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Comparison of stochastic and fuzzy dynamic programming models for the operation of a multipurpose reservoir

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Abstract

Reservoir management is a highly complex problem, which includes the uncertainty in the inflows as well as in the objectives. Stochastic dynamic programming (SDP) has been widely used to develop the optimal operating policies of multipurpose reservoirs. In the recent years, fuzzy optimization has been used to incorporate the uncertainty caused due to the imprecise nature of objectives. In the present study, a comparison is made between a conventional SDP model and fuzzy dynamic programming models for optimal operation of a multipurpose reservoir. The two models are developed for Hirakud Reservoir on River Mahanadi in the State of Orissa in India. The performance of the reservoir is evaluated under the operating policies derived from these models through simulation. The results indicate that the fuzzy dynamic programming model performs better in achieving the flood control objective and thus in the overall performan1ce of reservoir.

Introduction

Multipurpose reservoir operation involves various interactions and trade offs between purposes, which are sometimes complementary but often are competitive or conflicting. Reservoir operation may be based on the conflicting objectives of maximizing the amount of water available for conservation purposes and maximizing the amount of empty space for storing future flood waters to reduce the downstream damages. Studies on long-term storage re-allocations and designing seasonal rule curves are two important types of reservoir system modelling and analysis applications.

A major complicating factor in water resources system management is handling uncertainty. Reservoir management is one such complex problem, which involves the uncertainty. Optimal operation of reservoir has been an active area of research for many years. Various models have been reported in the literature for developing an optimal operation policy for a reservoir. Yeh (1985), Simonovic (1992) and Wurbs (1993, 1996) reviewed the various models used for optimal operation of reservoirs.

Stochastic dynamic programming (SDP) has been widely used for the optimal operation of reservoirs. The uncertainty caused due to randomness of hydrologic inputs to the reservoir, like inflows, is taken care in SDP models. However, the uncertainty caused due to the inherent imprecision and vagueness that is present in the objectives of water resource development is also a significant factor that effects reservoir operation. New approaches are to be developed to incorporate this uncertainty. In recent years, fuzzy optimization models have generated considerable interest.

The development and adoption of fuzzy logic for planning and management of complex water resources systems are becoming popular in the field of water resource engineering. Shreshta *et al.* (1996) constructed a fuzzy rule-based model to derive operating rules for a multipurpose reservoir. Russel & Campbell (1996) used fuzzy logic programming to derive the operating rules of a reservoir. Fontane *et al.* (1997) developed a SDP model with imprecise objectives. Owen *et al.* (1997) used probabilistic membership functions to model variability in experts' perception of satisfaction of fuzzy objectives, taking Flaming Gorge dam as a case study. Using fuzzy set theory, they developed a model to deal with imprecisely defined linguistic objectives for reservoir management. Teegavarapu & Simonovic (1999) modelled the imprecise penalty functions associated with reservoir loss functions as fuzzy. Swain (2001) developed an adaptive neuro-fuzzy inference system (ANFIS) model for operation of Hirakud reservoir, a multipurpose reservoir in

India. He has used the historical data of the operation of the reservoir to train the ANFIS model. Panigrahi & Mujumdar (2000) developed a fuzzy rule-based model for the operation of a single-purpose reservoir. Debrovin *et al*. (2002) developed a fuzzy rule-based model for the real-time operation of a reservoir. Mousavi *et al*. (2004) developed a fuzzy state SDP model for operation of a reservoir. They introduced the concept of fuzzy Markov chain to model the uncertainties caused due to randomness of the hydrologic inputs to the reservoir and the imprecision in variable discretization. Based on this concept of fuzzy Markov chain, they developed fuzzy transition probability matrices, which were used in the SDP model. Mousavi *et al*. (2005) developed a dynamic programming-based fuzzy rule-based model for operation of a reservoir. Deka & Chandramouli (2009) developed a fuzzy neural network model for the operation of a reservoir and applied it to a reservoir in India.

