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Research article

Rainwater harvesting and water balance simulation-optimization scheme to plan sustainable second crop in small rain-fed systems

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ABSTRACT

Environmental degradation in the form of water shortage and uncertainty has severely affected the food systems across the globe. Especially in India, which is dominated by rain-fed farmers, the need for sustainable water resource and its management at farm level is imperative for farming livelihoods and food security of the country. Rainwater harvesting in on-farm reservoirs (OFR) can enable crop diversification, year round cropping and seasonal vegetable cultivation in rain-fed farming systems in India. However appropriate sizing of OFR remains a serious concern especially for small and marginal farmers with limited land holdings. In this study, a novel and comprehensive simulation-optimization model was developed to determine the optimal size and utilization of OFR. The simulation consisted of water balance of soil and OFR using hydrological analysis for last 28 years, through which supplement irrigation needs and, rainwater harvesting potential was estimated. Optimal use of available water in OFR was designed using a multi-stage process wherein the model generated, compared and screened appropriate vegetable plans for Rabi cultivation. The model was simulated for different OFR sizes and the optimal size was chosen based on its economic feasibility. To demonstrate the model, a case study was simulated wherein high supplement irrigation was estimated, indicating a severe limitation in rain-fed farming. A minimum OFR size of 9.9% of the total land was required. With an increase in OFR sizes, the profits increased however, the growth rate declined as the cropping area was reduced. An OFR size of 15.5% of total land was found to be optimal which gave benefit-cost ratio and payback period of 2.4 and 6.8 years respectively. Trends in cultivation plans for different sizes of OFR was observed wherein for small OFR sizes, the model generated fewer options of cultivation plans and preferred crops with high water productivity over crops with high profitability. The proposed model is generic and applicable at multiple scales and scenarios. The model could be used by environmental decision makers, farm managers, policy makers and researchers to determine the feasibility of any water resource intervention using an ecosystem centric approach when multiple scenarios of cultivation are possible.

1. Introduction

Rise in demand for water, along with unwise land and water use practices possess serious concern for the food security (Richards et al., 2021) and water resource sustainability (Hao et al., 2022). The situation is even critical in developing countries (like India) where most of the farming systems are small rain fed and struggle with unreliable and limited water resources. Uncertain rainfall patterns, depleting groundwater tables and increasing demand for food require strong measures to develop knowledge and strategies for on-farm water management and ecosystem centric farming.

Improving water control strategies such as water arresting for groundwater recharge and surface storage have shown potential for redressing the water-related problem in small farming systems (Phansalkar and Verma, 2004). Rainwater harvesting is an effective management method (Kim et al., 2021) that could be used store the water in an on-farm reservoir (OFR). It could enable a secure and continuous water supply for irrigation in water-constrained farming systems during the erratic rainy (Kharif) season and non-monsoon (Rabi) season (Sahoo and Panda, 2014). OFR systems could support cultivation of additional crops in Rabi season, hence ensuring food security in the country and livelihood generation in farming systems who cultivated only a single

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crop in monsoon and rain-fed conditions.

Even though the OFR systems have proven to be profitable in many parts of India (Banerjee, 2019), their proliferation is not significant. OFR pricing and sizing remain crucial concerns, especially for small and marginal farmers as OFR competes with valuable cropping area for a limited landholding setting and budget (Panigrahi et al., 2005). Moreover, small farmers operate with limited resources, and therefore, appropriate sizing and utility planning of OFR is crucial to realize maximum gains and returns from the available resources.

In countries like India, the sizing of OFRs constructed by many organizations is generally based on a thumb rule. As reported by Roy et al. (2009), allocation of 20% of field area for OFR seems to be the most popular thumb rule followed in general. However, the cropping patterns, resource availability, land topography, rainwater harvesting potential, and construction cost are essentially region-specific. Hence, it is difficult to bring parity among available OFR designs for more sustainable, and productive farming. Therefore, it is envisaged that appropriate tools are necessary to suggest the optimal size of an OFR given the interplay of many uncontrollable variables. It is difficult to quantify these variables in isolation as they are interdependent and have a complex interaction with each other.

OFR sizing is a classic analytical problem wherein estimation of water demands followed by an economic analysis is the most popular approach. Panigrahi et al. (2005) and Roy et al. (2009) used water-balance simulation and economic indicators such as benefit to cost ratio, payback period etc. to determine optimal OFR size for the rice-mustard based cropping system. Similarly, Panigrahi and Panda (2003) and Srivastava (2001) used simulation modelling to estimate supplement irrigation needs for rice-based cropping system and determined optimal OFRs for their respective regions of study. In addition to simulation modelling and economic analysis, a few studies have also proposed optimal utilization of the designed OFR. For example, Ambast and Sen (1998) used linear programming along with water balance simulation to design OFR and optimize the cropping pattern for a set of crops in Sundarbans, India. Popp et al. (2003) developed Modified Arkansas off-stream reservoir analysis model for irrigation optimization and investment simulation that can provide economics of optimal OFR sizes for rice and soybean farms. The existing studies have developed efficient hydrological, economic, and agronomical models related to OFR sizing, but their focus was primarily on a fixed set of crops and agro-ecological conditions. To address the research gap in this domain, Roy et al. (2009) considered multiple variables and developed a user-friendly software that can adapt to different crops, cropping systems, irrigation management, and soil types to determine the optimal OFR size. But they considered only one crop per season, which does not reflect the real-life scenario. Small farmers prefer a multi-cropping system to increase crop diversity and reduce risk of crop failures (Joshi et al., 2006). Given the diversity in crop choices, the farmers make seasonal choices, therefore, designing OFR based on a fixed cropping plan pose practical limitations. Thus, to be able to create realistic picture, a robust and versatile tool is necessary which can incorporate all feasible multi-cropping systems in the decision making process. Another important component missing in the existing OFR sizing studies is the uncertainty analysis of the farming system. Such analysis would be crucial in the decision-making process.

The current study proposes an innovative approach for sizing and optimal utilization of OFRs. A linked simulation-optimization approach is used as it could plan the physical behaviour of water resource and design best management plans in conjunction (Goorani and Shabanlou, 2021). A novel simulation-optimization model scheme is developed that integrates analytical tools of water-balance simulation, combinatorics, optimization, cluster analysis, multi-criteria decision making, uncertainty analysis, and economic analysis to address the presents needs and limitations in the previous studies.

The model determines an optimal size of OFR and provides a scope for inclusion of multi-cropping cultivation plans and full-factorial crop-mixes. In addition, the model provides flexibility to the users to select any one of the cropping plans from the optimal scheme keeping uncertainty at bay. The fluctuating market rates, produce yields and variable climate conditions affect the farm economics. The uncertainty analysis of above variable is warranted, therefore, the proposed features strengthens the model as compared to existing models of sizing OFRs. Proposed model scheme is versatile and not constrained by any specificities (by location, farm type, soil characteristics etc.) therefore it is applicable for all the rain-fed systems who want to benefit from rainwater harvesting for second cropping. This model's key deliverables are estimation of rainwater harvesting potential, explorations of all feasible cropping scenarios for different sizes of OFRs and eventually an optimal size of OFR along with a list of most profitable and least risky cropping plans. The current work contributes in sustainable water resource design and management, while the integration of various analytical tools demonstrates the potential of such algorithms to solve multidimensional problems. The proposed simulation-optimization scheme is demonstrated using a case study (which represent a typical small rain-fed farming system) in the next section.

