Modelling the management of multiple-use reservoirs: Deterministic or stochastic dynamic programming?

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Abstract

Modelling complex systems such as multiple-use reservoirs can be challenging. A legitimate question for scientists and modellers is how best to model their management under uncertain rainfall. This paper studies whether it is worth using a stochastic model that requires more effort than a much simpler deterministic model. Both models are applied to the management of a multiple-use reservoir in southern Vietnam. Although no single modelling approach is universally superior, this study indicates that the desirable modelling approach is stochastic if reservoir capacity and water use demands have a high enough impact on the optimal timing of reservoir water use.

Keywords: deterministic dynamic proramming, stochastic dynamic programming, water management, irrigation, fisheries, multiple-use reservoir

1. Introduction

There is a vast of literature on reservoir water management using dynamic optimization models (Abdallah *et al.*, 2003, Barros *et al.*, 2003, Biere *et al.*, 1972, Butcher *et al.*, 1969, Cervellera *et al.*, 2006, Chaves *et al.*, 2003, Georgiou *et al.*, 2008, Ghahraman *et al.*, 2002, Karamouz *et al.*, 1987, Nandalal *et al.*, 2007, O'Loughlin, 1971, Reca *et al.*, 2001a, Reca *et al.*, 2001b). These studies employed either stochastic or deterministic approaches to determine optimal water release strategies for a reservoir. The approaches chosen to define the optimal release strategies in these studies depended on available data sources, computing power, the skills of the researchers and the time available to them. For example, O'Loughlin (1971) and Dudley (1971) concluded that although using stochastic dynamic optimization took much time, it yielded better results compared to a deterministic approach.

Due to developments in computer software and computing power over the past two decades, the problems of time-consuming computations have lessened and facilitated the use of stochastic dynamic optimization for reservoir management. However, this application of stochastic dynamic optimization requires access to long-term rainfall and reservoir inflow data in order to calculate meaningful probabilities for stochastic variables. Ensuring the

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availability of such data is often difficult for researchers investigating reservoir management in isolated areas of developing countries. The simpler method of deterministic dynamic optimization, may be easier where data is limited.

This paper investigates the relative merits of the stochastic and deterministic approaches to reservoir management, using multiple-use reservoirs in southern Vietnam to illustrate the problem and highlight its relevance to decision-making.

This paper is structured as follows. The next section briefly describes a reservoir management model based on either a stochastic or deterministic approach. Then parameter estimation and data collection are presented. Finally, the model results are presented for a range of reservoir configurations and reservoir management objectives, and conclusions are drawn about when a particular modelling approach is likely to be most relevant.

2. A dynamic optimization model for managing multiple-use reservoirs

Tran *et al.* (2011) constructed a dynamic optimization model for managing multiple-use reservoirs in southern Vietnam. The model addressed the problem of reservoir water management for two competing uses of the water: crop irrigation and fish production. The time horizon of the model included 8 stages (where each stage was 25 days long) covering 2 rice crop seasons (where each crop comprised 4 growth periods described as initial, development, mid-season, and late-season), and a fish harvesting season from stage 4 to stage 7. The state variable was the amount of water in the reservoir at the beginning of an irrigation season, as measured by the percentage of reservoir capacity (% RC). The decision variable was the amount of water to be released at each stage (also expressed as % RC). Finally, the objective function was to maximize the expected stream of the present value of profits (ENPV) generated by the reservoir which included profits from rice and fish production.

The rice profits were calculated as follows:

$$B_{rn} = A_r P_r Y_r - C_{rn} \tag{1}$$

where B_{rn} represents rice profits (mVND); A_r is rice irrigated area (ha); P_r is the price of rice (mVND/tonne); Y_r is rice yields (tonnes) obtained in stage n; and C_{rn} is total rice production cost in stage n (mVND). The other rice production inputs, such as fertilizer, chemicals, and labour, were assumed to be applied at optimal levels. In Eq.(1), rice yields Y_r was determined using a water production function (Paudyal *et al.*, 1990):

$$Y_r = Y_p \left(1 - \sum_{n=1}^{8} k_{y_n} \left(1 - \frac{W}{W_0} \right)_n \right) \tag{2}$$

where Y_r is the rice yield (tonnes/ha); Y_p is the potential yield of rice (tonnes/ha); k_{y_n} is the yield response factor to water at stage n; W_0 is the rice water requirements (%RC); W_n is total water supply at stage n (%RC).

$$B_{fn} = TR_{fn}\left(1 + PCE_n\right) - C_{fn} \tag{3}$$

where B_{fn} is fish profits (mVND); TR_{fn} (mVND) is total fish return obtained from the BRAVO model (Truong *et al.*, 2010); C_{fn} is the total cost of fish production (mVND); and PCE_n is the physical concentration effects coefficient (Tran *et al.*, 2011).

$$PCE_n = \left(\theta\gamma\omega A_0^{(\theta+1)} s_t^{(\gamma\theta-1)}\right)\left(\frac{s_t}{Y_f}\right)(\%\Delta s) \tag{4}$$

where θ is the parameter obtained from the reservoir hypsographic equation, $A = A_0 s^{\theta}$, which indicates the relationship between reservoir surface area A (ha) and reservoir capacity s (%RC); A_0 is the reservoir surface area when the reservoir is full (ha); γ and ω are the parameters obtained from Nguyen *et al.* (2001) who indicated the relationship between fish yields and reservoir surface area as $Y = \gamma A^{\varpi}$.The other fish production inputs, such as weight of fingerlings and labour, are assumed to be applied at optimal levels.

