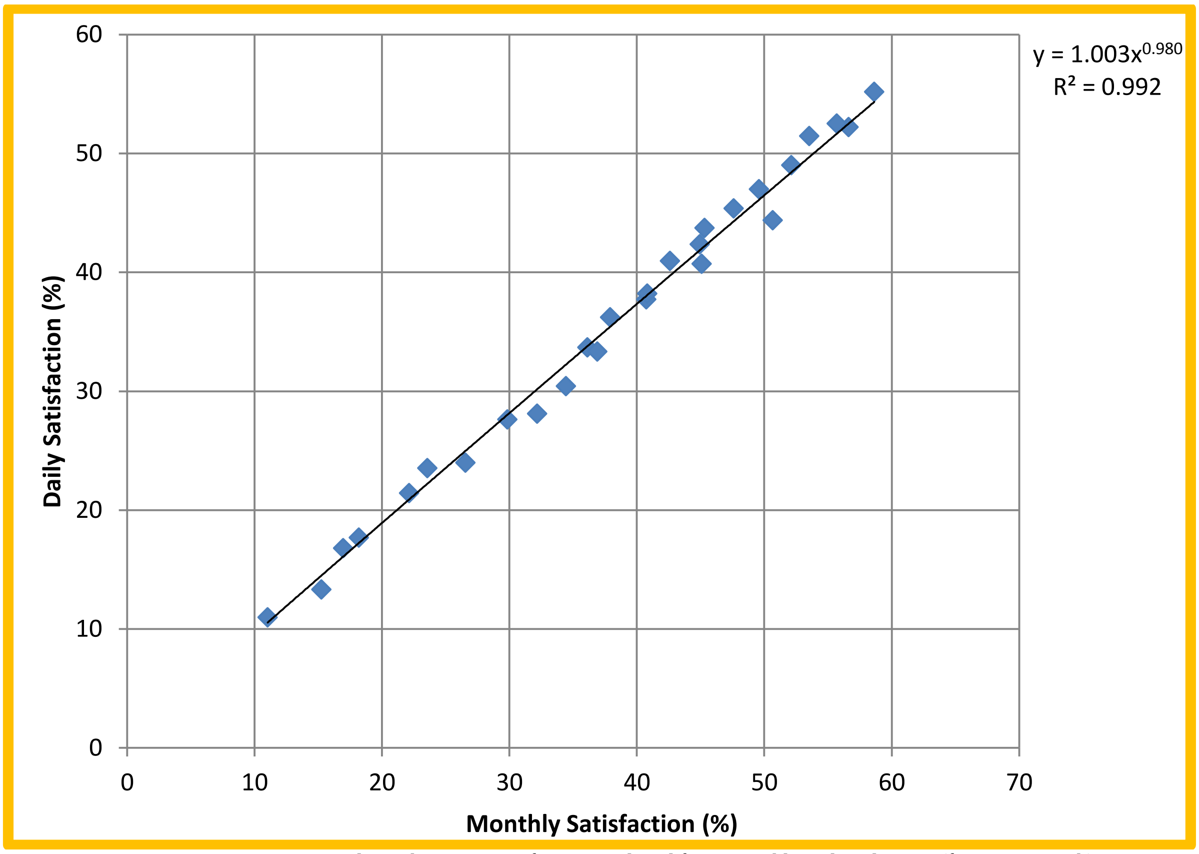

FIGURE NO. 16 Relation between Satisfaction Predicted from Monthly and Daily Data (for 4500 L Tank)