1.1. Study area

A typical example of a resource-constrained farming system is examined. A village densely populated by small and marginal farmers is selected for this study. The village lies in the Palghar district of Maharashtra state of India. Fig. 1 (a) depicts the location of the study area with contour and rainfall intensity maps of the district and India. The average rainfall per annum in this region is 2600 mm, which is considerably higher than the state average of 1450 mm (Fig. 1 (b)). Due to the topography (Fig. 1 (a)), the water runoff rate is high and the rainwater is generally lost unless harvested or stored. The average landholding is 1000 m^2 (0.25 acre), and they cultivate rain-fed rice as a subsistence crop during the Kharif season. The local rice variety ideally yields 1 ton/acre for 100 days crop duration, but the farmers often experience yield losses due to erratic rainfall patterns (Fig. 1 (c)) as they use no other source of irrigation than rainfall. Since most of the farmers do not have the provision of water storage or rainwater harvesting, they cannot cultivate a second crop and, therefore, migrate to nearby cities during the non-monsoon season. A few progressive farmers store rainwater in self-built OFRs to support supplement irrigation needs during rice cultivation in Kharif and cultivate vegetables on small portions of their land in winter or Rabi season. However, across many similar regions, the adoption of OFR technology is slow due to small landholdings, high cost of investment, absence of planning in terms of returns on investment, and lack of economic analysis (Rao et al., 2017). Efficient sizing and planning of OFR could justify the economics of investment and profitability. Moreover, other social benefits of OFR adoption include secure livelihoods through year-round cultivation, which would reduce migration and food security in the region. Typically, sowing for winter vegetables generally happens in mid-November, and the produce is sold in nearby cities. Farmers generally follow a crop mix of 3–4 different vegetable types to get better market returns and avoid the risk associated with mono-cropping cultivation. Since water availability is low, a drip irrigation system is the most popular choice to utilize the water efficiently. The soil is favourable for cultivating a variety of vegetables, as observed during the field-level investigation and through experts. The calculated average volumetric moisture content at the permanent wilting point, field capacity, and saturation for a sample soil are 27.7, 39.7, and 48.6%, respectively.

1.2. Development of model

1.2.1. Simulation-optimization scheme

The simulation-optimization scheme is represented in Fig. 2. The scheme has two major components: (i) the water balance simulation and (ii) second crop planning. The output of component-I becomes the input

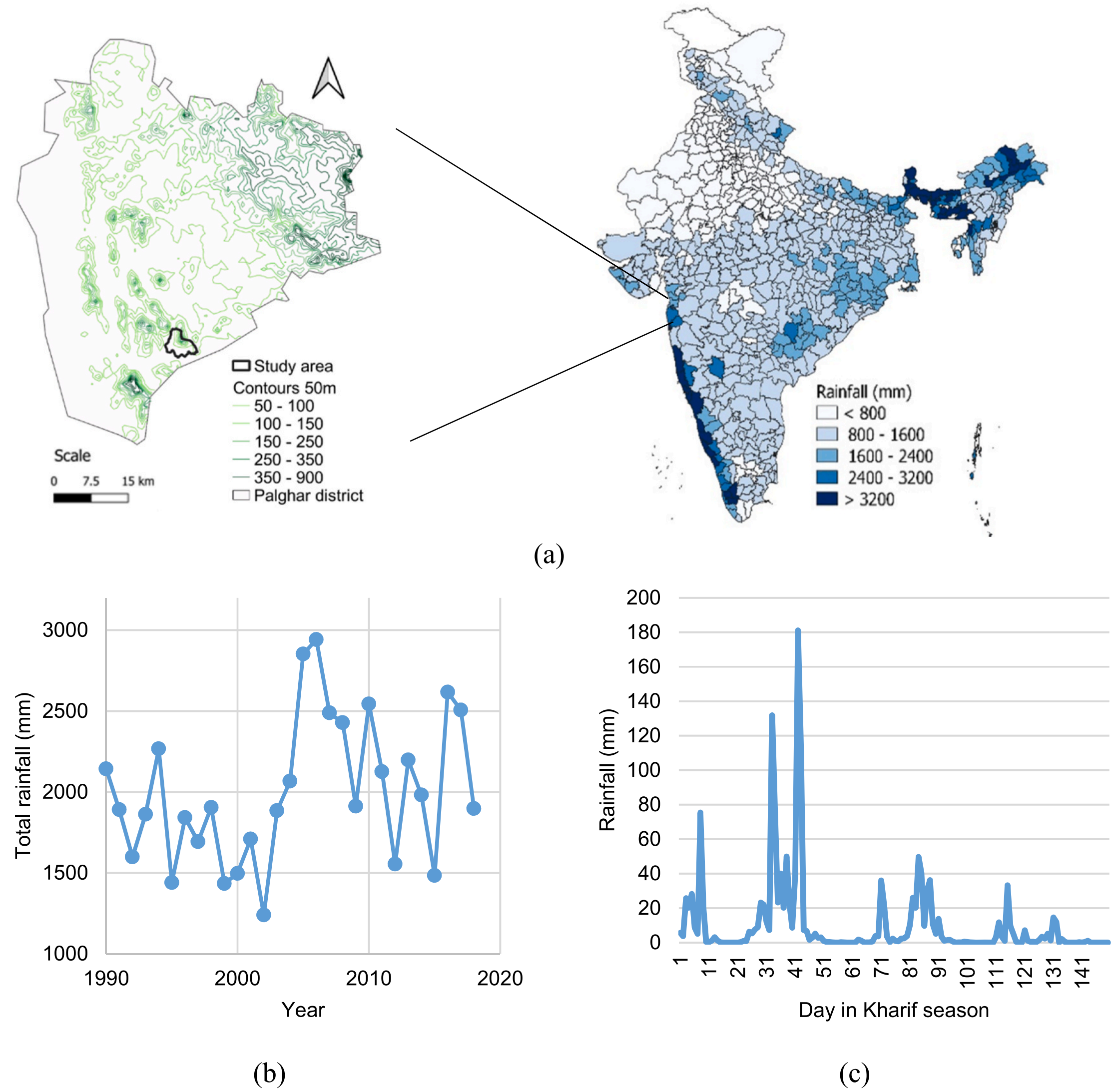


Fig. 1. (a) Location of the study area in district and India map, (b) the annual rainfall in the study area over last 25 years, (c) daily rainfall in Kharif season for a sample year-2000.

for component-II. The data flow and model elements remain the same for all rain-fed systems, hence making this scheme generic and applicable for any rain-fed system. The description of the scheme is done in the following paragraph using the case-study context for enhanced understanding.

A daily soil water balance (DSWB) is simulated for the Kharif season from 1990 to 2018 for the case-study area. The temporal resolution of climatic data can vary for other study systems depending on the data availability. The Kharif season is considered from 1st June till 31st October for all years wherein $j = 1:153$ represents a day of Kharif season such that $j = 1$ for 1st June. The parameters for DSWB consist of precipitation, evapotranspiration, runoff, and infiltration. DSWB provides the daily supplement irrigation demands of rice for rain-fed Kharif cultivation. The Kharif crop can vary for other study system and its respective properties as mentioned in Fig. 2 would be needed. Initially, a 3 m deep square trapezoid-shaped OFR (this shape is standard in Indian context) with a top area of 50 m2 is considered. The daily water balance of OFR (starting from $j = 1$) is computed to estimate the inflows, outflows, and water level. If the volume of water in OFR suffices the supplement irrigation demands for the jth day, then the DSWB and water balance of OFR is computed for the $(j+1)^{th}$ day. Otherwise, the OFR top area is increased by 0.1% of the farm area with each iteration until OFR volume suffices the irrigation demand. The OFR water capacity on 31st October is computed for all years, and an 80% probability of exceedance (PE) value (Srivastava, 2001) is estimated using the methodology described by Helsel and Hirsch (2002). Here, 80% PE value suggests an 80% probability that the OFR water capacity would equal or exceed the specified PE value. This value gives the water availability in a particular size of OFR for Rabi or second crop cultivation.