The backward induction method was employed to find the optimal release strategy for managing the reservoir for single-use rice or fish production, and joint production of rice and fish. The model was validated for the Daton reservoir in southern Vietnam. The maximum storage capacity of this reservoir was much greater than the water requirements it served. An important modelling result obtained for the Daton reservoir (Tran *et al.*, 2011) was that variations in rainfall do not significantly affect the intra-year release strategy and benefits generated by the reservoir. A legitimate question for the modelling approach then arose as to whether it was worthwhile to employ a stochastic model, which involves complex computations and a large amount of time for its construction. Would the use of a deterministic model be preferable? In this study, we alter and revise the Tran *et al.* model to consider various scenarios for water management and compare modelling results from stochastic and deterministic models.

In the Tran *et al.* model, when the reservoir is managed solely for rice production, fish profits are assumed to be zero; and rice profits are assumed to be zero if the reservoir is managed purely for fish harvesting. However, in reality, when the reservoir is managed solely for the use of one enterprise, the other enterprise can also benefit. For example, if the reservoir water is managed purely for rice production, fish are still harvested to a limited degree. Fish profits vary according to the storage levels of the reservoir which are determined by the optimal water release for rice production. Similarly, when the reservoir is managed exclusively for fish production, rice is still cultivated. Rice profits vary according to rainfall and the release of water to facilitate fish harvesting.

The objective function of the Tran *et al.* model is:

$$B_n = B_{rn} + B_{fn} \tag{5}$$

where B_n is total profit, B_{rn} is rice profit, and B_{fn} is fish profits All are measured in mVND. Equation (5) becomes $B_n = B_{rn}$ if the reservoir water is managed for rice production, and is $B_n = B_{fn}$ if the reservoir is managed for fish harvesting. In the present study, the objective function is extended as follows:

If the reservoir is managed solely for rice production, the objective function is:

$$B_n = B^{*}_{rn} + B^{'}_{fn} \tag{6a}$$

If the reservoir is managed solely for fish production, the objective function is:

$$B_n = B'_{rn} + B^*_{fn} \tag{6b}$$

where B^*_{rn} and B^*_{fn} are the maximum profits obtained from optimal release for rice production and fish harvesting, respectively. B^*_{rn} and B^*_{fn} are found using the method proposed by Tran *et al.* (2011). B'_{fn} is fish profit determined by the optimal water release for rice production; and B'_{rn} is rice profit determined by the optimal water release for fish harvesting. All are measured in mVND.

The objective function for the optimization model is to maximize the expected net present value of profits (ENPV), and for the deterministic case the net present value (NPV) is maximized. For convenience, total net profits (TNP) are used here to represent both ENPV and NPV.

The objective function for stochastic optimization model is

$$V_n\{s_n\} = \underset{u_n}{Max}\left[E\left[\sum_{k=1}^{m} p_n\{q_n^k\}\left(B_n\{s_n, u_n, e_n, q_n^k, i_n^k\} + \delta V_{n+1}\{s_n, u_n, e_n, q_n^k, i_n^k\}\right)\right]\right] \tag{7}$$

$$(n=8, \ldots, 1)$$

$$\sum_{k=1}^{m} p_n\{q_n^k\} = 1 \tag{8}$$

where s_n reservoir water level at the beginning of each stage; u_n is the release at stage n; e_n is the evaporation at stage n; q_n is rainfall at stage n; and i_n is the reservoir inflows at stage n. All are expressed in %RC.

In addition to modifying the objective function of the Tran *et al.* model, the model structured in the present study considers both deterministic and stochastic cases of reservoir water management. In the stochastic model (Tran *et al.*, 2011), the reservoir water level (state variable) at the next stage was unknown depending on rainfall distribution in the previous stages which was represented by the (14 x 8) rainfall distribution matrix (Eq. 8). The objective function for the deterministic case is similar to (Eq.7) except that in the deterministic case the probabilities of rainfall occurrences are not considered and rainfall distribution matrix is replaced by a (1 x 8) vector of rainfall averages, one for each stage.

3. Parameter estimation for the reservoir water management model

3.1 Time horizon of the model

The Daton reservoir is used to irrigate two consecutive rice crops each of approximately 1000 hectares during the dry season from December to June. The first crop is grown from December to March and the second crop is from April to July. Each crop lasts about 100 days and is divided into four growth periods: the initial, development, mid and late season periods as defined in the Cropwat 8.0 model (Swennenhuis, 2006). Each rice growth period as modelled is 25 days long, consistent with the experimental results obtained by Le and Duong

(1998). To account for the two consecutive rice crops, each with four growing periods, a model with eight 25-day stages was developed.

