Australian Agricultural and Resource Economics Society

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AARES National conference 2010

Adelaide convention centre

February 10-12, 2010

Dynamic trade-offs in water use between irrigation and reservoir aquaculture in Vietnam

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Abstract

Conflicts of interest between irrigation and aquaculture in water use from reservoirs in Vietnam can be resolved when trade-offs in the economic value of water can be quantified over time. Determining these trade-offs can be used as a benchmark for making decisions about managing reservoirs tending to develop rural areas in Vietnam. To solve this problem, a stochastic dynamic programming model was constructed. This model maximizes the expected net present values generated by both agriculture and aquaculture by finding the optimal release paths throughout a year, under conditions of uncertain rainfall. The model was constructed using two main components. First, a dated water production function is used to evaluate responses of crop yields for different levels of applied irrigation. Second, a bio-economic model for reservoir fisheries is employed to estimate fish yields at different levels of water during a harvest season. Using this model, we present a case study of reservoir water management in Vietnam.

Key words: irrigation, reservoir aquaculture, stochastic dynamic programming, and dynamic trade-offs.

1. Introduction

In common with other countries in Asia, most reservoirs in Vietnam are constructed for irrigation; more than 90% of the reservoirs are used for this purpose (Nguyen S.H, Bui T.A et al. 2001). However, in recent years the reservoirs have also been used for aquaculture. This use has helped people living around the reservoirs to earn income and particularly useful for most poor people engaged in aquaculture who lost land and were displaced when the reservoirs were built (Schilizzi 2003).

Despite the benefits generated from reservoir aquaculture, there are a number of conflicts of interest between agriculture and aquaculture in the relative use of the water. In particular, to minimize reductions in crop yields caused by a lack of water in the dry season (from November to May), the reservoirs often store water for use by agriculture. Conversely, to obtain high productivity of fish, aquaculture requires low levels of water during the harvest season (from February to May); this is because the more water is released, the fish become more concentrated and the easier it is to harvest them; resulting in a high productivity of fish harvesting.

These conflicts are further complicated by the fact that rainfall, coming early or late, may result in different net benefits generated from both agriculture and aquaculture. In the harvest season, aquaculture will benefit from release of water early but will be penalized by later release, irrespective of whether rainfall comes early or late. By contrast, if rainfall comes late, agriculture benefits from later release of water but is penalized if water is released early to satisfy the demand for aquaculture. Water released to enhance the harvesting of fish is likely to reduce the amount of water available for crops later in the dry season and may result in a reduction in crop yields. Therefore, this raises the issue of whether water should be released earlier for the use of aquaculture in the harvest season or later for the agricultural use during the dry season.

The decision to release water earlier or later for the two users requires knowledge of reservoir water management in terms of timing and quantifying the amount of water released. Optimal water release decisions, in this case, must take into account two factors. First, when and how much water should be released in order to retain certain water levels for full potential growth of crops. Second, how fish can be maximally harvested as reservoir water levels fluctuate during a harvest season.

The contrasting demands of water use between the two users highlighted above indicate that there are trade-offs in the economic value of water use between agriculture and aquaculture. This study focuses on finding the optimal water release paths over an irrigation season and under uncertain conditions of rainfall to first maximize the expected net present values generated from the system (as defined later in section 4.3.1.1), and then to quantify the trade-offs involved.

This study describes a stochastic dynamic programming (SDP) model used to find the optimal release paths of water. The output from this model is then used as a benchmark to quantify the trade-offs involved. Descriptions of the research areas and the research approaches used in this study are presented in sections 2 and 3, respectively. The structure of the model of reservoir water management is described in section 4. In particular, we will discuss how to incorporate both agricultural penalty and aquaculture benefit functions into a SDP. The results of the model and quantification of the trade-offs are discussed in section 5. Finally, main findings and limitations of the model are stated in section 6.

2. Dynamic trade-offs in water use between irrigation and reservoir aquaculture: water management in the south of Vietnam

2.1 Climatic conditions of the research area

The south of Vietnam is located in the monsoon tropical zone which is the meeting place between the Asian continent and the Pacific Ocean. The region is influenced by the northeast and southwest monsoon, and is also affected by the Pacific Ocean tropic atmosphere from April to October. As a result, the climate of the region is distinguished by a six-month wet season extending from June to October, and a six-month dry season from November to May. Temperatures are mostly stable during the year (from 26^0C to 28^0C) with a mild winter, humidity of about 70%, and few storms. Rainfall mainly occurs in the wet season while during the dry season the weather is hot together with a high rate of radiation. Over three decades, from 1977 to 2007, the annual average rainfall varied from 1,400 to 2,500mm (the Sub-institute of Hydrometeorology and Environment of South Vietnam).

2.2 Descriptions of rice practices and reservoir aquaculture operations in the research area

This study investigates the problem of managing water from a reservoir for use by both agriculture and aquaculture. The common structure of a production system using water from a reservoir in the south of Vietnam is indicated in Figure 1. It includes aquaculture operations within the reservoir and irrigated rice in the surrounding areas.

