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Development and validation of surface water yield model (SWYMOD) for fitting curve numbers of different land uses in micro-watershed of Ranga Reddy district, Telangana

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ABSTRACT

A surface water yield model (SWYMOD) was developed and validated by integrating SCS CN method and on-farm reservoir (OFR) water budgeting with the objective of generating CN (Curve Number) values of land uses of agriculture, forest and farm roads in a micro watershed of 14.5 ha area in Ranga Reddy district of Telangana state, India. The watershed is provided with on farm Reservoir (OFR) as storage structure for monitoring the daily water balance components of runoff, seepage and evaporation on daily basis. The watershed covers agriculture (7 ha), forest (7 ha) and farm roads (0.5 ha) with Alfisols as major soil group. The model was developed based on iterative procedure of estimating runoff as storage depth in OFR with the criterion of model efficiency (ME>90%) calculated using observed and simulated OFR storage depths. The model requires input file of date, rainfall, observed water loss, storage depth, seepage and evaporation on daily basis. The model was calibrated with the observed data of 2008 for initial abstraction (Ia = 0.2S, 0.25 S and 0.3 S) and validated with 2009 and 2010 observed data. The initial abstraction of Ia=0.2 S was found to have the maximum ME of 94.48% as compared to Ia=0.25 S and 0.3 S for the set of CN values of 67, 33 and 72 for agriculture, forest and farm roads with weighted curve number of 49 which is less than the other initial abstraction values. SWYMOD was validated with two years of observed data of 2009 and 2010 with ME of 95% indicating close agreement with observed and simulated water storage depth hydrographs of OFR. These curve numbers fixed by the SWYMOD are found to differ from SCS CN values for AMC II condition of micro-watershed. This study indicates the necessity of generating CN values with changed rainfall pattern in semi arid areas in view of climate change for accurate estimation of water yield/runoff and optimizing the design parameters of rainwater harvesting structures like OFR.

Key words: SWYMOD, Curve number, On farm reservoir (OFR), Micro-watershed

INTRODUCTION

Soil and water are the two critical natural resources that influence the agricultural production and productivity in semi-arid regions of India. In the context of climate change, the occurrence of rainfall and its pattern, high intensity with less duration, frequent dry spells, reduced rainy days, etc. would influence hydrology of micro-catchments when used for rainwater harvesting with different land uses. It has been estimated that 50-60% of rainfall goes as run off carrying away 16 t ha^{-1} of top soil annually (Singh, 1990). South Central India is having predominant area more than 60% under rainfed farming with different levels of land degradation which is more prone to climate change impacts in terms of increased rainfall (5 to 10%) and increased temperature by 1 to 2^{o}C (Reddy *et al*., 2014). South Central India falls in the category of low to medium rainfall ranging from 600 to >1000 mm annually particularly in a state like Telangana. All these climate induced events call for management of surface run-off and water conservation measures in the rainfed areas.

Telangana state has 55% area under rainfed farming with light textured soils (Alfisols) having low water holding capacity, severe soil erosion due to water, less productive soil depth, low organic matter content (<1%) and soil crustation. These soils contribute to major production of nutrient pulses, oil seeds and course cereals. The average productivity of these soils range between 0.8 to 1.0 t/ha. Runoff water control and conservation measures like on farm rainwater harvesting through small reservoirs with proper lining is the solution for enhancing water productivity in the region (Reddy *et al*., 2012). A combination of

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agronomic and engineering measures reduces the runoff and soil erosion, but complete control of runoff by absorption into the soil profile is not possible under tropical climate, in view of the tropical rainfall distribution. The next best alternative is to manage the inevitable runoff by storing in on farm reservoirs (OFR), popularly known as farm ponds conserving water within farm. However, accurate estimation of runoff potential from such micro-catchments is the necessity for optimizing the design parameters of OFR for on farm rainwater harvesting.

The major objective of models is to scientifically estimate the water yield of the micro-watersheds so that an appropriate strategy is evolved to harness this water. The rate and amount of water yield depends on amount of rainfall, its intensity, the physical properties of the soils and shape, size and land use of catchments in micro-watersheds. At present, there are several sophisticated and complicated models starting from continuous watershed models to event-based watershed models and empirical relations (Reddy *et al*., 1994). The most common problems faced while applying hydrologic models to Indian watersheds is their large input data requirement for calibration and their location specific use. Annual runoff estimation is generally by developing regression equations (Sharma, 1983; Verma, 1987; Selvarajan, 1990) to different watershed parameters. This annual runoff estimation does not help much in design of OFRs because water is needed at some critical stages of crop growth. Unfortunately, small watershed hydrology has mostly been neglected field in the country and proper small stream gauging data are extremely scanty. This indicates the necessity to develop a simpler model to be understood and used by a field staff with minimum input data requirement like daily rainfall and land use information which are generally available in the micro-watersheds of rainfed areas. Daily water yield models are better suited for the design of storage structure and to study the availability of stored water for proper crop planning in the rainfed farming. The most commonly used method is Soil Conservation Service curve number (SCS) method for estimation of runoff from small watersheds because of its simplicity. This is a semi-empirical method, which uses a number of qualitative attributes of watershed parameters and predicts the runoff as a resultant interaction of watershed parameters with rainfall. For Indian conditions, handbook of hydrology (Ministry of Agriculture, 1972) has given the appropriate curve numbers (0 to 100), which can be used to estimate the runoff for given rainfall from ungauged watersheds. Several researchers have studied the runoff potential of watersheds by generating appropriate CN values for different land uses (Pandey and Sahu, 2002; Sarangi *et al*., 2005; Zade *et al*., 2005; Sahu *et al*., 2005). Therefore, use of CN values developed for larger watersheds in runoff estimation, may result in over or under-estimation in micro-catchments affecting the design of rain water harvesting structures. The present study was undertaken to develop a user-friendly water yield model by establishing appropriate curve numbers and its validation over selected micro-watershed of semi-arid region of Telangana state.