There are not many studies undertaken to compare the traditional SDP models and the fuzzy optimization models for reservoir operation. Tilmant *et al*. (2002) compared the operating policies derived from fuzzy and nonfuzzy SDP models. They considered the hydropower and irrigation as fuzzy constraints in their fuzzy SDP model. They showed that both the models produce similar performance under the two policies.

In the present study, two SDP models are developed to derive the operating policy of a multipurpose reservoir. The first model is a conventionally used SDP formulation (Loucks *et al*., 1981), popularly used for deriving the long-term operating policy of a reservoir. In the second SDP model, the objectives of the reservoir are treated as fuzzy and maximizing the combined level of satisfaction of the objectives is taken up as the objective function. These two models are applied to derive the operating policy of an existing reservoir, namely, Hirakud Reservoir on River Mahanadi in the State of Orissa in India. The performance of the reservoir under these two operating policies is compared through simulation.

Hirakud reservoir system

The Mahanadi is one of the major river basins in the eastern region of India. It covers the states of Madhya Pradesh, Maharashtra, Bihar and Orissa. The total basin is bound by Central Indian hills on the north, Eastern Ghats on the south, Bay of Bengal on the east and Maikela range on the west. Owing to frequent floods in Mahanadi and droughts in the western part of Orissa, people of the region face a gloomy economy. Therefore, the Hirakud reservoir across Mahanadi was conceived to safeguard the delta from flood and provide irrigation to drought-prone areas (Department of Water Resources, 1997).

Hirakud project is a multipurpose project on river Mahanadi in the State of Orissa in India. The project is situated at latitude 21°32′N and longitude 83°52′E. An index map showing the location of Hirakud Reservoir is shown in Fig. 1. The reservoir has a live storage of 5818 million cubic metres (MCM) and a gross storage of 7189 MCM. The project provides irrigation for 1 55 635 ha during Kharif season (June to October) and for 1 08 385 ha during Rabi season (November to February) in the districts of Sambalpur, Bargarh, Subarnapur and Bolangir of Orissa State. Installed capacity for generation of hydropower at this project is 307.5 MW through its two power houses at Burla (at right bank toe of the dam) and at Chipilima (22.5 km downstream of the dam). Besides this, the project provides flood protection to 9500 km^2 of the Mahanadi delta.

The 10 daily flows into the reservoir are available for 19 years (from 1981 to 1999). The database is divided into two periods: monsoon and nonmonsoon. The monsoon period (rainy season) is from 21 June to 31 October (13 ten daily time periods, i.e. June III to October III). The nonmonsoon is considered as a single time period (from November I to June II). In the present study, the first time period starts from June III (third 10-day period in June) and the last time period is the nonmonsoon period that is the 14th time period. The average flows into the reservoir during these time periods are given in Table 1. The reservoir operation during monsoon is complicated due to conflicting objectives like flood control, irrigation, power generation and conservation at the end of the period. The nonmonsoon operation is relatively simple. Hence, reservoir operation only for monsoon period is considered in the study and the entire nonmonsoon season is lumped as one time period. The demands in each time period are shown in Table 1.

Model formulation

In the present study, two SDP models are formulated to derive the operating policy of the Hirakud Reservoir. The first model, SSDP, is a conventional SDP model. The second model, FSDP, is a SDP model in which the objectives are treated as fuzzy.

Formulation of SSDP model

SSDP is a relatively simple model that uses SDP technique to minimize the expected sum of the squared deficit from a target release and a target storage. This is the most popularly used objective function for the long-term operation of a reservoir (Loucks *et al*. 1981). The objective function can be written as