For the case study, list of vegetables preferred by the farmers, number of crop mix or cropping pattern, the economics of vegetable production, resources capacity, cultivation criteria, and OFR construction costs are taken as input for planning Rabi cultivation for the size of OFR. A multi-stage optimization is implemented to generate all feasible cropping plan options and screen the most appropriate ones. The labels “stages-1 to 5” in Fig. 2 represent this multi-stage procedure. Stages-1 to 5 mimics the decision-making process of the farmer while designing cropping plans. Essentially, the decision making involve (i) setting up cultivation objective (ii) processing information, (iii) identifying and evaluating options of plans and (iv) choosing appropriate plans. The stages in this scheme are placed such that stage-1 and stage-2 are used to generate full factorial options of crop mixes/combinations and allocate acreages to form plans as per resource availability and cultivation objectives. Then, stage-3 and 4 allows choosing appropriate plans by first

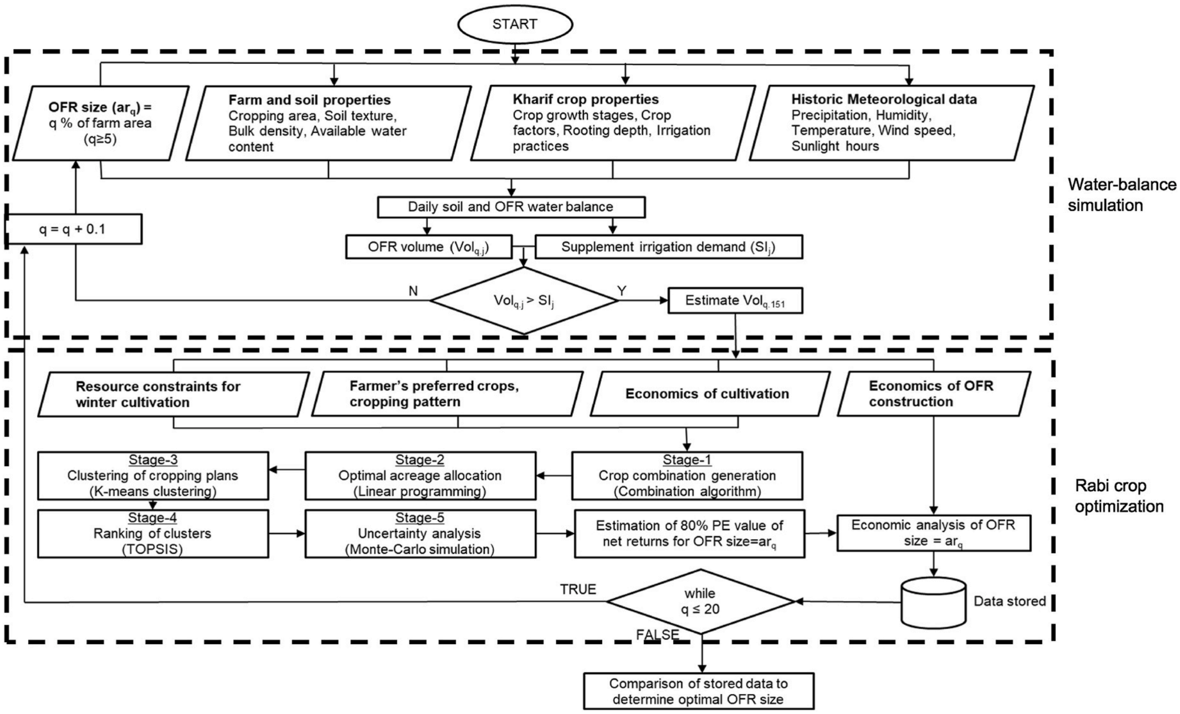


Fig. 2. Step-by-step exposition of the proposed simulation-optimization scheme.

grouping/clustering the alternatives and then selecting the best cluster of alternatives using sustainability indices (described in section 3.4.3) as criteria. In stage-5, an uncertainty analysis is carried out for all the cropping alternatives/plans in the top-ranked cluster such that a list of most profitable and least risky plans are screened.

An 80% PE value of net returns from the most appropriate cropping plans is estimated. These values are used for economic analysis to evaluate the economic feasibility of that particular size of OFR. The economic analysis data is stored, and the above procedure is repeated till the OFR area reached 200 m^2. The economic analysis data of all OFR sizes are compared to compute the optimal size of OFR. This simulation-optimization scheme enables consideration of all intermediate possibilities while avoiding exhaustive experimentation efforts.

The description of analytical tools, formulation and model assumptions are described in section 3.2, 3.3, 3.4 and 3.5.

1.3. Water balance of kharif cultivation

Taking the effective root zone of rice in a single layer, a generalised water balance equation for unsaturated soil is used for DSWB estimation which is represented by equation (1) (Khepar et al., 2000) (Panigrahi et al., 2005) (Roy et al., 2009).

$$SW_j = SW_{j-1} + P_j + SI_j - AET_j - SP_j - SR_j \quad (1)$$

where SW_j and SW_{j-1} are the soil water/moisture (mm) of jth and $(j-1)^{th}$ day, respectively. P_j is precipitation (mm), AET_j is actual evapotranspiration (mm), SI_j is supplement irrigation (mm), SP_j is seepage and percolation losses (mm) and SR_j is surface runoff (mm), respectively, on the jth day. Capillary rise is ignored in this study because the groundwater table is much below the root zone of rice. For the simulation, the soil moisture on the first day is considered at the wilting point (Roy et al., 2009). The SP_j losses for the unsaturated state of soil are considered to be 4 mm/day (Brouwer and Heibloem, 1985). Estimation of AET_j and SR_j are described in section 3.2.1 and 3.2.2 respectively.

Rice is flood irrigated in the study region. A nursery is prepared in about 8% of the total land to develop saplings. The soil is kept at saturation for the first week from sowing. After the first week, ponding with a depth of 2.5 cm is observed till transplanting. The land is puddled before transplanting the saplings in the main land. A ponding depth of 5 cm is observed post transplanting till the last two weeks from harvest. The land is allowed to drain and dry with no irrigation for the last two weeks.

Equation (2) represents the DSWB for the saturated and ponded state of the soil.

$$D_j = D_{j-1} + P_j + SI_j - AET_J - SP_j - SR_J \quad (2)$$

where D_j and D_{j-1} is the ponding depth (mm) of jth and $(j-1)^{th}$ day, respectively. During the saturation stage, the excess water above the ponding depth is drained as runoff. During the saturated stage of the puddled soil, the SPj losses are considered to be 1.5 mm/day (Razavipour and Farrokh, 2014).