MATERIALS AND METHODS

Study area

A micro-watershed (78° 40′ N, 17º 2′ E) at Gunegal Research Farm (GRF) of ICAR-CRIDA Institute, occurring at 621m above MSL was selected (Fig.1). The daily climate data on rainfall, and evaporation are recorded from an automated weather station (AWS) installed at Gunegal Research Farm (GRF), during the period 2008-10. The average annual and seasonal rainfall of the area is 700 and 478 mm, respectively. The average temperature of study area is 25.5°C with average minimum and maximum of 8.94 and 42.06°C, respectively. The micro-watershed has the slopes varying from 1-3% with major soil group of alfisols having texture of sand :62.3%, Silt :15.7%, Clay 22% with average bulk density of 1.33 Mg/m^3 which are well drained with high infiltration rates with soil depth of 0.5 to 1 m depth. The organic carbon content (OC) was 0.5%. The average steady infiltration rate was between 30-40 mmhr^{-1} in the micro-watershed. In these soils, soil crustation after the recession of the rainfall, is a problem in the watershed reducing the initial abstraction for short duration storms though the infiltration rates are high.

Model formulation

The background literature survey warranted that an event-based model could be more suitable within an acceptable limit of model efficiency. The estimation of water yield was done by a modeling approach primarily the hydrologic soil cover complex method. The necessary input data for using this method are the rainfall, land cover, land treatment, antecedent moisture condition and hydrologic soil group. The AMC values were

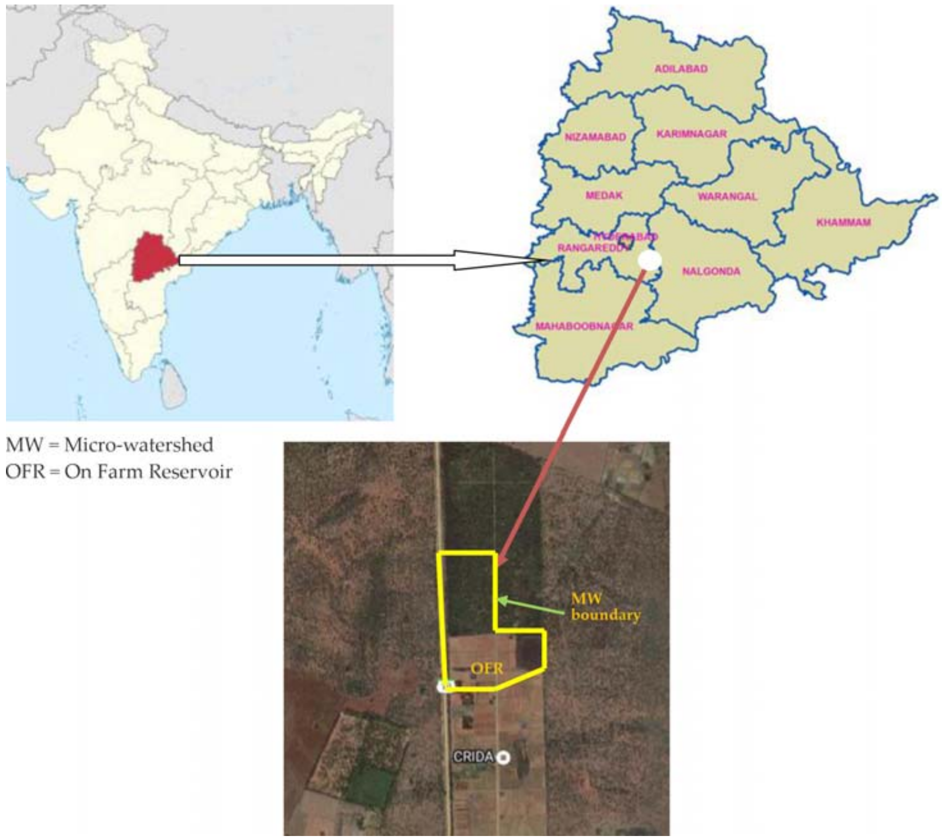

Fig. 1. Study area showing the location of the experiment

calculated using the recorded daily rainfall data. The hydrologic soil group was based on the physical properties of soil like texture, infiltration, soil depth, *etc.* The soils of this region fall in the category of soil hydrology group B having the properties of good drainage and high infiltration. The climate input data like daily rainfall and pan evaporation data were recorded from automatic weather station during 2008-10, whereas water storage depth in OFR, total water loss were observed on daily basis through gauging OFR. Actual seepage on daily basis was calculated by subtracting pan evaporation from the observed total water loss.