$$\text{Min}\, E[(TR_t - R_t)^2 + (TS_t - S_t)^2], \quad (1)$$

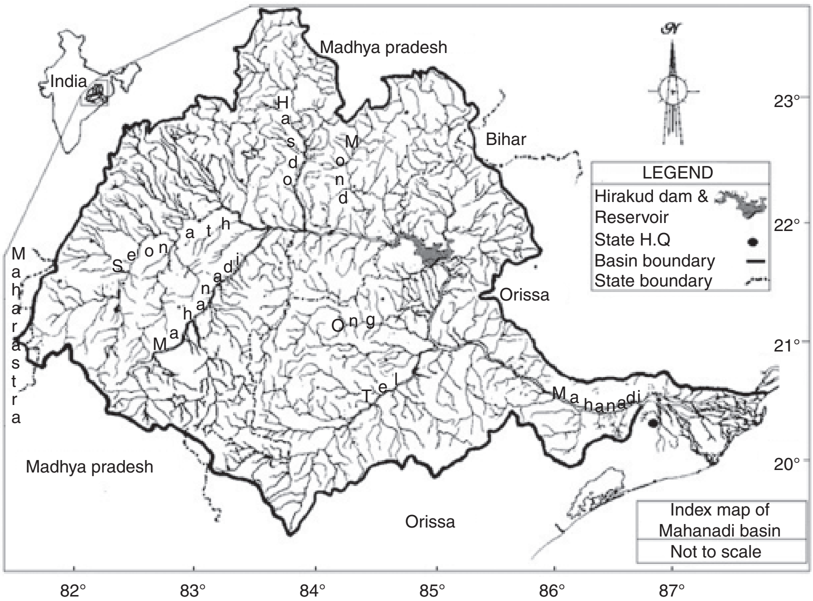

Fig. 1. Map showing the location of Hirakud Reservoir.

Table 1 Mean inflows, demands, target releases and target storages of the reservoir

Time period*	Mean flow (MCM)	Total demand (MCM)	Irrigation demand (MCM)	Power demand (MCM)	Target releases (MCM)	Target storages (MCM)
1 (June III)	14 110	3028	435	2593	799	407
2 (July I)	13 990	4235	658	3577	1117	0
3 (July II)	23 390	5124	839	4285	1352	0
4 (July III)	31 020	6587	958	5629	1738	0
5 (August I)	37 100	6093	783	5310	1608	2095
6 (August II)	36 630	6158	797	5361	1624	3007
7 (August III)	40 080	6120	886	5234	1615	4168
8 (September I)	34 310	5713	849	4864	1508	4618
9 (September II)	27 430	5809	861	4948	1533	5333
10 (September III)	14 590	5307	961	4346	1400	5376
11 (October I)	9920	5248	1008	4240	1385	5376
12 (October II)	7550	4818	1003	3815	1271	5376
13 (October III)	5740	4816	1018	3798	1271	5376
14 (Nonmonsoon)	18 830	64 195	14 259	49 936	16 940	5818

*The monsoon season is divided into 13 ten daily time periods (21 June to 31 October).

where TR_t is the target release in time period t, TS_t is the target storage in time period t, S_t is the storage in the reservoir at the beginning of time period t, R_t is the actual release made from the reservoir and $E[]$ is the expectation operator. The target releases for the reservoir are fixed based on the estimated demands and on the past experience of operating the reservoir. The target storages for each time period are fixed based on the operating rule curve adopted by the Hirakud project authorities. The values of target releases and target storages for different time periods are given in Table 1.

A backward recursion SDP model is developed for deriving the steady-state operating policy of the reservoir with the above objective function. The optimal releases are related to two state variables, namely, the inflow into the reservoir during the time period and the storage at the beginning of the time period. Let Q_t represent the inflow into the reservoir during any time period t. This continuous variable Q_t can be discritized into several class intervals. Any value within the range of a class interval can be represented by a single value. Let i be the index to represent the class interval for inflow during the time period t. Thus, Q_{it} is the representative flow of ith class interval in time period t. Similarly, let j be the index for representing the class interval for inflow during time period t+1 and Q_{jt+1} be the representative inflow of the class interval. Similar to the other state variable, the reservoir storage at the beginning of time period t (S_t) is also discritized. Let the indices k and l represent the class intervals for the storage at the beginning of time period t and t+1, respectively. Thus, S_{kt}, and $S_{l,t+1}$ are the representative values of the storage in the respective class intervals.