1.3.1. Actual evapotranspiration and supplement irrigation

The actual evapotranspiration is calculated using equation (3) (Idike et al., 1982).

$$AET_j = K_c \times K_s \times ET_{oj} \quad (3)$$

AET_j and ET_{oj} are the actual evapotranspiration (mm) and reference evapotranspiration (mm), respectively. K_c and K_s are the crop coefficient and soil moisture stress factor, respectively. FAO Penman-Monteith method (Allen et al., 1998) is used to estimate the reference evapotranspiration. The crop coefficients of rice considered for this study are 1.15, 1.23, 1.14, and 1.02 for initial, crop development, reproductive, and maturity stages, respectively (Tyagi et al., 2000). The soil moisture stress factor ranges from 0 to 1. At the saturated state of the soil, the K_s is 1, while in the unsaturated state, it varies linearly with soil moisture (Allen et al., 1998). For unsaturated state, the K_{sj} is given by equation (4) (Panigrahi, 2001)

$$K_{sj} = \frac{SW_j}{SAT} \quad (4)$$

where SAT is the moisture content at saturation. The effective root zone of rice is 0.5 m, and the calculated value of SAT is 243 mm.

1.3.2. Surface runoff

SWAT is a widely used hydrology tool because of its applications and generic framework (Karki et al., 2020) and has been used by many well cited studies such as Golden et al. (2014), Glavan et al. (2015) to estimate surface runoff. SWAT was used in this model scheme because (i) it allows daily time step (ii) allows continuous simulation over long durations (ii) software codes available in open domain (iv) used by estimate surface runoff in over 3000+ peer reviewed papers (Wang et al., 2019). SWAT provides two methods for estimating surface runoff, the SCS curve number procedure, and the Green and Ampt infiltration method. For this study, we use the SCS curve method because of its simplicity and moderate input data complexity. The SCS runoff equation is an empirical model that is commonly used since the 1950s. As per the SCS runoff procedure, the soil in this region belongs to the hydrological soil type D, and the soil runoff curve number (CN2) is 89 (Neitsch et al., 2011).

1.3.3. Bare soil evaporation

During pre-germination, the land is fallow, and the soil evaporation reduces the soil moisture. ET_{oj} is used to estimate the Bare soil evaporation (ES_j) in mm subjected to P_j condition of the jth day using the following equations (Jensen et al., 1993):

$$ES_j = 0.1ET_{oj} \quad \text{if} \quad P_j = 0 \tag{5}$$

$$ES_j = ET_{oj} \quad \text{if} \quad P_j \geq ET_{oj} \tag{6}$$

$$ES_j = P_j \quad \text{if} \quad 0 < P_j < ET_{oj} \tag{7}$$

Equations (5)–(7) are used to compute the DSWB in the pre-germination period by replacing AET_j with ES_j in equation (1).

1.4. Water balance of OFR during kharif cultivation

A square-sized trapezoidal OFR which is commonly used in the study region is considered. A depth of 3 m, slope 1:1, and berm of 0.5 m around the OFR, with a lining of low-density polyethylene (LDPE) is used for the OFR. The model is simulated for different top areas of the OFR. Water balancing of OFR considers all the inflows and outflows. The inflows include precipitation and runoff captured by the OFR, while outflows are evaporation and supplement irrigation. Seepage losses in OFR are trivial because of LDPE lining's hot sealing; hence, the seepage losses are ignored. Equation (8) represents the water balance of OFR (Mishra et al., 2009).

$$Vol_{q,j} = Vol_{q,j-1} + P_j \times ar_q + SR_j \times Land - E_J \times ar_q - SI_j \tag{8}$$

where, $Vol_{q,j}$ and $Vol_{q,j-1}$ are the OFR volume (m^3) on jth and j-1st day respectively for the q top area of OFR size while q = 50:200; ar_q, Land and E_j are the OFR top area (m^2), cultivated land (m^2), and evaporation losses (m), respectively; Land is the difference between total land and ar_q. E_j is estimated using equation (3), where the AET_j can be replaced with E_j while K_c and K_s are equal to 1 for open water bodies like OFR (Kohli and Frenken, 2015). During heavy inflows, the OFR might overflow, and the excess water is drained out of the farm. The overflow condition of the OFR is represented by equation (9).

$$\text{if} \ \left(Vol_{q.max} - Vol_{j-1} < P_j \times ar_q + SR_j \times Land\right) \text{then} \ Vol_{q,j} = Vol_{q.max} \tag{9}$$

where $Vol_{q.max}$ is the maximum volume of the OFR in the qth day iteration. Volume of OFR on j = 153 is calculated for all years, and an 80% PE value is considered for vegetable cultivation.

1.5. Planning of rabi cultivation

The multi-crop planning is computed for one cultivation cycle per season. The optimization-based Rabi vegetable cropping plans are computed in five stages. In the case study, vegetables are preferred for second/Rabi cropping therefore the formulations in the following sections are for vegetable cropping. The inputs for the optimization model and details of its stages are described below:

1.5.1. Inputs for planning vegetable cultivation

A participatory exercise was conducted in the study region to understand the resource capacities, including land, man-hour availability, budget, and production targets for a sample farming household. Along with this, preferred vegetables and their local agricultural practices were also recorded. Table 1 describes the economics of cultivation for the selected/preferred crops. The cost of cultivation and human work hours are calculated based on local agricultural practices. The market data is acquired from AGMARKNET (2020). The crop water requirement is calculated using the FAO Penman-Monteith method (Allen et al., 1998), where Kc values are sourced from Brouwer and Heibloem (1985). It is calculated according to the date of sowing as 15th November. The vegetables are irrigated by drip irrigation which has volumetric losses. An irrigation efficiency of 90% (Brouwer and Heibloem, 1985) is considered for drip irrigation. The crop irrigation requirement value is calculated for all years, and an 80% PE value is mentioned in Table 1.

1.5.2. Crop combination generator (Stage-1)

Combination algorithm (Ryser, 1963) is used to generate full factorial crop combinations/mix from a pre-defined list of crops given by the farmer. t crop combinations ($^{N}C_y$) are formed when y crops are chosen from N number of crops. The set of crop combinations can be depicted as $CC_k \ \forall \ k = 1 \ldots t$. For the study region, the farmers suggested a list of 15 crops (N) with the preferred cropping pattern as 4 crop mix (y = 4). Hence, 1365 crop combination (t) are possible such that k = 1 … 1365.

1.5.3. Optimal allocation of land to crop combinations (Stage-2)

An optimization algorithm is used with acreage as the decision variable (generally used in similar land-use studies (Singh, 2012)). The present problem of maximizing the gains from Rabi vegetable cultivation can be simplified to a linear programming problem (Singh, 2015). Linear programming has been used for its simplicity of computation considering the large data set that the model encounters. However, if the cultivation objectives or constraint equation demands non-linear variable in a study system, then it is advised to use non-linear programming or equivalent optimization technique in the model scheme. An optimal acreage is allotted to each crop in crop combinations through the optimization algorithm such that it satisfies an objective of profit maximization and is subjected to resource constraints. The objective function $(Zmax)_k$ is represented by equation (10) for the kth crop combination;

$$(Zmax)_k = \sum(((p_{ki} \times M_{ki}) - C_{ki}) \times X_{ki}) \tag{10}$$

where X_{ki} is the decision variable/crop area (m^2) while p, M, and C are productivity (Kg/m^2), market-rate (INR/kg), and cost of cultivation (INR/m^2) of the ith crop respectively. The index i represents the crop order in a crop combination such that i = 1, 2, 3 and 4. These index values are followed for the following resource constraints equations.

$$\sum X_{ki<.=.L-.\ ary} \tag{11}$$

$$\sum W_{ki} \times X_{ki} \leq Vol_{q.153} \tag{12}$$

$$\sum C_{ki} \times X_{ki<=B} \tag{13}$$

$$\sum H_{ki} \times X_{ki<.=.HR} \tag{14}$$

$$p_{ki} \times X_{ki>=.MPT} \tag{15}$$

where equations (11)–(15) are cropping area, water, budget, time, and production constraints, respectively. X, W, C, H, and p are cropping area (m^2), crop water requirement (m^3/m^2), cost of cultivation (INR/m^2),

Table 1
List of preferred crops and their economics of cultivation (1$ ≈70 INR).