Formulation of the model development has been done in two parts. In the first part, the runoff from a given rainfall was estimated by using the following equations:

$$Q = \frac{(P - \lambda S)^2}{(P + (1-\lambda)S)} \tag{1}$$

$$Ia = \lambda S \tag{2}$$

where,

Q = Runoff depth, mm

P = Rainfall depth, mm

λ = Coefficient (fraction)

S = Maximum potential retention, mm

Ia = Initial abstraction, mm and

$$S = \frac{(25400 - 254CN)}{CN} \tag{3}$$

Where, CN = Curve number.

An iterative process/logic was developed by integrating the water balance of OFR and the SCS method, for finding the appropriate curve number (eq. 1, 2 and 3) for different land uses in the catchment of micro-watershed. The weighted curve number was used to calculate the value of S and Q using eq. (1) for given rainfall and S. If on a particular day $P < \lambda S$, Q is taken as zero. In the second part of model development, the calculated runoff depth was converted into runoff volume by multiplying with the micro-watershed area. The volume of runoff was then converted into OFR water storage depth by using depth-volume relation of the OFR. For this depth, the water spread area was estimated using the corresponding rating curve (depth-water spread area of OFR). The information of water spread area was then used to estimate seepage and evaporation losses. The daily seepage losses were taken as input for calculating

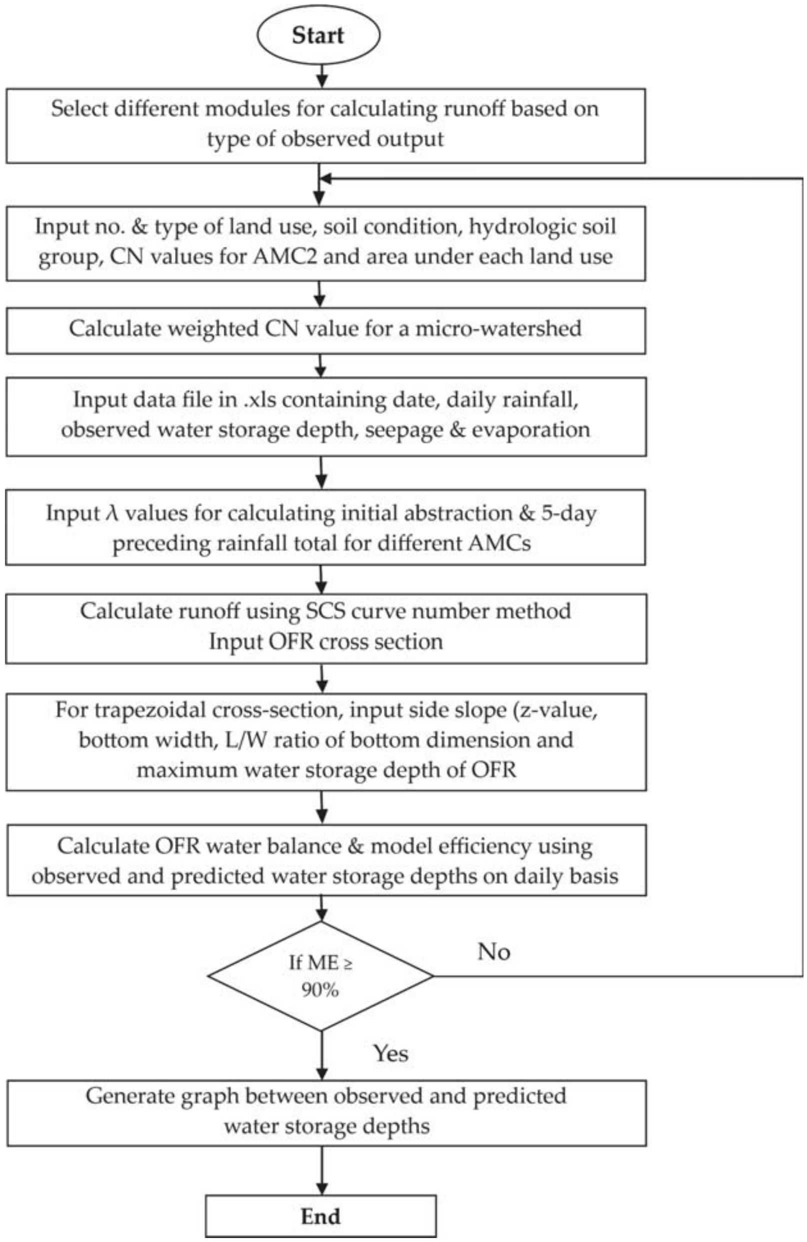

Fig. 2. Flow chart showing different operation in SWYMOD

seepage volume. Thus, the operation of second part resulted in a new value of water level as a consequence to runoff accumulation or water level decline in a non-rainy day. The flow chart of the model is given in Fig. 2.