Given the initial storage volume S_{kt}, the inflows Q_{it} and final storage volume $S_{l,t+1}$ in period t, the release R_{kilt} is determined by the continuity equation

$$R_{kilt} = S_{kt} + Q_{it} - EL_{klt} - S_{l,t+1}, \tag{2}$$

where EL_{klt} is the possible evaporation loss that depends on the initial and final storage volumes in period t. For a given initial storage state k and inflow state i, some of the final storage states l may not be feasible as they result in a negative value of R_{kilt}. The general backward recursive equation for this model can be written as follows:

$$f_t^n(k,i) = \underset{\{l\}}{\mathrm{Min}}\left[(TR_t - R_t)^2 + (TS_t - S_t)^2 + \sum_j p_{ij}^t \times f_{t+1}^{n-1}(l,j)\right], \tag{3}$$

where $\{l\}$ represents the feasible set final storage states l and p_{ij}^t is the transition probability of inflow from state i in time period t to state j in time period t+1. Equation (3) is solved recursively till a steady-state operating policy is obtained.

Formulation of FSDP model

Fuzzy objectives

The main objectives of the Hirakud project are irrigation, hydropower generation and flood control. In this model, these three objectives are considered as fuzzy. The following are the three main objectives of the reservoir.

- To keep the reservoir as empty as possible during the monsoon season to absorb the anticipated flood.
- To satisfy the irrigation demand at different time periods.
- To generate sufficient amount of hydropower in each time period.

The objectives are treated as fuzzy, and membership functions are developed for the linguistic variables describing the objectives, namely 'as empty as possible', 'satisfy irrigation demand' and 'sufficient hydropower'. The opinions of the experts and reservoir managers, who were involved in operation of the reservoir, are collected and analysed. Their perception towards fulfilling a particular objective like irrigation water supply is noted. It is observed that the degree of satisfaction has a nonlinear variation with the fulfillment of the objective. For any given objective, the 'highest degree of satisfaction' is assigned a membership value equal to 1.0. The 'lowest degree of satisfaction' is assigned a membership value of 0.0. The intermediate values are arranged between these two extremes, based on the average level of satisfaction expressed by the experts.

Membership functions for irrigation and hydropower

Membership functions for irrigation and hydropower have been developed on the basis of percent of water released and the corresponding degree of satisfaction achieved. The general trend is if the amount of water released is $<50\%$ of the target release, then the degree of satisfaction is treated as 0. Thus, the value of membership grade is 0. If the supply is same as target release, then the value of the membership grade is 1. Depending on the percent of water released, membership grade ranges between 0 and 1. Membership grades are assigned for different possible values of releases using the opinion of the project authorities. For each time period, the membership function has been developed separately. Taking the values of percent of water released and degree of membership grade (0–1) assigned by the experts, a sigmoid membership function as given in Eq. (4) is fitted by regression.

$$\mu(x) = \frac{1}{1 + \exp(-a(x - c))}, \tag{4}$$

where μ is the membership grade assigned for the given value of x, and a and c are the parameters. The values of a and c for different time periods for irrigation and hydropower are given in Table 2.

Membership function for flood control

Membership function for flood control objective has been developed on the basis of percent storage available in the reservoir for flood control. If the reservoir is full, then the degree of satisfaction is treated as 0. Thus the value of membership grade is 0. If the reservoir is empty, then the degree of satisfaction is treated as 1. Thus, the value of membership grade is 1. The membership grades for the intermediate states of the reservoir are assigned based on the perception of the experts involved in the operation of the reservoir. The flood control objective is significant only during the flood season. Hence, the membership grade is assigned as 1 for all states of reservoir in the time periods where the flows are usually low and the chance of occurrence of flood is low. A sigmoid function given in Eq. (4) is fitted through regression. The values of the parameters of the membership function a and c for flood