Harvesting of fish occurs when the reservoir water is at its lowest levels, during the period from mid February to June (Nguyen, 2008a). In the eight-stage model the fish harvest season covers four 25-day periods, starting in stage 4 and ending in stage 7.

3.2 Rainfall, evaporation, and hydrologic data

Rainfall data

Daily rainfall data from 2001 to 2008 was collected from the Daton irrigation branch (Dinh, 2008). This data was used to calculate rainfall probability density functions in each stage (Table 1), the inflows of the reservoir, and the amount of water that the rice fields directly received from rainfall.

Table 1 Rainfall

Rainfall	Rainfall probability							
(mm)	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
0.0	0.955	0.98	0.98	0.95	0.865	0.745	0.635	0.545
37.5	0	0	0	0	0.005	0.005	0.015	0.03
87.5	0.005	0	0.01	0	0.015	0.01	0.035	0
137.5	0	0	0.005	0.015	0.01	0.03	0.025	0.025
187.5	0.01	0.005	0	0	0.025	0.01	0.035	0.04
237.5	0.005	0	0.005	0	0.03	0.005	0.01	0.035
287.5	0	0	0	0.005	0.005	0.01	0.015	0.02
337.5	0	0	0	0.01	0	0.01	0.02	0.03
387.5	0.005	0	0	0.015	0.005	0.02	0.005	0.03
437.5	0.01	0.01	0	0	0	0.01	0.01	0.005
487.5	0	0.005	0	0	0.01	0.02	0.02	0.03
537.5	0	0	0	0.005	0	0.005	0.01	0.02
587.5	0.005	0	0	0	0.005	0.005	0.015	0.015
625.0	0.005	0	0	0	0.025	0.115	0.15	0.175

Evaporation data

The average evaporation in each stage is estimated using the monthly evaporation data from the Dong Nai province (1977 – 2006) provided by the Sub-Institute of Hydrometeorology and Environment of South Vietnam. The average of monthly evaporation was calculated using the evaporation data of the Dong Nai province. These values were then divided by 30 to obtain an average daily evaporation for each month. The average evaporation value for each stage, 25 days, was then obtained by multiplying the average daily evaporation by 25 for the relevant month. In cases where a stage bridges two months, the average evaporation of that stage was considered to be the sum of the evaporation calculated for the number of days of each of the corresponding months. For example, stage 1 lasts for 25 days from December 25th to January 18th; therefore, the average evaporation for this stage was the sum of seven days of average evaporation for December and 18 days for January.

Hydrological data

The physical parameters of the reservoir were obtained from the Daton irrigation branch (Dinh, 2008) including maximum and minimum storage capacity, discharge capacity, reservoir surface area, reservoir catchment area, and reservoir inflows. The hypsographic coefficient, which indicates the relationship between reservoir water availability and reservoir surface area, was obtained from the hypsographic curve provided by the Daton irrigation branch. All parameters are presented in Table 2.

Table 2 Parameters used in the model

Parameters	Unit	Value	Descriptions
s_{max}	MCM	19.6	Maximum reservoir capacity
s_{min}	MCM	0.4	Minimum storage water level required for safety
DC	m^3/second	2.5	Reservoir discharge capacity
A_0	ha	350	Reservoir surface area at full level of water
R_c	km^2	21	Reservoir catchment area
θ	no.	0.5732	Hypsographic coefficient
σ	no.	0.3	Reservoir inflow coefficient

MCM = Million Cubic Metres, or $m^3 \times 10^6$

3.3 Rice production data

A seasonal calendar for rice production and the actual cultivated area of rice were obtained from the 2008 annual report of the local authority (Nguyen, 2008b). The maximum observed yields over the period from 2001 to 2008 were used to indicate the potential yield of rice in this area. It was 6.5 tonnes/ha for the first rice crop and 6 tonnes/ha for the second rice crop. Irrigation efficiency, expressing the percentage of irrigation water used efficiently, was fixed at 85% (Thang Pham, 2009, personal communication, 15 January). To simulate rice yields in response to different levels of applied irrigation, the rice water requirements (RWR), and the rice yield response factor must be known. They are estimated as follows.

Rice water requirements (RWR)

To estimate rice yields in response to different levels of applied irrigation, the RWR obtained from the field water balance must be specified. The Cropwat 8.0 model was used to define RWR. Several versions of this model have been developed by the FAO (Swennenhuis, 2006, Smith, 1992). Cropwat has also been applied to a wide variety of crops in many countries with different soil types and climatic conditions (Tran *et al.*, 2011, Muhammad, 2009, Toda *et al.*, 2005).

The total irrigation requirements can be used to define the RWR level at which rice can achieve its potential yield. RWR requirements associated with the amount of water released and the amount of water that the rice field receives directly from rainfall determine rice water deficits which can then be used to estimate rice yields.