The depth-water spread area and volume were calculated by using power equations as given below (eqns. 4 and 5):

$$WSA = a(D)^b \tag{4}$$

$$V = c(D)^m \tag{5}$$

Where,

WSA = Water spread area of OFR, m^2

D = Depth, m

a,b,c,m = regression coefficients

V = Volume of water, m^3

The values of regression coefficients (a,b,c,m) were obtained through regression analysis as shown in Fig. 3.

The OFR water balance was calculated as given below (eq. 6):

$$PVOL\ (I) = TRNVOL\ (I) - \{SEEP\ (I) X APOND\ (I)\} - \{EVAPO\ (I)\ X\ APOND\ (I)\} \tag{6}$$

Where,

PVOL (I) = Water storage volume of OFR on i^{th} day, m^3

TRNVOL (I)= Total runoff volume on i^{th} day, m^3

SEEP (I) = Seepage loss on i^{th} day, m

APOND (I) = Water spread area on i^{th} day, m^2

EVAPO (I) = Evaporation loss on i^{th} day, m

The depth-water spread area and the depth-run off volume relationships for the selected OFR in a micro-watershed are given in Fig. 3.

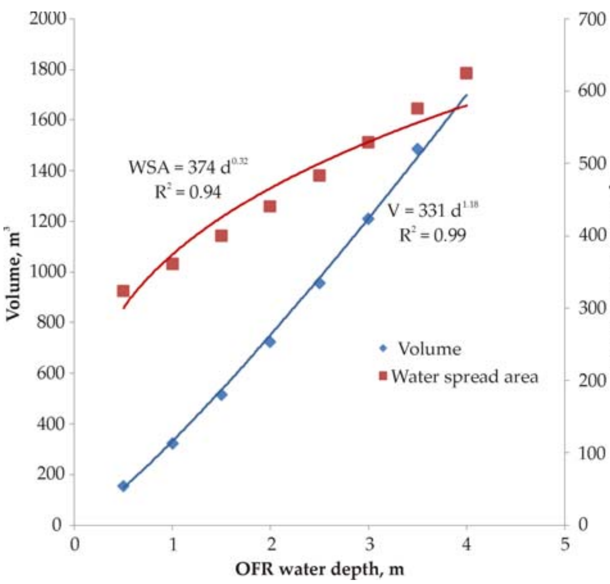

Fig. 3. Depth-volume and water spread area relationships of OFR in micro-watershed

Model Development

The different steps involved for fixing CN values of different land use in micro-watershed are given in Fig. 4. The model was developed using visual basic platform. The model has two options of i) measuring the direct run off in a micro-watershed through flumes, and ii) measuring the water depth in the rain water harvesting structure like OFR as outlet. In the present study, OFR was constructed as outlet for storing runoff and hence the second module was selected for executing the model. The model requires giving the input information of land use types, hydrologic soil condition, hydrology soil group, CN value and the area under particular land use in micro-watershed. After inputting these values, the model calculates weighted CN value of the micro-watershed. The model requires an excel file containing the observed data for date, rainfall, water deposited in the OFR in mm/day, evaporation and seepage in mm/day as an input into the model for calculating run off and OFR water balance. The model has the provision of calibrating the λ value for selected set of CN values in the model and the 5-day preceding cumulative rainfall for defining antecedent moisture condition (AMC) of the micro-watershed. In the present study, the cumulative total of 5-day preceding rainfall was less than 35 mm for AMC 1, 35-52.5 mm for AMC 2 and >52.5 mm for AMC 3 were considered as given by SCS, 1964. However, the model was calibrated for different λ values of 0.2, 0.25 and 0.3. Generally, for Indian micro-watersheds with black soils, λ = 0.2 and for red soils, λ = 0.3 was suggested (Yuan *et al*., 2012). Using the above set of information, the model calculates daily runoff data for a given set of land use and rainfall data. This information was integrated with the OFR water balance eq. no. 6. The model has two options of selecting the OFR cross-section, like trapezoidal and rectangular/square. However, under field conditions, OFRs are constructed with trapezoidal cross section with side slopes of 1.5 or 2:1 depending upon the soil type. The present study considered the trapezoidal cross-section and the depth water spread area and depth volume relations were developed through regression analysis and these equations (1-6) were used in the model. For trapezoidal cross-section, the model is having options of side slope, selected bottom width, length-width (L/W) ratio and maximum depth of water storage in OFR. After entering the above information in the model, the OFR water balance is calculated for obtaining the predicted water storage depths on daily basis. Using observed and predicted water depths, the model calculates model efficiency using the equation as given below (eq. no.7):

$$Model\ efficiency\,(ME) = 1 - \sum_{i=1}^{n}\left(\frac{(Dpi - Doi)^2}{(Doi - Doa)^2}\right) \qquad \ldots(7)$$

Where,

D_{pi} = Predicted water storage depth on i^{th} day, mm

D_{oi} = Observed water storage depth on i^{th} day, mm

D_{oa} = Average observed water storage depth, mm

Criterion used in the model for fixing the curve numbers was ME>90%. If ME<90%, the user has the provision for re-entering the CN values of different land uses in a micro-watershed. Finally, the model has the provision of making graph for observed and predicted water storage depth series on daily basis for visual observation of the model performance and comparison.