Table 2 Parameters of membership function of the fuzzy objective

	Irrigation		Hydropower		Flood control	
Time period	*a*	*c*	*a*	*c*	*a*	*c*
1	35.49	0.307	5.95	1.84	–	–
2	23.47	0.465	4.31	2.53	− 1.668	4.356
3	18.39	0.594	3.60	3.03	− 1.668	4.356
4	16.11	0.678	2.74	4.00	− 1.668	4.356
5	19.70	0.554	2.90	3.76	− 1.592	4.495
6	19.34	0.565	2.87	3.79	− 1.592	4.495
7	17.41	0.627	2.95	3.70	− 1.592	4.495
8	18.16	0.601	3.17	3.44	− 2.794	5.237
9	17.91	0.610	3.12	3.50	− 2.794	5.237
10	16.05	0.680	3.55	3.08	− 2.794	5.237
11	15.31	0.711	3.64	3.00	–	–
12	15.38	0.710	3.04	2.70	–	–
13	15.15	0.721	3.88	2.82	–	–
14	1.08	10.091	0.31	35.35	–	–

control are given in Table 2. The membership functions for flood control are computed on a monthly basis. Hence the membership functions for time periods 2–4 (corresponding to July) are same. Similarly, the membership functions of time periods 5–7 (corresponding to August) and time periods 8–10 (corresponding to September) are same. The membership function for flood control decreases with an increase in level of storage in the reservoir. Hence, the values of the parameter *a* of the membership function are negative.

FSDP model

The objective function of the FSDP model is to maximize the minimum expected satisfaction level of the fuzzy objectives. The level of satisfaction of an objective (membership grade) is a function of reservoir release (R_t) for irrigation and hydropower and initial reservoir storage (S_t) for flood control. The objective function of FSDP model is given in following equation

$$\underset{l}{\text{Max}}\, E[\mu_{\text{D}}(k,i,l,t)], \tag{5}$$

where $E[]$ denotes the expected value, k indicates the initial storage state, i indicates the inflow state during the time period t and l is the final storage state. μ_{D} is the combined satisfaction level of all the three objectives and is given in following equation

$$\mu_{\text{D}} = \text{Min}\,(\mu_{\text{I}}, \mu_{\text{P}}, \mu_{\text{F}}), \tag{6}$$

where μ_{I} is the level of satisfaction attained for irrigation, μ_{P} is the level of satisfaction of hydropower generation objective and μ_{F} is the level of satisfaction obtained for flood control objective.

Using the usual notation, the general recursive equation for the FDP model for time period t, and stage n can be written as

$$f_t^n(k,i) = \underset{\{l\}}{\text{Max}}\left[\mu_{\text{D}}(k,i,l,t) + \sum p_{i,j}^t \times f_{t+1}^{n-1}(l,j)\right], \quad \text{for all } k,i, \tag{7}$$

where $\{l\}$ is the set of feasible l, $p_{i,j}^t$ is the probability of transition of inflow from state i in t to state j in time period t+1. Equation (7) is solved recursively, until a steady-state solution is reached, defining the optimal policy $l^*(k, i, t)$ for all values of k and i for all time periods t.

Results and discussions

The two models formulated in the previous sections are applied to derive the operating policy of the Hirakud Reservoir. The active storage of the reservoir is 5818 MCM. It is divided into 10 discrete intervals. Similarly, the inflow in each time period is divided into eight discrete states. A periodic first-order auto regressive model is fitted to the historical streamflow series. The synthetic data generated using this model are used to derive the transitional probability matrices necessary for the SDP models. The two models, namely, SSDP model and FSDP model, are applied to derive the operating policy of the reservoir.

The SSDP model is a conventional model used widely for the development of the operating policy of a reservoir. The FSDP model is a multi-objective model that treats the objectives as fuzzy. Both the models are SDP models. The two models differ in the complexity and in the way the objectives are treated. The SSDP model does not explicitly consider the multiple objectives of the reservoir, while the FSDP model considers the multiple objectives as fuzzy and optimizes the combined level of satisfaction of the objectives. The FSDP model for Hirakud reservoir is formulated by taking into consideration the multipurpose nature of the reservoir. The performance of the reservoir under the operating policy derived by this model is compared with that of the standard SSDP model to evaluate the FSDP model.