Crop Index - j	Crop	Market rates (INR/kg) - M_j	Coefficient of Variance for Market rates -CVM_j	Productivity (kg/acre)- p_j	Cost of cultivation (INR/acre) - C_j	Irrigation requirement (mm/season) - W_j	Human work hours (hour/acre) - H_j
1	Cluster beans	33	0.34	2025	17584	264	193
2	Carrot	12	0.24	10122	18367	308	203
3	Cucumber	16	0.35	3239	18987	297	204
4	Eggplant	16	0.35	10122	19624	447	216
5	Onion/dry	12	0.36	10122	20674	602	223
6	Capsicum	24	0.49	6073	21162	668	237
7	Radish	12	0.27	6073	16975	107	167
8	Spinach	6	0.24	3239	18654	151	176
9	Tomato	11	0.26	12146	21049	470	217
10	Okra	26	0.19	2025	18147	302	199
11	Bitter gourd	29	0.36	2430	17584	310	202
12	Chilly	26	0.42	4049	17584	424	212
13	Pumpkin	14	0.29	7288	17584	312	202
14	Cowpea	31	0.20	1620	17584	274	197
15	Coriander leaves	13	0.28	2430	17454	417	201

human work hour requirement (h/m^2), and productivity of ith crop in kth crop combination respectively. The total land (L) is 1000 m^2, while the water available of Rabi cultivation is the volume of water in OFR on the last day or 153rd day ($Vol_{q.153}$). There is a general practice of putting the plastic lining on the top of OFR during Rabi season to avoid evaporation. This practice is avoided during Kharif season due to high wind speeds and storms which might damage the plastic lining on the top. Therefore, no evaporation losses are considered from OFR during Rabi season. The available funds or budget (B) for Rabi cultivation is INR 5000/- while the total human work hours available for Rabi season (HR) is 160 h. To maintain crop diversity, each crop should have a minimum production target (MPT) which is estimated with farmers as 100 kg.

This process is done for all crop combinations individually. The cropping plans are developed by allotting the optimal acreage to each crop in the crop combinations. A profile is calculated for each cropping plan using indices that are termed sustainability indices. These indices describe the sustainability of the cultivation based on the output generated, resource utilization, and stability of the cropping plan. These indices are selected based on literature and field knowledge. These consist of net returns (INR/cultivation), human work hours (h/cultivation), diversity index, and relative time dispersion index. The diversity index is a measure of how well the production is distributed among the crops during the cultivation season. While in the cultivation season, the relative time dispersion index is a measure of the uniformity in the net returns over time. It distinguishes between plans producing income at once versus regular/continuous income (McConnell et al., 1997). The diversity index and relative time dispersion index indicate the evenness of production among crops and the income distribution over time, respectively. High values of diversity index and relative time dispersion index for a cropping plan indicate less risk of income losses. The diversity index in this study is adapted from Simpson's diversity index that is popular in fields such as biological sciences and agroforestry (Kumar et al., 1994) (Pandey et al., 2006). The empirical formula for diversity index (DI_k) and relative time dispersion index ($RTDI_k$) for kth cropping plan is mentioned in equation (16) and equation (17), respectively (McConnell et al., 1997):

$$\frac{\left(\sum_{i=1}^{y} R_{ki}\right)^2}{\sum_{i=1}^{y} \left(R_{ki}\right)^2} = DI_k \qquad (16)$$

where R_{ki} is the income and $0 \leq DI_k \leq 4$ (when number of crop mix is 4)

$$1 - \frac{CV_{CP_k}}{CV_{max.=.RTDIk}} \qquad (17)$$

where CV_{CPk} is the coefficient of variation of income distribution in the total cultivation duration. CV_{max} is the maximum coefficient of variation of income distribution in the total cultivation duration among all k cropping plans. The value of $RTDI_k$ ranges from 0 to 1.

1.5.4. Clustering of cropping plans (Stage-3)

This stage uses sustainability indices as criteria to groups/clusters similar cropping plans to simplify or reduce alternatives to a manageable data set. It divides the cropping plans into distinct groups. Silhouette average method (Kaufman and Rousseeuw, 2009) is used to determine the optimal number of clusters, and the K-means algorithm (MacQueen, 1967) is used to allot cropping plans in appropriate clusters. K-means algorithm is used in this model scheme for its simplicity, capability to handle large dataset and ensure convergence.

1.5.5. MCMD in clusters (Stage-4)

Multi-criteria decision making (MCDM) is a technique to structure and solve decision problems that involve multiple criteria. TOPSIS is widely used for MCDM because the tendency of rank reversal is low in this method (Hwang and Masud, 2012). The clusters formed in stage 3 are computed with TOPSIS using sustainability indices as multiple criteria and weight-age of these criteria. TOPSIS ranks the clusters such that the cluster attaining rank 1 (top cluster) is the most favourable. The cropping plans in the top cluster are more appropriate as compared to other clusters. Through participatory field-level investigation, farmer's preferences were noted in sustainability indices while planning their cultivation. The farmer was explained about each index and instructed to prioritize the indices by marking each one on a scale of 10 (higher marks being higher priority). The priority order computed as per farmer's marking schemes is net returns, diversity index, human work hours, and relative time dispersion with weights of 45%, 25%, 20%, and 10%, respectively.

1.5.6. Uncertainty analysis of the best (top) cluster (Stage-5)

The cropping plans in the top cluster are used for uncertainty analysis. Parameters such as market rates, yield, and cost of cultivation of crops tend to fluctuate during the cultivation. Monte-Carlo simulation is applied to quantify the variation caused due to the uncertain parameters. Gaussian kernel density with optimal bandwidth approximation is used to generate the probability density function of uncertain variables. The objective function equation is fed with random values of uncertain parameters, which are generated from the distribution curve. The mean of the objective function values and coefficient of variation (CV) are calculated for each cropping plan. The CV defines the stability of the cropping plan, wherein a lower CV represents a safer cropping plan. Percentile values of mean net returns and CV are calculated with the set of cropping plans. The cropping plans with mean net returns higher than the 75th percentile and CV less than the 25th percentile are screened as the most appropriate plans for the given context. These screened cropping plans are found to be most profitable and least risky plans.

1.6. Economic analysis

An economic analysis is conducted to compare the OFR sizes and determine the optimal size. As proposed by Palmer et al. (1982), a present worth analysis is used for this study wherein interest rate, and inflation factor in investment are considered to evaluate all cash flows. This analysis considers net returns from Rabi cultivation only because the Kharif cultivation is done for subsistence, and there is no income from the same. The cost of cultivation for Kharif crop (rice) is minimal due to the use of preserved seeds, self-labour, and collective farming. The OFR intervention stabilizes the Kharif yield when dry spells predominate during the rainy season, but the yield is not considered for economic analysis of the OFR investment.