RESULTS AND DISCUSSION

The micro-watershed has 7 ha of forest, 7 ha of agriculture and 0.5 ha of dirt roads with an outlet of OFR for rainwater harvesting and storage of runoff. The dimensions of the OFR are 24x24 m^2 top, 17x17 m^2 bottom with maximum depth of 3.5

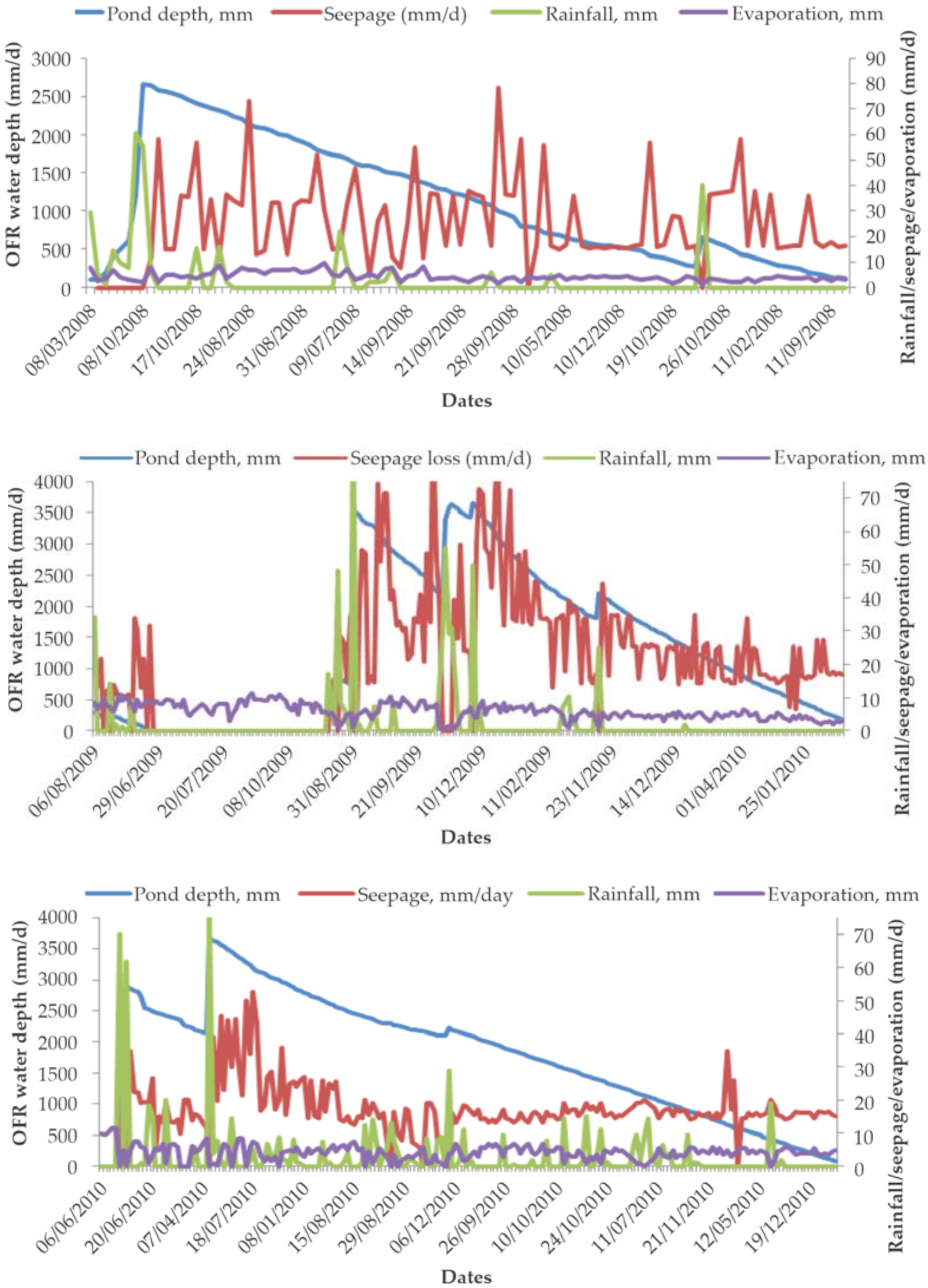

Fig. 4. OFR water balance for different years (2008-2010)

m. The side slopes were kept at 1.5:1 for the stability of the soil strata. The depth-water spread area and volume relationships were developed through regression analysis by fitting the power equations (eq. 4 and 5). The regression coefficient obtained were a=374, b=0.32, c=331 and d=1.18 with coefficient of determination, R^2=0.94 for water spread area and R^2=0.99 for volume (Fig. 3). These relationships were used in a model to convert the run off as output from SCS CN method into the storage depth of OFR and the corresponding water spread area at a given depth of storage.