The performance of the two models is evaluated and compared by simulating the reservoir using the operating policies derived by these models. The simulation is carried out using 150 ten daily flow sequences each of length 19 years generated using the periodic AR(1) model. Two performance indicators, namely, reliability and resilience, along with the level of satisfaction of each of the objective are used to evaluate the performance. The reliability of a system under a given operating policy is defined as the probability that the system output is satisfactory

Table 3 Reliability of meeting the demands

Time period	Reliability of meeting the irrigation demand (%)		Reliability of meeting hydropower demand (%)	
	SSDP	FSDP	SSDP	FSDP
1	9	11	0	0
2	81	78	71	70
3	92	97	0	0
4	99	98	93	93
5	0	1	99	97
6	99	99	0	0
7	100	100	0	0
8	100	100	0	0
9	1	1	99	99
10	2	6	95	86
11	79	69	0	0
12	6	5	0	0
13	64	55	55	47

Table 4 Level of satisfaction (%) obtained in the monsoon season

Time period	Irrigation		Hydropower		Flood control	
	SSDP	FSDP	SSDP	FSDP	SSDP	FSDP
1	92	92	82	81	100	100
2	83	80	76	72	95	99
3	95	97	87	92	86	90
4	98	98	95	94	87	66
5	98	98	98	97	9	48
6	98	99	98	98	4	38
7	99	99	99	99	5	96
8	99	99	99	98	4	99
9	99	99	99	99	29	99
10	97	95	96	90	39	99
11	86	79	79	69	100	100
12	74	74	63	63	100	100
13	81	78	68	61	100	100

(Hashimoto *et al*. 1982). The system output in this study is defined to be satisfactory in a given period *t* if the water available for irrigation/hydropower is at least equal to the total irrigation/hydropower requirements in that period. Resilience is defined as the probability of system recovery from a failure when it occurs. The level of satisfaction of an objective is measured in terms of the membership grade obtained for that objective.

The reliability in meeting the irrigation and hydropower demands in each of the 13 time periods in monsoon season as obtained from SSDP and FSDP models is presented in Table 3. It is observed from the results that the reservoir is unable to meet the full irrigation and hydropower demands in most of the time periods. In the case of hydropower, both the models indicate zero reliability in seven out of 13 time periods, indicating that the reservoir is unable to meet the full demand even once during the period of simulation. It may be interpreted from these results that the irrigation and hydropower demands are more than what the reservoir could probably meet.

Table 4 shows the levels of satisfaction of the three objectives of irrigation, hydropower and flood control for each of the 13 time periods in monsoon season computed through simulation using the operating policies derived from SSDP and FSDP models. It is observed from these results that both the models give a significantly high degree of satisfaction for irrigation and hydropower, although the corresponding reliabilities obtained are very low. For example, both the models indicate zero reliability for hydropower in time periods 1, 3, 6, 7, 8, 11 and 12 (Table 3). However, the corresponding level of satisfaction of hydropower in these time periods is high. Reliability is defined as the probability of meeting the full demand, while the degree of satisfaction is defined as a fuzzy set. A low reliability but a high degree of satisfaction indicates that although the reservoir is unable to meet the full demand, it is able to nearly meet the full demand. The degree of satisfaction achieved for both irrigation and hydropower are significantly high in most of the time periods. Both the models give similar performance in terms of irrigation and hydropower objectives. In fact, the degree of satisfaction achieved under the operating policy derived by FSDP is lower in some time periods than that obtained from SSDP model, but for other periods is lower in SSDP (Table 4). Although the performance of the reservoir is rated as poor in terms of reliability, in terms of degree of satisfaction achieved for the two objectives of hydropower and irrigation the performance can be considered as good.