Rice yield response factor

The yield response factor (k_{y_n}) is a coefficient which quantifies reductions in crop yields due to water deficits in different growing periods (Doorenbos *et al.*, 1979). If a water deficit occurs in a particular crop growth period, then crop yields will be lowered, depending on the degree of sensitivity of the crop in that period. The yield response factor was first researched by Doorenbos and Kassam (1979). In a report presented to FAO, Smith (1992) stated that k_{y_n} can take values ranging from 0.2 to 1.15. Another empirical study undertaken by the International Atomic Energy Agency in 1996 found that k_{y_n} ranged more broadly from 0.08 to 1.75. This study uses the k_{y_n} values from the rice data file of Cropwat 8.0 model (Swennenhuis, 2006). These values are 1.0 for the initial period, 1.09 for the development period, 1.32 for the mid season, and 0.5 for the late season. The research carried out by Tran *et al.* (2010) and Tran *et al.* (2011) in Vietnam also employed these k_{y_n} values to measure the rice yields in response to water deficits in different rice growing periods. More importantly, these k_{y_n} values are also in agreement with the impact of water deficits on rice yields as published by De Datta (1981).

Simulation of rice profits

To simulate rice profits in response to different levels of applied irrigation and rainfall, two main tools used are: (1) Cropwat 8.0 model (Swennenhuis, 2006), and a water production function (Paudyal *et.al* 1990).

First, RWR in every rice growing period were calculated using the Cropwat 8.0 model. These RWR calculations used the average humidity, rainfall, evaporation, and radiation data. Second, these values of RWR were then used to measure rice yields in response to different levels of applied irrigation, using the WPF proposed in Eq (2). The amount of water released from the reservoir for each rice growing period (the decision variable in the optimization model) was made discrete, ranging from minimum to a maximum of the reservoir discharge capacity. These values can be higher or lower than RWR in each stage. The chosen values associated with rainfall in each stage were used to specify the degree of rice water deficits which were then used to simulate rice yields in each stage. In the case where these chosen values were lower than RWR, water deficits occurred, causing reductions in rice yields in that stage. Conversely, if the chosen values of water released were higher than RWR, then there was a surplus of water. This surplus can be assumed to exit into rivers without a negative effect on rice yields. There are two reasons for choosing values that are higher than RWR. Firstly, an over-release may be reasonable when considering water releases for fish harvesting. Secondly, in reality, an over-release will not affect rice yields because rice farmers can control how much water is taken into their farms from the irrigation canals.

The average production cost and return per hectare of rice production was obtained from surveying the farmers. The average production costs per hectare included the costs of seeding, weeding, fertilizing, chemical use, labour, and harvest. The average production cost per hectare for the first and the second rice crop were mVND 8.82 and 6.72, respectively. The average return per hectare for rice production was estimated by multiplying the price of rice (mVND 2.5 per tonne)[2] by the rice yields. Total returns and total costs for the cultivated area were estimated by multiplying these average values by the actual cultivated area. Total rice profits in each stage were estimated by subtracting the total costs from the total returns.

3.4 Fish production data

The fish yields for each species harvested were estimated using the BRAVO model (Truong and Schilizzi, 2010). All required input data for this model (such as weight of fingerlings, stocking costs, and labour cost) was obtained from the 2008 annual report of the Daton cooperative (Nguyen, 2008a). Tran *et al.* (2011) also used this data to estimate fish yields at the Daton reservoir. The fish yield-reservoir area multiplicative factor (γ = 0.7422) and fish yield-reservoir area power factor (ω = -0.7445) in equation (4) were obtained from Nguyen *et al.* (2001)

Table 3 Weight and price of each fish species

Fish species	Prices (10^6VND per tonne)	Fish yields (tonnes)							
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Common Carp	16	0	0	0	3.506	3.026	2.636	2.262	0
Silver Carp	6	0	0	0	8.861	7.666	6.693	5.758	0
Grass Carp	8.5	0	0	0	7.043	6.239	5.573	4.887	0
Bighead Carp	6	0	0	0	4.477	3.93	3.479	3.027	0
Mrigal	8.5	0	0	0	4.154	3.584	3.121	2.678	0

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[2] The average price of rice in 2008 obtained from the survey

The total fish production cost in 2008 was mVND 615. The price of each fish species varies according to fish size at harvest. In this study the price of each species (Table 3) was represented by the fish price at its average size, which accounted for 70% to 80% of the total weight of fish harvested (Nguyen, 2008a).

Simulation of fish profits

To simulate fish profits in response to fluctuations in the reservoir water level, the method proposed above was employed. Total fish returns in each stage were estimated using the BRAVO model. To examine the effects of the reservoir water fluctuations on fish production, these total fish returns were then multiplied by the PCE coefficient (Tran *et al.*, 2011). Fish profits in response to the reservoir water fluctuations in each stage were obtained by subtracting the total fish production cost from the total fish returns obtained under PCE.

4. Results and discussion

Reservoir water management is analysed for three production scenarios where the reservoir water is used for: rice production only (scenario 1), fish production only (scenario 2) and joint production of rice and fish (scenario 3).