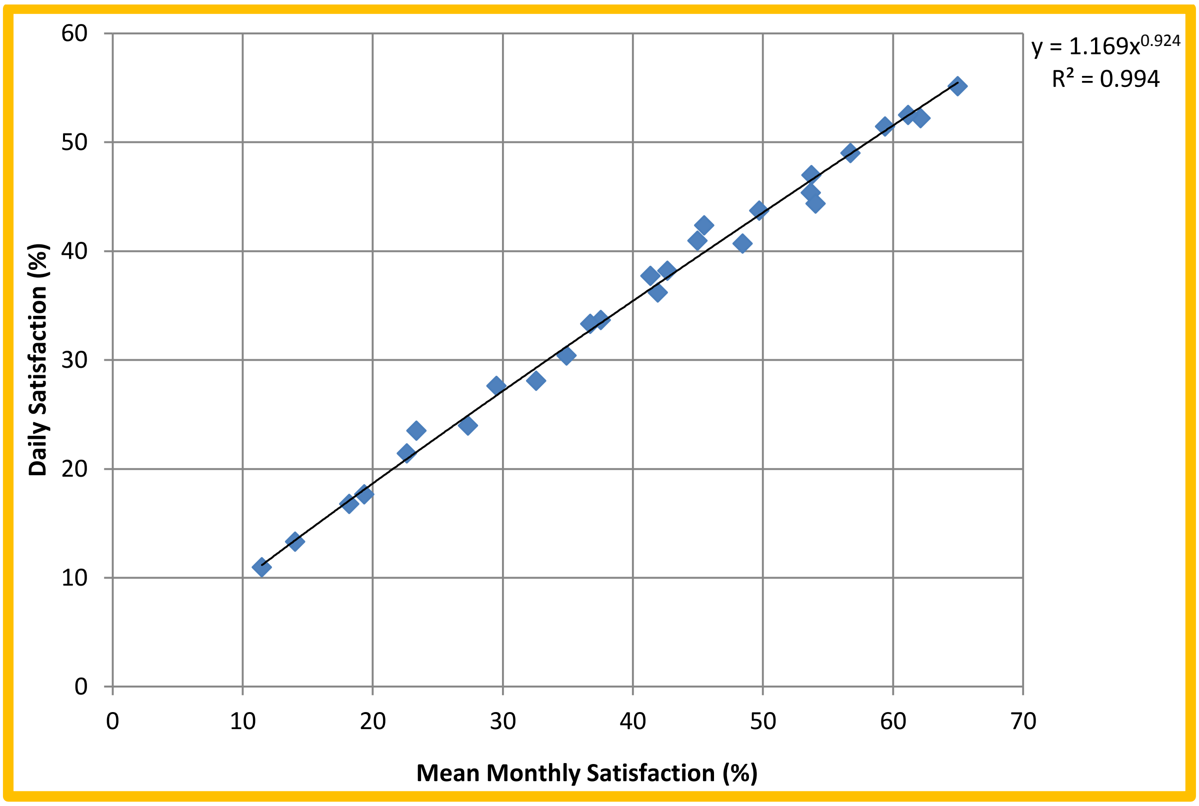

FIGURE NO. 17 Relation between Satisfaction Predicted from Mean Monthly and Daily Data (for 4500 L Tank)

For predicting adjusted performance parameters, variable "x" in equations shown in Figure No. 06 to Figure No. 17 becomes non-adjusted performance parameter and variable "y" becomes corresponding adjusted performance parameter. It is concluded that equations can be used safely for predicting adjusted performance parameters since determination coefficient R^2 is greater than 0.90. No generalized equations are developed for determining adjusted system efficiency since it can be determined directly after determining adjusted storage efficiency.

Based on the results of performance parameters for twenty households, average adjusted and non-adjusted performance parameters predicted by RAINMOD and observed daily data is tabulated in Table No. 03 corresponding to tank size of 2250 Liters. Similarly, based on the results of performance parameters for ten households, average adjusted and non-adjusted performance parameters predicted by RAINMOD and observed daily data is tabulated in Table No. 04 corresponding to tank size of 4500 Liters.

TABLE NO. 03 Average Performance Parameters Predicted by Various Models at Tank Size of 2250 L

Performance Parameters	Model Name			
	RAINMOD			Observed Daily Data
	DD*	DM**	DMM***	
Storage Efficiency (%)	65	68	73	62
System Efficiency (%)	35	32	27	38
Reliability (%)	23	25	27	25
Satisfaction (%)	29	32	34	31
Adj. Storage Efficiency (%)	65	66	66	62
Adj. System Efficiency (%)	35	34	34	38
Adj. Reliability (%)	23	23	24	25
Adj. Satisfaction (%)	29	29	30	31

* Generated Daily Data from Historic Daily Data by RAINMOD
** Generated Daily Data from Historic Monthly Data by RAINMOD
*** Generated Daily Data from Historic Mean Monthly Data by RAINMOD

TABLE NO. 04 Average Performance Parameters Predicted by Various Models at Tank Size of 4500 L

Performance Parameters	Model Name			
	RAINMOD			Observed Daily Data
	DD	DM	DMM	
Storage Efficiency (%)	69	72	78	68
System Efficiency (%)	31	28	22	32
Reliability (%)	35	37	41	38
Satisfaction (%)	39	43	46	43
Adj. Storage Efficiency (%)	69	70	70	68
Adj. System Efficiency (%)	31	30	30	32
Adj. Reliability (%)	35	35	36	38
Adj. Satisfaction (%)	39	40	40	43

In Table No. 03 and Table No. 04 same results as non-adjusted performance parameters are shown for adjusted performance parameters from RAINMOD utilizing generated daily data from historic daily data and observed daily data as they do not make any adjustment for performance parameters. It can also be seen that adjusted performance parameters predicted from monthly and mean monthly data by RAINMOD is much close to corresponding parameters predicted from daily data by RAINMOD. RAINMOD predicts average adjusted performance parameters within the range of just 1 per cent under different rainfall data. It is also concluded that RAINMOD predicts average adjusted performance parameters within the range of 4 per cent of observed daily data corresponding parameters.