The expenditures for this analysis consist of OFR construction cost, annual maintenance cost, irrigation system cost, and cost of cultivation. The income source is the returns from Rabi vegetable cultivation. The particulars of OFR construction cost are mentioned in Table 2. The OFR size with a top area of 48 m^2–64 m^2 generally requires 2 man-day, and beyond 64 m^2, the man-days increases at a rate of 0.5 man-days for every 8 m^2 increase in OFR size (Panigrahi et al., 2005). The OFR maintenance includes annual desilting, and it is assumed to be 2% of the cost of construction of OFR (Panigrahi et al., 2005). The Rabi vegetables are considered to be irrigated with the drip system. The equipment cost of the drip system in this region is INR 25000 per acre. Annual maintenance of cleaning filters and pipes is required, whose cost is considered 4% of the drip system's equipment cost. The cost of cultivation of vegetables includes land preparation, seed, fertilizers, pesticide, irrigation, and labour costs. The cost of cultivation and market rates for vegetables are derived from primary and secondary data sources, as mentioned in Table 1. The model generates net returns with an uncertainty range for all screened plans. Considering the range of net returns values of all screened plans, 80% PE value is considered in economic analysis for a size of OFR. An inflation rate (I) of 4%, the interest rate for the agricultural loan (f) as 8%, and life (w) for OFR and drip system as 15 years is considered for the economic analysis.

The net returns is the difference between income (INC) and cost of cultivation (COS) of vegetable cultivation. The net present value or present worth value of the annual net returns (PWV_{nr}) is given by equation (18)(Panigrahi et al., 2005).

$$PWV_{nr} = \sum_{u=1}^{w}\left[(INC - COS)(1+f)^{u-1}(1+I)^{-u}\right] \tag{18}$$

The annual cost (A) is the maintenance cost of OFR and drip system. The total cost of OFR irrigation system ($Total_{OFR}$) is the sum of OFR construction cost (OFR_c), irrigation equipment cost (Irr_e) and present worth value of the annual cost. Equation (19) is used to calculate the total cost of OFR irrigation system (Panigrahi et al., 2005).

$$Total_{OFR} = OFR_c + Irr_e + \sum_{u=1}^{w}\left[A(1+f)^{u-1}(1+I)^{-u}\right] \tag{19}$$

1.7. Economic indices

Benefit-cost (BCR) and payback period (PBP) are used as indices for economic analysis. These indices are studied for each case of OFR size and compared to determine an optimal size. Equation (20) (21) represent BCR and PBP respectively

$$BCR = \frac{PWV_{nr}}{Total_{OFR}} \tag{20}$$

$$PBP = \frac{OFR_c + Irr_e}{INC - COS - A} \tag{21}$$

1.7.1. Kharif crop yield response to water stress

The yield of Kharif rice in rain-fed and OFR condition is calculated. With OFR intervention, the cropping area for cultivation reduces because the OFR utilizes land equal to its size. The yield loss due to deficit irrigation (rain fed condition) is estimated and compared with the yield from cultivation with OFR. Doorenbos and Kassam (1979) studied the yield response of various crop to water stress. They developed a relationship which is represented in equation (22). The relation would change depending on the Kharif crop for different study systems.

$$1 - \frac{Y_a}{Y_m} = K_y\left(1 - \frac{ET_a}{ET_m}\right) \tag{22}$$

Y_a, Y_m, ET_a, ET_m and K_y are actual yield, maximum yield, actual evapotranspiration, maximum evapotranspiration, and crop yield response factor. The ET_a is calculated as the difference between the ET_m and supplement irrigation requirement. The maximum yield for Kharif rice in this region is 1011 kg/acre, while the K_y is considered as 1.1 (Sarkar et al., 2006).

2. Results and discussion

The proposed model scheme is used to determine an optimal size of OFR for given field conditions. For the case study, the kharif crop is rain-fed rice while preferred Rabi cultivation are multi-crop vegetables. First, the model calculates the Kharif water demands (SI demand) with 20% PE and rainwater harvesting potential with 80% PE during Kharif cultivation. Secondly, for different OFR capacities, it designs Rabi production plans and estimates net returns with 80% PE. Finally, a comparative analysis of different OFR sizes is done to determine the optimal size of OFR. The formulations and simulations in computed in MATLAB 2019b software package.

2.1. Water balance simulations

For the study region, the dry spells during Kharif cultivation are evident in the past years' data. The model estimates an actual irrigation deficit or SI need for the Kharif crop in the range of 57 mm–189 mm with a value of 115 mm as 20% PE. Similarly, the total AET is estimated in the range of 405 mm–585 mm and 502 mm as 20% PE. The value of supplement irrigation is significant as compared to the total AET value. Therefore, yield loss is expected in the rain-fed Kharif cultivation. Thus, a need for an auxiliary source of irrigation or OFR could be highlighted through this analysis. The historical data suggest that many high rainfall intensity events have occurred in the past, causing high runoff. The model estimates a runoff in the range of 816 mm–2346 mm with 1037 mm as 80% PE. The amount of runoff is substantially large as it almost 40% to the average rainfall in the region. There is a huge runoff tapping potential however, the amount of runoff captured depends on the volume of the OFR.

2.2. Minimum OFR size to suffice peak SI demand

The model is simulated by varying the OFR size (top area) from 5% to 20% of the farm land such that by increasing 0.1% area, the OFR volume would increase by 2.48 m^3. Considering a top area beyond 20% was inappropriate because OFR utilized a sizable portion of farmer's

Table 2
Particulars of OFR construction cost (2020).

Particular	Unit cost
Excavation cost	INR 60.60/m^3
Lining material with hot sealing	INR 90/m^2
Labour cost	INR 200/man-day

cultivable land, hence reducing their effective area of cultivation. The OFR size, which satisfies the daily SI demands throughout the season and for all years, qualifies for further simulations. A minimum OFR size of 9.9% of the total land is estimated by the model that satisfies the peak SI demands computed for given years. The vegetable production plans are designed for OFR sizes starting from 9.9% to 20% of the total land. For OFR size of 9.9%–20%, the volume of water in OFR t at the start of Rabi season ranges from 69.5% to 75% of the respective maximum OFR capacity.

2.3. Rabi cultivation planning

Out of 1365 cropping plans (as discussed in section 3.4.2), certain cropping plans with smaller OFR sizes do not satisfy the resource constraints mentioned in section 3.4.3. For example, a plan containing 4 high water-consuming crops may not be cultivated as per the given field conditions with the available water. The number of possible cropping plans increases from 947 to 1365 for OFR sizes from 9.9% to 14.2%, respectively. The cropping plans generated in the 2nd stage (section 3.4.3) possess non-homogenous characteristics or sustainability indices therefore filtering procedure (3rd stage-section 3.4.4) is essential. Sample results of the optimization procedure for OFR size 9.9% are discussed below. Figure S1 in the supplementary file represents the normalized values (min-max scaling) of sustainability indices for 947 cropping plans. For OFR size 9.9%, Stage-3 (section 3.4.4) makes 10 clusters among 947 cropping plans, while stage-4 (section 3.4.4) ranks the clusters and chooses the best one based on sustainability indices. The top cluster for OFR size 9.9% consists of 36 cropping plans. Stage-5 (section 3.4.6) performs uncertainty analysis and generates CV and mean net returns for the 36 cropping plans as presented in Fig. 3 (a). Similarly, results of uncertainty analysis for OFR size 13.1% and 16.1% (these sizes are selected randomly for demonstration of results) is represented in Fig. 3 (b) and (c), respectively, wherein there are 43 and 120 plans in the top cluster for size 13.1% and 16.1% respectively. For OFR size 9.9%, finally 4 plans are screened in stage-5 as per procedure mentioned in section 3.4.6. This results in a list of homogeneous, most profitable, and least risky plans. It is observed that the average number of screened cropping plans to the total possible cropping plans for an OFR size is about 0.75%. The variation in net returns values of selected/screened cropping plans is fitted in a probability distribution to estimate 80% PE value for an OFR size. These net returns values are used for subsequent economic analysis.