The observed daily water balance components of OFR in a micro-watershed are presented (Fig. 4) for the duration 2008-10. The major components include the water storage depth corresponding to the volume of runoff received into OFR, daily rainfall and daily evaporation data. The seepage was calculated from the total water loss by subtracting the daily evaporation on a given date. During the initial year, 2008, the seepage rates were observed to be high ranging from 20-70 mm/d, though the seepage varied with respect to the depth of storage and wetted area/ water spread area

(WSA) of the OFR. These data were used for calibration of the model for fitting the CN values of different land uses in a micro-watershed. Similar trends in the seepage were observed during the year 2009 also, however, during 2010, the seepage rates were stabilized ranging from 20-40 mm/d even at the maximum depth of storage in OFR. The data collected during 2009-10 were used for validation of the model.

SWYMOD calibration

The calibration of SWYMOD for fitting curve numbers of different land uses in a selected micro-watershed was done for different values of λ for calculating initial abstraction in the SCS CN method for estimating runoff (Table 1). For λ=0.2 (I_a=0.2 S), there were almost 12 iterations for fixing the best fit CN values with the maximum model efficiency of 94.48%. The first iteration started by selecting the USDA recommended CN values for AMC 2 condition of micro-watershed. The values of CN are 72, 30 and 87 for agriculture, forest and dirt roads giving the model efficiency of 32.48% which is far below the accepted limits. Then, the repetitions of iterations were carried out with the selection of a new set of CN values by decreasing it and the model efficiency increased with decrease in CN values. The final sets of CN obtained were 67, 30 and 72 for agriculture, forest and dirt roads, respectively with a maximum model efficiency of 94.48%. Similarly, the iterations were carried out by changing λ values by 0.25 and 0.3. For λ=0.25, the maximum iterations were 7 and the final set of CN values of 71, 33 and 75 for agriculture, forest and dirt roads, respectively with a maximum model efficiency of 94.11%. For λ=0.3, the maximum iterations were 8 and the final set of CN values were 75, 35 and 77 for agriculture, forest and dirt roads, respectively with a maximum model efficiency of 94.02%. As the λ value is increased, the set of CN values also get increased for different land uses in a micro-watershed which coincides with the observations reported (Yuan *et al.*, 2012). The observed and predicted water storage depths in OFR are in close agreement with each other as presented in Fig. 5 for different λ values with 2008 data. The observed and predicted hydrographs simulated by the model are very close and similar with maximum efficiency of 94.48 % for λ=0.2.

Model validation

The model was validated with the data collected during 2009 and 2010 with the calibrated set of CN values for λ=0.2 with maximum efficiency. The results (Fig. 6) are in close agreement between observed and predicted water depth hydrographs by the SWYMOD with model efficiency close to 95%. Therefore, the model can be replicated in similar micro-watersheds for fitting new CN values for Indian conditions. The CN values fitted by the SWYMOD indicated that the set of curve numbers obtained with maximum efficiency are different from the set of CN values given (SCS, 1964) for λ=0.2. Also, the CN values fixed (Pandey and Sahu, 2002) for λ=0.3 are different from the present study for the land uses of agriculture, forest and dirt roads for hydrology group B and good soil condition (Table 2). The weighted CN values of micro-watershed were 49, 53 and 56 for λ=0.2, 0.25 and 0.3, respectively. The above results indicate that there is a need to develop CN values for different hydrological conditions and land uses which are

Table 1. Fitting of curve numbers of different land use with different iterations and model efficiency for different coefficients (λ) of initial abstraction

λ values	Type of Land use/Iterations	1	2	3	4	5	6	Final*
0.2	Agriculture (7 ha)	72	70	68	67	66	66	67
	Forest (7 ha)	30	30	30	30	29	29	30
	Roads (0.5 ha)	87	80	78	76	72	70	72
	Model efficiency (%)	32.48	65.7	87.81	93.04	93.7	92	94.48
0.25	Agriculture (7 ha)	67	70	71	71	71	71	71
	Forest (7 ha)	30	33	33	33	33.5	33	33
	Roads (0.5 ha)	72	75	76	77	77	80	75
	Model efficiency (%)	54.12	93.46	94.07	94.01	93.24	93.76	94.11
0.3	Agriculture (7 ha)	77	78	77	76	74	74	75
	Forest (7 ha)	34	34	35	35	37	35	35
	Roads (0.5 ha)	59	62	82	75	72	77	77
	Model efficiency (%)	93.96	92.89	86.21	93.05	93.47	93.03	94.02