E. Statistical Analysis

Table No. 05 shows number of observations and mean for different parameters estimated from RAINMOD under different rainfall data and observed daily data. Table No. 06 shows the summary of Two-way ANOVA test at 5 per cent significance level for different parameters estimated under different rainfall data and at various roof areas from RAINMOD and observed daily data.

TABLE NO. 05 Number of Observations and Mean for Different Parameters

Parameters	n*	DD	DM	DMM	D**
		Mean			
Storage Tank Size (L)	30	4267	4067	4192	4742
Adj. Sto.Eff (%) (for 2250 L Tank)	20	64.54	66.04	66.29	61.57
Adj. Sys.Eff (%) (for 2250 L Tank)	20	35.46	33.96	33.71	38.43
Adj. Reliability (%) (for 2250 L Tank)	20	22.97	23.35	23.81	24.71
Adj. Satisfaction (%) (for 2250 L Tank)	20	28.72	29.31	29.67	30.65
Adj. Sto.Eff (%) (for 4500 L Tank)	10	68.98	70.14	69.84	67.99
Adj. Sys.Eff (%) (for 4500 L Tank)	10	31.02	29.86	30.16	32.01
Adj. Reliability (%) (for 4500 L Tank)	10	34.79	34.59	35.71	38.05
Adj. Satisfaction (%) (for 4500 L Tank)	10	39.35	39.63	40.46	42.76

* Number of Observations
** Observed Daily Data

TABLE NO. 06 Summary of Two-Way ANOVA Test at 5% Significance Level

Parameters	Source of Variation	df*	MS**	F	$F_{critical}$
Storage Tank Size (L)	Roof Area	29	5563505.7	132.16	1.60
	Nature of Rainfall Data	3	2612500	62.06	2.71
	Error	87	42097.701		
Adj. Sto.Eff (%) (for 2250 L Tank)	Roof Area	19	571.82332	213.73	1.77
	Nature of Rainfall Data	3	93.902411	35.10	2.77
	Error	57	2.6754433		
Adj. Sys.Eff (%) (for 2250 L Tank)	Roof Area	19	571.82332	213.73	1.77
	Nature of Rainfall Data	3	93.902411	35.10	2.77
	Error	57	2.6754433		
Adj. Reliability (%) (for 2250 L Tank)	Roof Area	19	318.90254	566.96	1.77
	Nature of Rainfall Data	3	11.296238	20.08	2.77
	Error	57	0.5624819		
Adj. Satisfaction (%) (for 2250 L Tank)	Roof Area	19	246.11277	413.05	1.77
	Nature of Rainfall Data	3	13.183181	22.13	2.77
	Error	57	0.595843		
Adj. Sto.Eff (%) (for 4500 L Tank)	Roof Area	9	413.39303	134.67	2.25
	Nature of Rainfall Data	3	9.3167919	3.04	2.96
	Error	27	3.0695684		
Adj. Sys.Eff (%) (for 4500 L Tank)	Roof Area	9	413.39303	134.67	2.25

	Nature of Rainfall Data	3	9.3167919	3.04	2.96
	Error	27	3.0695684		
Adj. Reliability (%) (for 4500 L Tank)	Roof Area	9	653.3046	377.74	2.25
	Nature of Rainfall Data	3	25.133104	14.53	2.96
	Error	27	1.7295148		
Adj. Satisfaction (%) (for 4500 L Tank)	Roof Area	9	542.71481	463.05	2.25
	Nature of Rainfall Data	3	23.953589	20.44	2.96
	Error	27	1.1720328		

* Degrees of Freedom
** Mean Square

Values of F and $F_{critical}$ in Table No. 06 clearly shows that parameters exhibits significant differences under both roof areas and nature of rainfall data. Table No. 07 shows pair-wise comparison for different parameters estimated under different rainfall data from RAINMOD and observed daily data by Tukey's HSD test at 5% significance level.