The model is applied to Daton reservoir in southern Vietnam where the reservoir has a maximum water storage capacity (RC) much greater than its current irrigation requirements (IR). This model is then used to find the optimal water release strategy for other reservoir configurations by modifying the Daton reservoir parameters. In particular, as each initial water level of the Daton reservoir represents a full reservoir for different sizes, two groups of reservoir configurations can be distinguished: R_{11} and R_{12} (see Table 5). The results obtained from scenario 1 indicate that when the initial water level of the Daton reservoir is at 70% RC, the amount of reservoir water available for irrigation is sufficient to fully satisfy the water demand for 1000 hectares of rice production. Given this fixed irrigated area, as the initial water level in the reservoir at the beginning of the irrigation season decreases, the ratio $R = \frac{RC}{IR}$ decreases. In particular, when the initial water level is 70% RC (or fluctuates around this level), the ratio R approaches 1. Therefore, 70% RC is a useful benchmark. In addition, when the initial water level is at 50% RC, the reduction in irrigation increases the magnitude of water deficits for rice, leading to a significant reduction in rice profits due to reduced yields. Therefore, 50% RC is another benchmark point. For this reason, the following sections use 50% RC, 70% RC and 100% RC as the benchmark water levels to define reservoir configurations.

In the following sections, modelling results are presented for two ranges of initial water levels (R_{11} and R_{12}) of the Daton reservoir at the beginning of the irrigation season. R_{11} represents the case when the initial water level is high, 70% - 100% RC. By contrast, R_{12} represents the case when the initial water level is low, 50% - 70% RC (see Table 5).

Table 5 Reservoir configurations

Initial water level	Reservoir configurations	Descriptions
70%- 100% RC $(R \geq 1)$	R_{11}	Reservoirs are full at the beginning of the irrigation season and have RC greater than or equal to total IR
50% - 70% RC $(R < 1)$	R_{12}	Reservoirs are full at the beginning of the irrigation season and have RC smaller than total IR

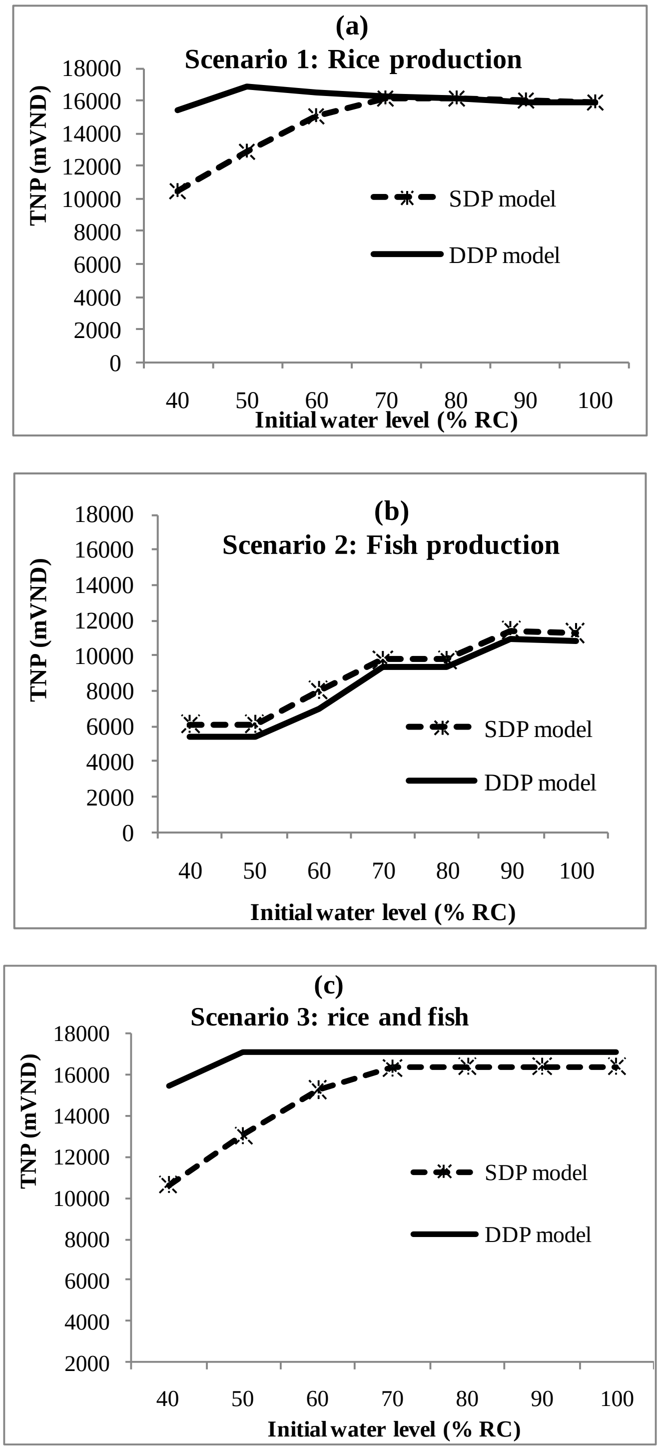

Figure 1 Comparing total net profits (TNP) in the three production scenarios for the DDP and SDP models

Scenario 1 – Rice production

For scenario 1, differences in total net profits (TNP) obtained from deterministic and stochastic models vary according to the initial water level (Figure 1a). When the initial water level is high (70% - 100% RC), or for R_{11}–type reservoirs, the differences between the models in TNP range from 0.2% to 0.5%. This is because within this range of the initial water level, there is always sufficient reservoir water available for rice production. Therefore, rice yield is independent of rainfall and the water releases do not differ between the two modelling approaches (Figure 1 b, c). The absence of differences in TNP suggests that when the initial water level is high, the simpler deterministic approach to RWM is more appropriate, as it reduces the complexity of calculation and is less time consuming.