*λ=0.2 was 12^{th}, 0.25 was 7^{th} and 0.3 was 8^{th} iteration

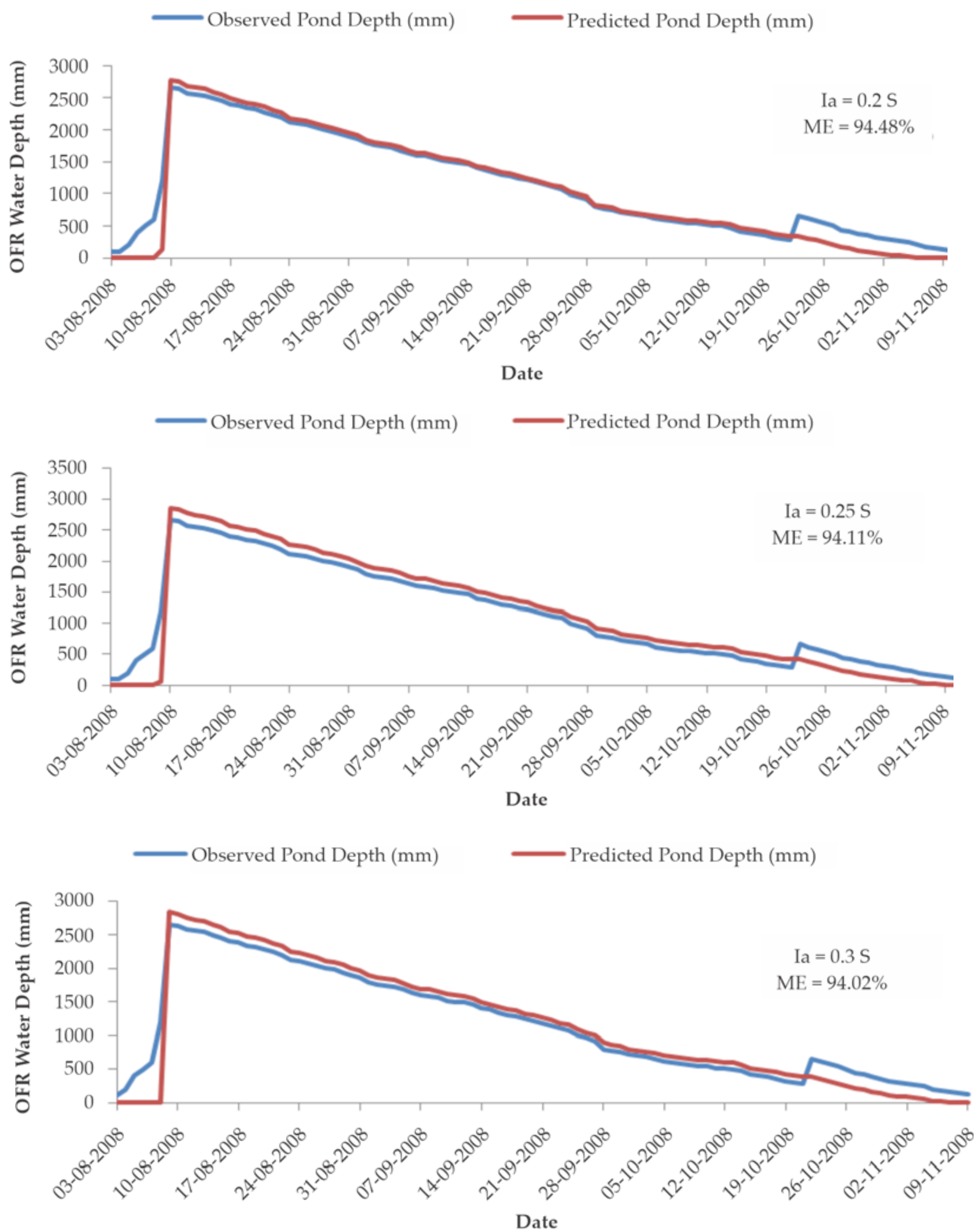

Fig. 5. Calibration of model for initial abstraction (Ia) using observed and predicted pond water depths

Table 2. Simulated Curve Numbers through SWYMOD and their comparison for different land uses

Type of land use	Area, ha	Initial Abstraction (Ia)			USDA CN for AMC II (Ia=0.2S)	CN for AMC II (Ia=0.3S) for Indian conditions[12]
		0.2 S	0.25 S	0.3 S		
Agriculture (HG: B, Good)	7	67	71	75	78	86
Forest (HG: B, Good)	7	30	33	35	58	40
Roads (Dirt) (HG: B, Fair)	0.5	72	75	77	82	80
Weighted CN	49.31	52.79	55.76	68.48	63.58	
Max. Model Efficiency (%)		94.48	94.11	94.02		