TABLE NO. 07 Pair-Wise Comparison for Different Parameters by Tukey's HSD test at 5% Significance Level

Parameters	q*						$q_{critical}$
	DD-DM	DD-DMM	DM-DMM	DD-D	DM-D	DMM-D	
Storage Tank Size (L)	5.34**	2.00	-3.34	-12.68**	-18.02**	-14.68**	3.704
Adj. Sto.Eff (%) (for 2250 L Tank)	-4.1**	-4.78**	-0.68	8.12**	12.22**	12.91**	3.743
Adj. Sys.Eff (%) (for 2250 L Tank)	4.1**	4.78**	0.68	-8.12**	-12.22**	-12.91**	3.743
Adj. Reliability (%) (for 2250 L Tank)	-2.27	-5.00**	-2.74	-10.37**	-8.11**	-5.37**	3.743
Adj. Satisfaction (%) (for 2250 L Tank)	-3.42	-5.50**	-2.09	-11.18**	-7.76**	-5.68**	3.743
Adj. Sto.Eff (%) (for 4500 L Tank)	-2.09	-1.55	0.54	1.79	3.88**	3.34	3.870
Adj. Sys.Eff (%) (for 4500 L Tank)	2.09	1.55	-0.54	-1.79	-3.88**	-3.34	3.870
Adj. Reliability (%) (for 4500 L Tank)	0.48	-2.21	-2.69	-7.84**	-8.32**	-5.63**	3.870
Adj. Satisfaction (%) (for 4500 L Tank)	-0.82	-3.24	-2.42	-9.96**	-9.14**	-6.72**	3.870

* Studentized Range Statistic
** Significant Difference at 5% Level of Significance

From Table No. 07 it is concluded that at 5% significance level, storage tank size, adjusted storage efficiency and adjusted system efficiency for 2250 Liters tank exhibits significant differences when they are estimated from RAINMOD by utilizing daily and monthly data. Similarly, at 5% significance level, all the adjusted performance parameters exhibits significant differences for 2250 Liters tank when they are estimated from RAINMOD by utilizing daily and mean monthly data whereas none of the parameters exhibits significant differences when they are estimated from RAINMOD by utilizing monthly and mean monthly data.

Majority of the parameters exhibits significant differences at 5 per cent significance level when they are estimated from observed daily data and RAINMOD utilizing daily data, observed daily data and RAINMOD utilizing monthly data, observed daily data and RAINMOD utilizing mean monthly data. Reason for significant differences is that observed daily data makes use of past record with only one realization without utilization of Markov chains and Gamma distribution whereas RAINMOD makes use of Markov chains and Gamma distribution with 20 realizations for predicting tank size and performance parameters.

Overall, the RAINMOD performs well for estimating different parameters under different rainfall data indicating that it is a reliable model for estimating different parameters under different rainfall data.

IV. CONCLUSIONS

- Tank size was under-estimated for about 87% of houses on which complete system was installed with respect to average tank size estimated from RAINMOD by utilizing different rainfall data. RAINMOD predicted average tank size within the range of 200 Liters under different rainfall data. At 5% significance level, storage tank size did not exhibit significant differences when it was estimated from RAINMOD by utilizing daily and mean monthly, monthly and mean monthly data but exhibited significant differences when daily and monthly data was utilized by RAINMOD.

- RAINMOD predicted average adjusted performance parameters within the range of just 1% under different rainfall data. At 5% significance level, all the adjusted performance parameters estimated at 2250 Liters and 4500 Liters tank from RAINMOD did not exhibit significant differences when monthly and mean monthly data was utilized but exhibited significant differences at 2250 Liters tank when daily and mean monthly data was utilized. Similarly, only adjusted storage and adjusted system efficiency estimated at 2250 Liters tank from RAINMOD exhibited significant differences at 5% significance level when daily and monthly data was utilized.
- RAINMOD predicted average tank size within the range of 675 Liters of observed daily data predicted average tank size. Similarly, it predicted average adjusted performance parameters within the range of 4% of observed daily data corresponding parameters.
- Majority of the parameters exhibited significant differences at 5 per cent significance level when they were estimated from observed daily data and RAINMOD utilizing daily data, observed daily data and RAINMOD utilizing monthly data, observed daily data and RAINMOD utilizing mean monthly data.
- RAINMOD took a minimum of only 12 values (mean monthly data) for generating daily rainfall, sizing of storage tank and simulation of system performance indicating that it is a very useful model in developing countries like Pakistan where long-term daily rainfall data is either unavailable or expensive.

V. RECOMMENDATIONS

- RAINMOD deals with gravity-fed rainwater system which is common in hilly areas, however other design configurations like directly pumped system and indirectly pumped system may also be possible. Work in this regard needs to be done.
- Generalized equations for determining adjusted performance parameters are developed based on three humid regions i.e. Balakot, Kakul and Saidu Sharif and for two tank sizes i.e. 2250 Liters and 4500 Liters. Hence, similar equations need to be developed and investigated for other tank sizes and for semi-arid and arid regions.

VI. ACKNOWLEDGMENT

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