However, when the initial water level is low (50% - 70% RC), or for R_{12}–type reservoirs, the TNP of the two modelling approaches can differ by up to 24%. For any initial water level lower than 70% RC, the TNP obtained from the DDP model is always higher than the TNP obtained from the SDP model. At these low initial water levels there is insufficient water to satisfy the full irrigation requirements of rice. For the deterministic model, the use of mean rainfall data causes the stochastic impacts of low rainfall events to be overlooked. Therefore, the release in the deterministic model is greater in some stages. However, this likely causes an overestimation of TNP. For example, the deterministic model indicates that in stage 4 a release of 7% RC should be made (Figure 1a). However, the stochastic model indicates that water release should be lower in stage 4 to satisfy water requirements for rice production in stages 5 to 7. The overstated releases from the deterministic model also occur in the last three stages. This indicates that when the initial water level is low, using deterministic modelling can produce overstated optimal release strategies or at least cause reservoir managers to take higher risks than they might otherwise have taken when managing the reservoir. Therefore, although the SDP modelling is more complex and time consuming, it may be more appropriate than the DDP modelling, especially for reservoirs with a smaller size and where security of rice production is required.

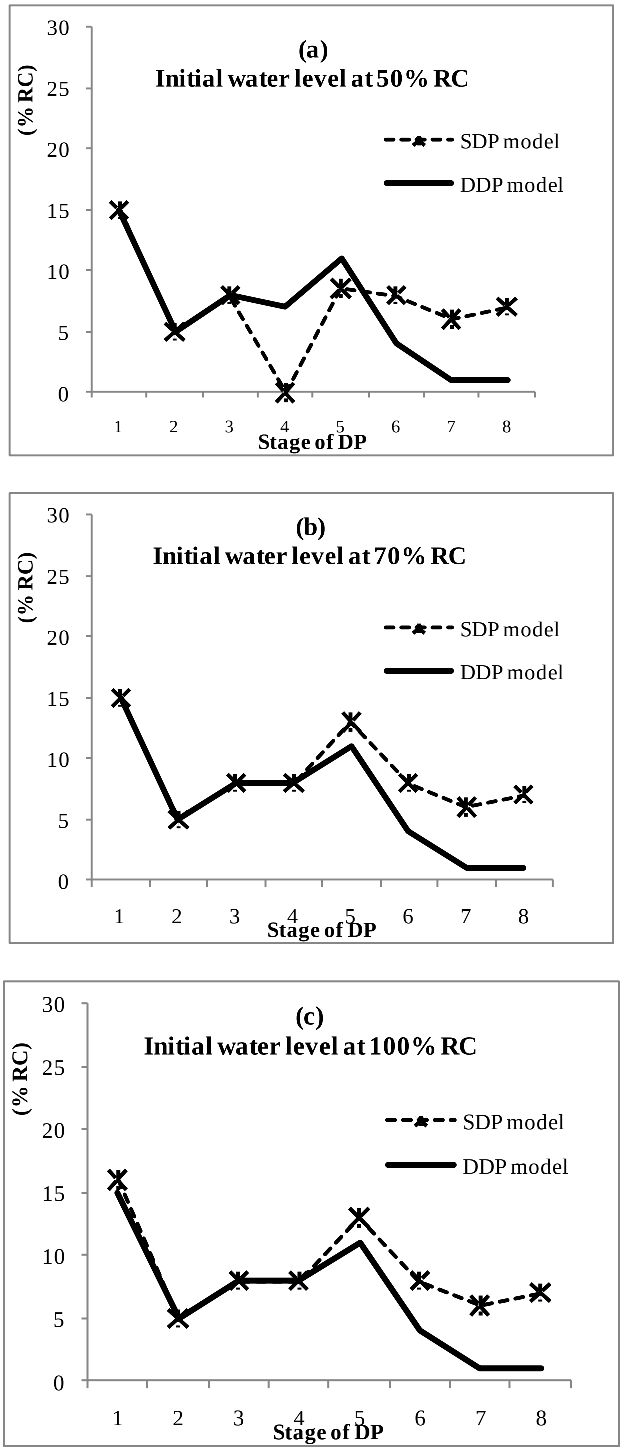

Figure 2 Comparing the optimal release for rice production between the DDP and SDP models. The results were compared at three initial water levels: 50% RC (a), 70% RC (b), and 100% RC (c)