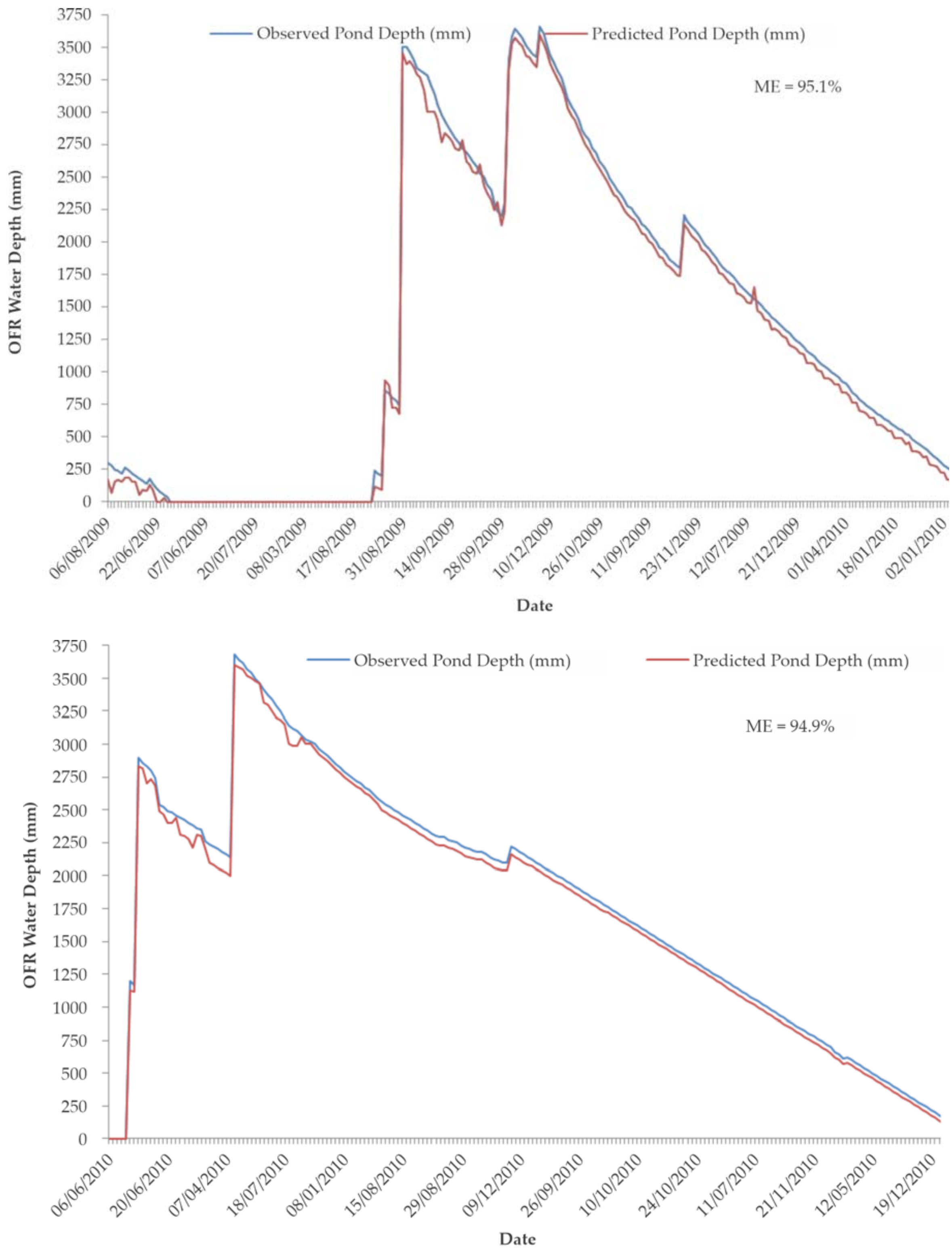

Fig. 6. Validation of SWYMOD for initial abstraction Ia = 0.2 S using observed and predicted pond water depths of (a) 2009 and (b) 2010

location specific, for accuracy in estimation of runoff into an OFR structures through modelling approach when used for ungauged micro-watersheds in the country. SWYMOD can meet this purpose with minimum input data of given watershed.

CONCLUSION

A Surface Water Yield Model (SWYMOD) is developed by integrating SCS CN method and OFR water balance for generating the CN values for different land uses through iterations with criterion of model efficiency more than 90% for accepting the curve numbers. The model is user friendly and CN values of different catchments with varying land uses can be fixed for estimating the runoff. The model is constructed in two modules namely, with direct runoff measurement at the outlet of selected catchments and with OFR structure at outlet of catchment.

The model has the capability to simulate the runoff in the form of water depth in OFR for optimizing the design of rainwater harvesting structures in the micro-catchments of semi-arid environment of south-central India. The best fit CN values with close agreement between observed and predicted water storage depths, are 67, 30, 72 for λ=0.2 for agriculture, forest and dirt roads, respectively in a selected micro-watershed. The model will be very useful in accessing the runoff potential with fitted CN values in Indian conditions for the design of OFR, particularly implemented by IWMP, SAU'S, MGNRES, state line department of agriculture and rural development agencies.

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