The OFR sizes are divided in the three categories for representing the results. The OFR size ranging from 9.9% to 13%, 13.1%–16% and 16.1%–20% of total land are termed as small, medium and large OFR, respectively. Similarly, the crop orders in the 4 crop mix are termed primary, secondary, tertiary, and quaternary in a cropping plan based on land proportions, with the primary crop occupying the maximum acreage. Fig. 4 represents the average land distribution among the four crops for different categories of OFR. The most feasible crops and their orders for different OFR categories are represented below the respective stacked columns in Fig. 4. The crop index from Table 1 has been used to represent crops in Fig. 4. It is observed that the land use distribution and the options of crops at various orders change for different OFR categories. The land use distribution remains statistically similar for small and medium OFR but varies for large OFR. The portion of primary crop increases in large OFR because high-profit crops at primary order are given larger acreages with increased water availability in large OFR. The options of crops in small OFR are fewer than other categories due to limited water availability. Therefore, the crops with relatively low water requirement and high profits or high water productivity (INR/m^3) are prevalent in small OFR. In the medium and large OFR, as the water availability increases, many crops qualify. In the large OFR category, crops with high profitability would be preferred over crops with high water productivity. Several crops do not appear in the results as they have high market rate uncertainty or low water productivity. In a crop combination, the crop with the highest profit is allotted maximum acreage. Sequential preference is then allotted to the other crops as per their profitability and system constraints. It could be observed that the quaternary crop occupies a very small portion of the land (~5%) and may not be contributing to the income substantially. Therefore, if the farmer wishes to switch to a three crop system, there would not be a significant change in income; however, crop diversity would reduce.

2.4. Economic analysis

The net returns from vegetable cultivation vary from INR 6377 to INR 11,493, when the size of OFR is increased from 9.9% to 20%. The net returns increase with an increase in OFR size because higher water availability would allow more acreage to profitable crops. However, the growth rate in net returns diminishes and finally becomes negative as OFR size crosses a certain threshold. Hence, the system constraints (such as land availability) do not allow an increase in net returns even when the water availability is increased. This elicits the need for optimal sizing of OFR for given system constraints.

Fig. 5 represents BCR and PBP for different OFR sizes. The values of BCR increase from 2.53 at 9.9% OFR size and attains its peak value of 2.77 at 10.9% OFR size. The BCR values obtained for all OFR sizes are greater than 2.17, indicating that benefits obtained are at least twice the costs incurred. This indicates that the OFR intervention is economically viable for the system under consideration. Similarly, the minimum PBP of 5.8 years is obtained at 10.9% OFR size, while the maximum PBP of 7.54 years is obtained at 20% OFR size. The economic analysis indicates that 10.9% OFR size is optimal for the given conditions. The OFR sizes greater than 10.9% would have higher capital investment and consume larger land, thus, reducing the cropping area and the production of Kharif cultivation. Whereas OFR size lower than 10.9% would provide less water for acreage allocation of high-profit crops. Though all OFR sizes produce economic benefits (BCR), yet through optimal sizing, we can maximize the returns while achieving the least PBP.

2.5. Kharif crop yield with optimal size OFR

The rice yield with deficit irrigation (rain-fed) condition is estimated to be 196 kg which is 54 kg less than the ideal yield of rice for the farm area of 1000 m^2. With an OFR intervention, the supplement irrigation demands could be fulfilled, but rice production would be reduced because the cropping area is decreased. With an OFR size of 10.9%, the area available for cultivation is 891 m^2, and the total yield of rice with full irrigation is estimated to be 222 kg. The total yield with OFR intervention is higher than the yield in rain-fed cultivation. Hence, the advantages of OFR intervention are more significant than the disadvantages.

2.6. Methodological implications, validation and limitations

Rainwater harvesting for second cropping is a complicated analytical problem which involves various uncertainties related to climate, crop choices, market rates, yields etc. The construction of OFR reduces the net cultivable area of the farm therefore, the decisions related to optimal OFR sizing stand crucial for the economics of the farming system. The proposed model scheme provides evidence whether the given field conditions have any rainwater harvesting potential. If so, then the scheme recommends its appropriate utilization. This is an important advisory to support decision making under uncertainty. The model inferences could enhance the information pool of agricultural extension services (such as “Krishi Vigyan Kendras” in India) and support policy makers in regulating agricultural schemes such National horticultural mission, MGNREGA, “More crop per drop” in India for on-farm water management. The dependency on regional surface and ground water resource could be reduced if there exists rainwater harvesting potential, hence the model inferences could also support regional water

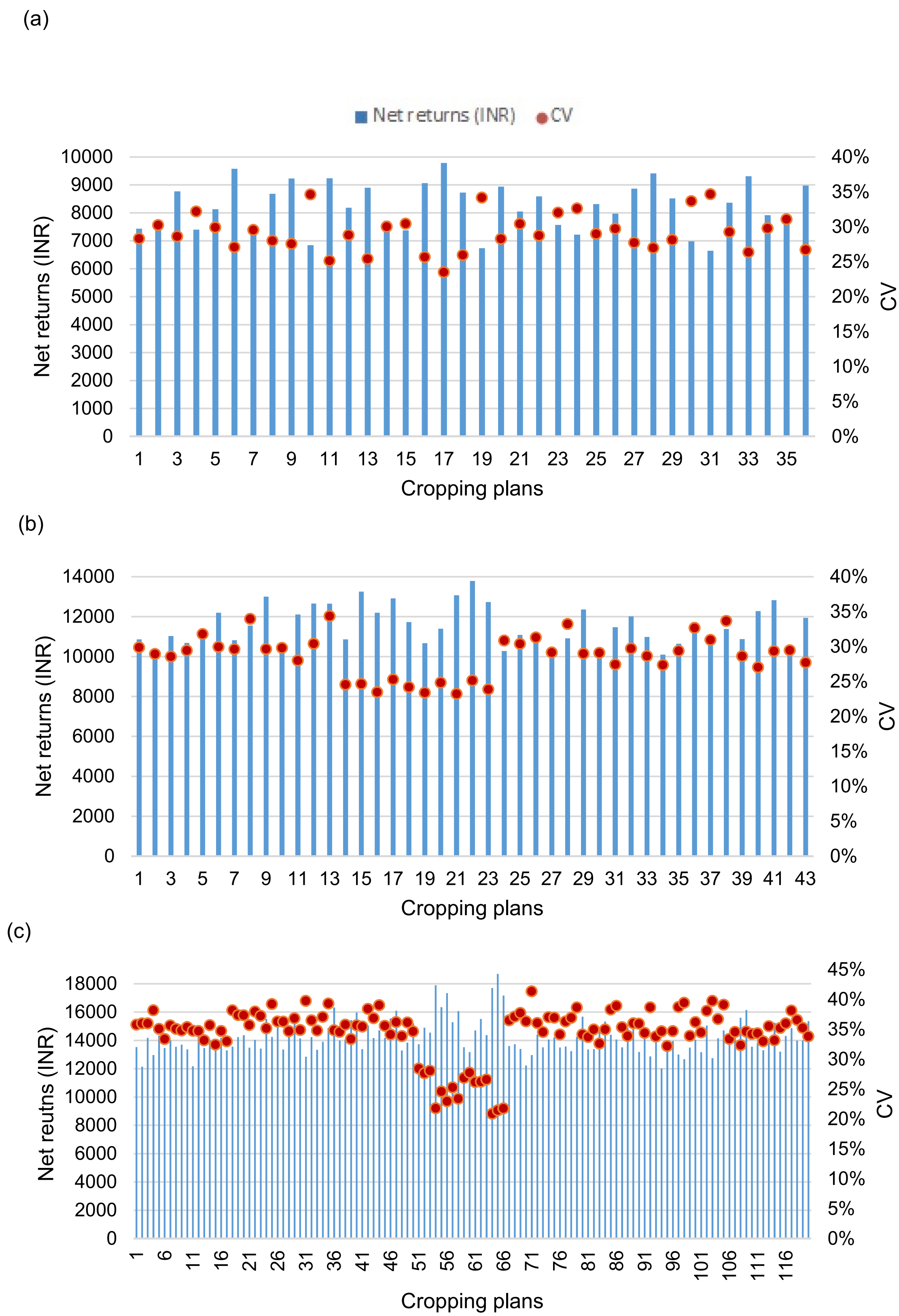
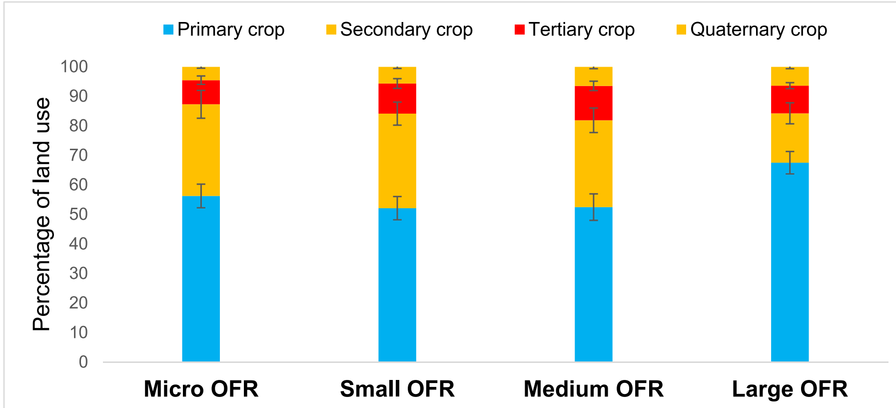