Scenario 2 – Fish production

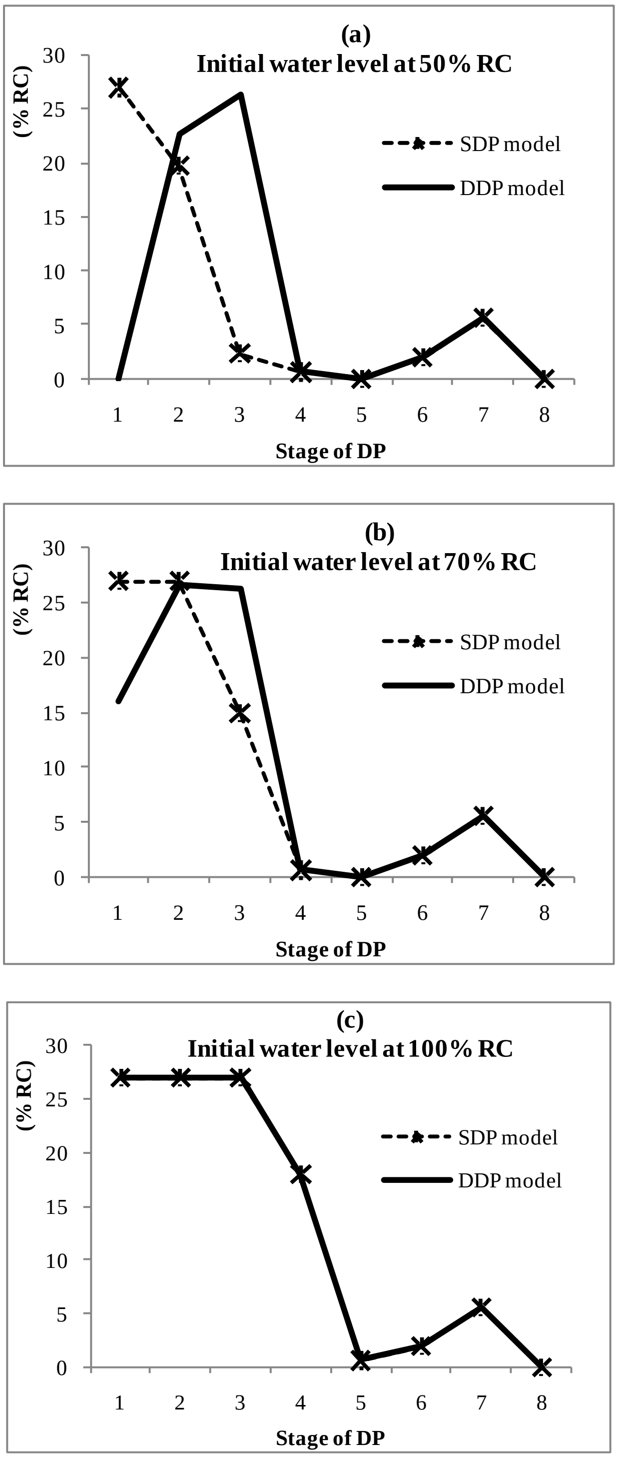

Figure 3 Comparing the optimal release for fish production between the DDP and SDP models. The results were compared at three initial water levels: 50% RC (a), 70% RC (b), and 100% RC (c)

For scenario 2, the TNP obtained from the DDP and SDP models are not significantly different (4 to 5% difference), irrespective of the initial water level in the reservoir (Figure 1b). Although the optimal releases from stage 1 to 4 are significantly different for the two models (Figure 2 a, b), the TNP for this scenario is unaffected (Figure 1b). This is because regardless of how much water is available in the reservoir and how much rainfall occurs, the optimal release is planned for the maximum water release prior to the fish harvest season (stage 4) to enhance fish harvest efficiency. The absence of significant differences in TNP obtained from the DDP and SDP models suggests the deterministic approach to RWM is appropriate for managing the reservoir for fish production.

Scenario 3 – Joint production of rice and fish

The optimal release for scenario 3 is more sensitive to the demands of rice production than of fish production. In this scenario, the differences in TNP obtained from the deterministic and stochastic models vary according to the initial water level (Figure 1c). When the initial water level is high (70% - 100% RC), or for R_{11}-type reservoirs, the differences in TNP range from 4% to 5%. At these initial water levels there is always sufficient water available for rice production; and in these situations rice profits are independent of rainfall. No differences in TNP obtained from the two modelling approaches imply that when the reservoir water level is high, the DDP model is sufficient for examining this scenario.

However, when the initial water level is low (50% - 70% RC), or for R_{12}-type reservoirs, the differences in TNP between the two models are approximately 24%. The reasons are similar to those outlined for scenario 1. At 70% RC or lower, the TNP obtained from the DDP model are always higher than those from the SDP model. Furthermore, overstating the release also occurs with the DDP model when the initial water level is low (50% - 70% RC). For example, at 70% RC, the optimal release at stage 3 obtained from the DDP model is 27% RC while it is only 8% RC in the SDP model. When the initial water level is at 50% RC, the optimal water release for the DDP model is 8% RC while for the SDP model it is 2% RC. The SDP model considers the likelihood of lower rainfall and saves more water for stages 5, 6 and 7 when rice plants are most sensitive to water deficits (Figure 4a). As argued in scenario 1, in these circumstances, the SDP model is the more appropriate one to use.