The reservoir planners use reliability as a measure of performance of a reservoir. The reliability measures the ability of the reservoir in meeting the full demand. It is conventionally defined as the probability of meeting the full demand. If the reservoir is not able to meet the full demand, it is considered as a failure, irrespective of the magnitude of the deficit from the full demand. The degree of satisfaction is a measure that takes into consideration the level of demand met by the reservoir. It indicates the extent to which the demand is satisfied on a scale of 0–1, the value of 1 indicating that the demand is fully satisfied. The results of the study indicate that the reliability and level of satisfaction are contradicting in most of the time periods. For example in time period 1, the reliability of meeting the irrigation demand under the operating policy derived from FSDP is 11%, while the degree of satisfaction of meeting the irrigation demand is 92%. It implies that the reservoir is not able to meet the full irrigation demand with a probability of 89%. But the reliability does not indicate the extent of deficit in meeting the irrigation demand. However, the high value of degree of satisfaction indicates that although the reservoir is not able to meet the full irrigation demand for most of the time in this time period, the level of deficit in meeting the irrigation demand is not very high. These results indicate that the fuzzy measure of degree of satisfaction may be a better measure for evaluating the performance of a reservoir than reliability.

The performance of the two models differs significantly in terms of flood control objective. The satisfaction levels achieved for flood control through SSDP model are low, especially during the time periods 5–10 (Table 4). These time periods fall in August and September when the risk of floods are very high. The FSDP model gives high satisfaction levels for flood control in all time periods except during the time periods 5 and 6. The flood control objective is not explicitly included in the SSDP model and it is indirectly taken care by fixing a lower target storage level during the flood season. The FSDP model explicitly involves the flood control objective. This could be the reason for better performance of FSDP model in terms of the flood control objective.

The annual performance indicators, namely, reliability, resilience and level of satisfaction achieved for both SSDP and FSDP models are presented in Table 5. The annual performance indicators are computed by considering the annual demand and the annual releases made for both irrigation and hydropower. The level of satisfaction of flood control is computed by considering the storage available at the beginning of the year, i.e., the storage available in time period 1. It is observed that the two models give a similar performance as far as irrigation and hydropower objectives are concerned, but FSDP model shows a better performance in terms of flood control objective. Usually, reservoirs are designed to provide a reliability of 75% for irrigation and 90% for hydropower. The reliability and resilience of the reservoir for both irrigation and hydropower objectives are very low (Table 5). However in terms of level of satisfaction achieved, the performance is good. The overall satisfaction level is computed as the product of the levels of satisfaction achieved for each of the three objectives. It is observed that the FSDP gives a higher overall satisfaction level than SSDP model. This is expected as the FSDP gives a higher degree of satisfaction for flood control than SSDP.

Table 5 Annual performance indicators

	Reliability (%)		Resilience (%)		Satisfaction levels (%)	
	SSDP	FSDP	SSDP	FSDP	SSDP	FSDP
Irrigation	53	52	72	68	92	92
Hydropower	37	36	89	89	88	86
Flood control	–		–		58	85
Overall satisfaction	–		–		47	67

The performance of the FSDP model depends on the membership functions of the objectives. The membership functions for the objectives are fitted based on the subjective opinion of the experts and reservoir managers. However, the performance of the model could vary with the type of membership function and the degree of membership function assigned by the experts. A sensitive analysis can be performed to study the effect of membership function on the performance of the model.

Conclusions

(1) The results of this study indicate that the reservoir is not able to meet the demands that are imposed on it, thus reflecting in the poor performance of the reservoir in terms of reliability and resilience.
(2) It is necessary to decrease both the irrigation demands and hydropower demands to improve the reliability and resilience of the reservoir.
(3) However in spite of low reliability, the system is able to meet the requirements with a reasonable degree of satisfaction as indicated by higher levels of satisfaction.
(4) The two models SSDP and FSDP show a similar performance as the irrigation and hydropower objectives are considered. But there is a significant improvement in the performance of the reservoir for flood control under the FSDP model.
(5) The results indicate that the degree of satisfaction defined as a fuzzy set is a better measure of the performance of a reservoir than the crisp value of reliability.
(6) The degree of satisfaction helps the planners in assessing the behaviour of the reservoir with reference to each objective.
(7) As observed from the results, the demands imposed on the reservoir are higher than what the reservoir can possibly meet. This is reflected in the poor performance of the reservoir in certain time periods.
(8) The results could help the planners in revising the demands to improve the performance of the reservoir.
(9) The advantage of the FSDP model is that it explicitly includes all the objectives of the reservoir system and can incorporate the vagueness associated with these objectives.
(10) The membership functions of the objectives can be constructed by incorporating the preferences of the users and the decision makers.
(11) The model can be used to develop the operating policy of a multipurpose reservoir.