Fig. 3. Uncertainty analysis (Stage-5) for cases of on-farm reservoir size-(a) 9.9%, (b) 13.1% and (c) 16.1% showing net returns (INR) and coefficient of variation (CV) in %.



	Micro OFR	Small OFR	Medium OFR	Large OFR
Primary crop	2,7	2,7,9	2,7,9	2,9
Secondary crop	2,7,9	7,8,9,12	1,2,7,9,11,12	2,6,7,9,11,12,13
Tertiary crop	5,12,13	1,5,6,7,8,9,11,12,13	1,2,3,6,7,8,9,11,12,13	2,6,7,12,13
Quaternary crop	5,9,13	5,7,9,13	5,6,7,9,13	2,5,6,7,13

Fig. 4. Land use distribution and options of crops at various orders for different categories of on-farm reservoir.

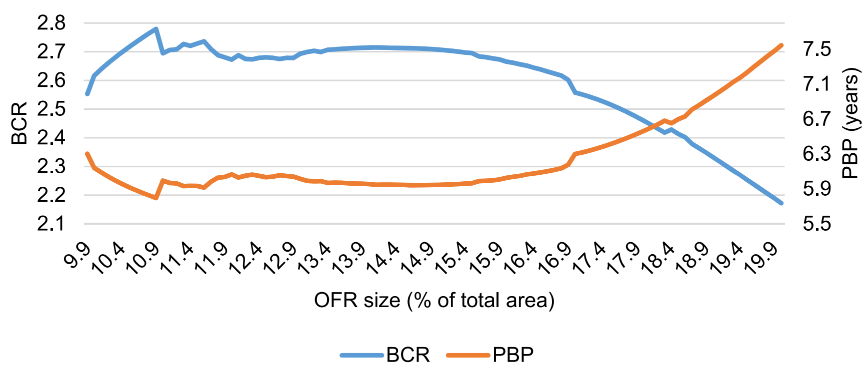


Fig. 5. Benefit Cost ratio (BCR) and Payback period (PBP) of different sizes of On-farm reservoir (OFR).

sustainability and agricultural prosperity.

The advantages of the proposed model scheme as suggested by the model results are as follows. First, the model estimate a minimum size of OFR (as suggested in section 4.2) to suffice rain fed cultivation in case the user doesn't want second cropping. Second, the model recommends multiple options of cropping plans for different size of OFR as suggested in Fig. 4. This enables the user to explore the benefits and trade-offs of various size of OFRs for second cropping (section 4.3 and 4.4) without actual experimentation. Third, the model scheme has uncertainty analysis therefore the results mitigate the risk in decision making.

The model used water balance simulation tool and values from well-established literature while the Rabi planning component uses local or field data and assumptions. The Rabi planning component was therefore validated using actual field experiments in the case study region wherein the model predictions were found to be reasonable precise to field values (Deo, 2022). Data from validation exercise can be found in supplementary file.

Currently, the model is tested on limited geographies. The model could be made more versatile by testing and getting feedbacks from different geographies, cropping conditions, construction materials and cultivation objectives. The main users of this model are small and marginal farmers whose risk appetite and resilience is low. They are generally hesitant in accepting a new cropping scheme (which may be unfamiliar to them). To be able to generate a representative sample for case studies, it is challenging to convince farmers to use model generated schemes on their fields. Support from state agencies and working with farmers in a participatory mode would encourage farmer's involvement and rigorous testing of the model scheme.

3. Conclusion and future work

The current study proposes rainwater harvesting in on-farm reservoirs (OFR) as a tool for sustainable water resource development and management. A generic simulation-optimization model is developed to check the feasibility of OFR and plan its optimal utilization in resource-constrained farming systems. For a sample case study system, the results indicate that the need for supplemental irrigation is significant; hence an OFR intervention is essential to stabilize Kharif cultivation. Our findings suggest that a minimum OFR size of 9.9% of farm land is required to suffice the peak supplemental irrigation need based on the past 28 years' data. The model designs appropriate cropping plans as per limited land, finance, manpower (properties of studied farm system) and availability of water in OFR. Optimal land use distribution and crop choices at various orders are generated for different categories of OFR. As the OFR size increases, the rate of growth in net returns increases initially but eventually becomes negative during higher OFR sizes. The economic analysis suggests 10.9% OFR size as the optimal size because of its highest benefit-cost ratio value of 2.77 and least payback period of 5.8 years. In comparison with the rain-fed cultivation, the Kharif yield is found to increase with an OFR of 10.9% size. The analysis supports that the OFR intervention in the considered size range is economically viable for the selected study system. Moreover, year-round cultivation would provide social benefits such as secure livelihoods and repatriation.

This simulation-optimization scheme provides an easy medium for analysing all intermediate possibilities while avoiding exhaustive experimentation efforts. The scheme could be developed into a web/mobile-based application and disseminated, wherein the farmers can input their local farm properties (ex. Tables 1 and 2) to get context-specific solutions. The software could facilitate a data warehouse wherein the farm level data could be aggregated for village level or regional planning. The proposed model scheme could be used as a foundation to build "Damage control" models that could accommodate phenomena such as floods in OFR sizing and agricultural planning. The current study also opens up avenues for social scientist to assess if optimized OFRs could enable reverse migration and encourage next generation in agriculture.

Author's contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Aniket Deo. The first draft of the manuscript was written by Aniket Deo and all authors revised previous versions of the manuscript. All authors read and approved the final manuscript. Third and second authors were involved in supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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