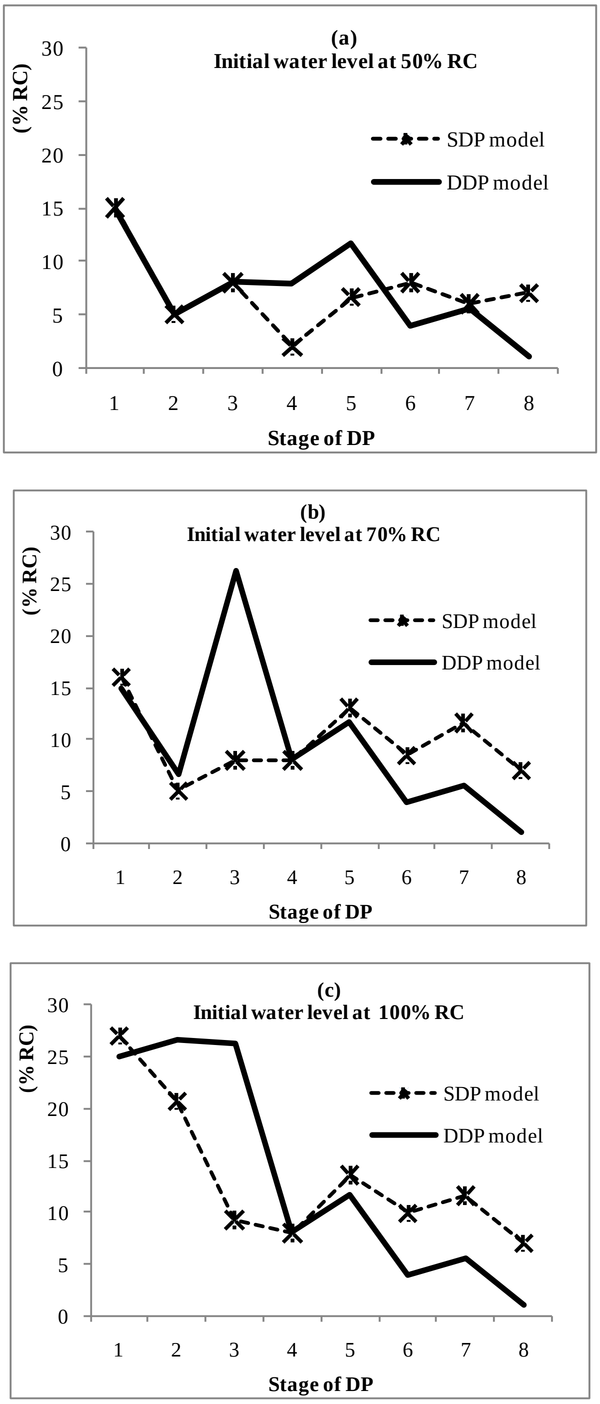

Figure 4 Comparing the optimal release for rice and fish production between the DDP and SDP model. The results are shown at three initial water levels: 50% RC (a), 70% RC (b), and 100% RC (c)

5. Conclusion

Profitable management of multiple-use reservoirs depends on many factors. Modelling complex systems such as multiple-use reservoirs can be challenging. A legitimate question for scientists and modellers is how best to model the management of a multiple-use reservoir. This paper studies whether it is worthwhile to use a stochastic modelling approach that requires more modelling effort, yet provides more realistic results compared to a deterministic model that is simpler to construct. To compare the two modelling approaches we apply both stochastic and deterministic models to the management of a multiple-use reservoir in southern Vietnam.

The optimal strategy for release of reservoir water is determined for two types of reservoir: (1) a reservoir full at the beginning of the irrigation season with a water holding capacity *greater than or equal to* total irrigation requirements (R_{11}-type reservoirs), and (2) a reservoir full at the beginning of the irrigation season with a water holding capacity *smaller than* total irrigation requirements (R_{12}-type reservoirs). Three production scenarios are examined: a focus on rice production, a focus on fish production, and lastly, focusing on joint production of rice and fish. Key findings for the focus on either rice production or joint production of rice and fish, are that for R_{11}-type reservoirs there are few differences in total profits between the stochastic versus deterministic models of the management of these reservoirs. These findings suggest that the deterministic approach is appropriate for these reservoirs as it reduces the complexity of calculations and is less time consuming.

However, the opposite is found for R_{12}-type reservoirs: the deterministic approach overstates optimal release strategies or at least may cause reservoir managers to take greater management risks than they might otherwise do. When fish production is the management focus, then the absence of significant differences in total profits obtained from the deterministic and stochastic approaches for either R_{11}- or R_{12}-type reservoirs suggests that the deterministic approach is appropriate for managing these reservoirs in these situations.

Hence, although no single modelling approach is universally superior, nonetheless the desirable modelling approach is stochastic if reservoir capacity and water use demands have a rather high impact on optimal temporal use of reservoir water.

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