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References

Debrovin, T., Jolma, A. and Tarunen, E. (2002) Fuzzy Model for Real-Time Reservoir Operation. *J. Water Resour. Plan. Manage.*, **128** (1), 66–73.

Deka, P.C. and Chandramouli, V. (2009) Fuzzy Neural Network Modeling of Reservoir Operation. *J. Water Resour. Plan. Manage.*, **135** (1), 5–12.

Department of Water Resources. (1997) *Data on Flood Control Operation of Hirakud Dam*. Government of Orissa, Bhubaneswar.

Fontane, D.G., Gates, T.K. and Moncada, E. (1997) Planning Reservoir Operations with Imprecise Objectives. *J. Water Resour. Plan. Manage.*, **123** (3), 154–162.

Hashimoto, T., Stedinger, J.R. and Loucks, D.P. (1982) Reliability, Resiliency and Vulnerability Criteria for Water Resources System Performance Evaluation. *Water Resour. Res.*, **18** (1), 14–20.

Loucks, D.P., Stedinger, J.R. and Haith, D.A. (1981) *Water Resources Systems Planning and Analysis*. Prentice Hall, Englewood Cliffs, NJ.

Mousavi, S.J., Karamouz, M. and Menhadj, M.B. (2004) Fuzzy-State Stochastic Dynamic Programming for Reservoir Operation. *J. Water Resour. Plan. Manage.*, **130** (6), 460–470.

Mousavi, S.J., Ponnambalam, K. and Karray, F. (2005) Reservoir Operation Using a Dynamic Programming Fuzzy Rule-Based Approach. *Water Resour. Manage.*, **19** (5), 655–672.

Owen, W.J., Gates, T.K. and Flug, M. (1997) Variability in Perceived Satisfaction of Reservoir Management Objectives. *J. Water Resour. Plan. Manage.*, **123** (3), 147–153.

Panigrahi, D.P. and Mujumdar, P.P. (2000) Reservoir Operation Modeling with Fuzzy Logic. *Water Resour. Manage.*, **14**, 89–109.

Russel, S.O. and Campbell, P.E. (1996) Reservoir Operating Rules with Fuzzy Programming. *J. Water Resour. Plan. Manage.*, **122** (3), 165–170.

Shreshta, B.P., Duckstein, L.E. and Stakhiv, E. (1996) Fuzzy Rule Based Modeling of Reservoir Operation. *J. Water Resour. Plan. Manage.*, **122** (4), 262–269.

Simonovic, S.P. (1992) Reservoir Systems Analysis: Closing Gap between Theory and Practice. *J. Water Resour. Plan. Manage.*, **118** (3), 262–280.

Swain, P.C. (2001) *Multi-purpose reservoir management using neural networks and neuro-fuzzy inference system*. PhD Thesis submitted to Kakatiya University, Warangal, India.

Teegavarapu, R.S.V. and Simonovic, S.P. (1999) Modeling Uncertainty in Reservoir Loss Functions Using Fuzzy Sets. *Water Resour. Res.*, **35** (9), 2815–2823.

Tilmant, A., Vanclooster, M., Duckstien, L. and Persoons, E. (2002) Comparison of Fuzzy and Nonfuzzy Optimal Reservoir Operating Policies. *J. Water Resour. Plan. Manage.*, **128** (6), 390–398.

Wurbs, R.A. (1993) Reservoir-System Simulation and Optimization Models. *J. Water Resour. Plan. Manage.*, **119** (4), 455–472.

Wurbs, R.A. (1996) *Modeling and Analysis of Reservoir System Operations*. Prentice Hall, Upper Saddle River, NJ.

Yeh, W.W-G. (1985) Reservoir Management and Operation Models: A State-of-the-Art Review. *Water Resour. Res.*, **21** (12), 1797–1818.