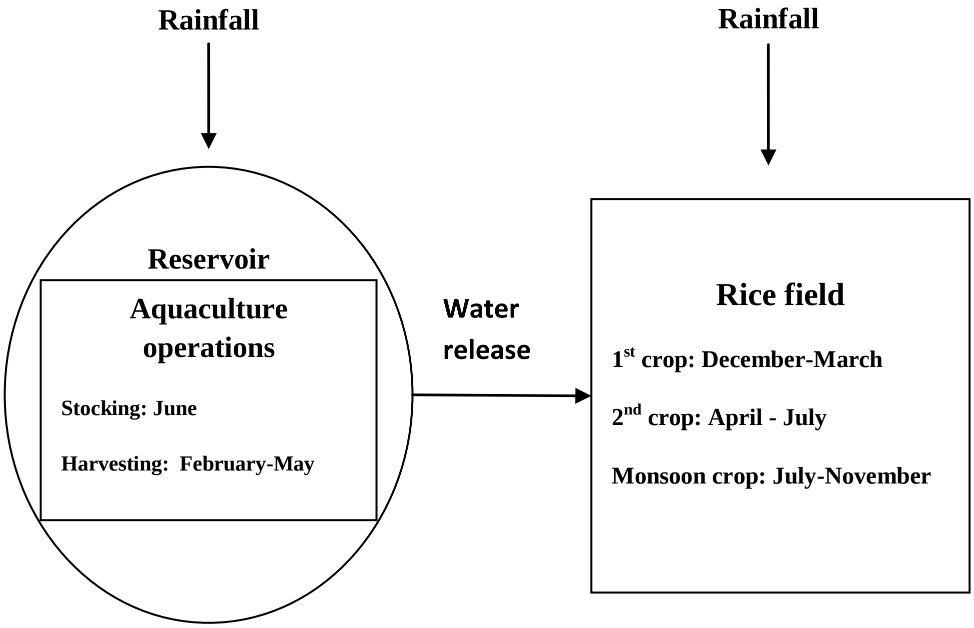

Figure 1 The common structure of a production system using water from a reservoir in the south of Vietnam

In Vietnam, excluding hydroelectric use, the primary role of reservoirs is to supply water for rice fields; aquaculture is considered as a combined purpose and is often given low priority. The reservoir is replenished by rainfall during the wet season and water is regularly released during the dry season (see Table 1). The reservoirs may or may not be full after the wet season. In general, water availability in the reservoir at the end of the wet season is defined by reservoir size, leftover water from the previous year and rainfall. Normally, water is at its highest level at the beginning of the first rice season in December and slightly declines from December to mild of March due to the release of water to crops. At the beginning of the second rice season in April, water usually remains at intermediate levels and is continuously released to the end of this season.

Three rice crops are successively cultivated around the reservoirs in one year (see Table 1). Each crop is about 100 days long and each is divided into four 25-day growing periods, called initial, development, mid-season and late- season growth periods. The first crop is from December to March. The second crop extends from April to July. These two crops must be irrigated during the period from December to June because of lower rainfall levels at this time of year. The third crop, called the monsoon crop, starts in July and ends in November. This crop does not require irrigation due to the high frequency of rainfall during this period.

Reservoir aquaculture also operates on a cycle of one year. Stocking of fingerlings into the reservoirs often starts in June when the wet season commences. Generally, five main species are stocked (common carp (*Cyprinus carpio)*, silver carp (*Hypophthalmichthys molitrix)*, grass carp

(*Ctenopharyngodon idella)*, bighead carp (*Aristichthus nobilis)*, and mrigal (*Cirrihinus mrigal))*, of which 40% -50% are silver carp and mrigal (Nguyen et al. 2001). Harvesting fish usually takes place from February to May, when the reservoir water is at low levels, and is divided into four 25-day periods as illustrated in Table 1. The total weight of fish harvested at different periods, in terms of both the amount and size of fish, varies depending on fluctuations of water levels in the reservoir (personal communication with fish farmers).

Table 1 Seasonal calendar of agriculture, aquaculture and reservoir operations

Months	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Climatic conditions	The dry season						The wet season					
Reservoir operations	Release							Storage				
Rice crop seasons	The first crop				The second crop				The monsoon crop			
Fish harvest seasons			Period 1	Period 2	Period 3	Period 4						

2.3 The trade-offs in water use between irrigation and reservoir aquaculture

The trade-offs in water use between irrigation and reservoir aquaculture are generally governed by the decision of when and how much water is released. In this study the trade-offs are measured in million of Vietnamese Dong (mVND), and are defined as the net changes between gains in aquaculture returns and losses in agricultural returns when there is a change in timing and quantity of the amount of water released.

The timing and quantity of released water will affect the returns of both agriculture and aquaculture. First, crops are highly sensitive to applied irrigation at different growing periods. A deficit or an abandonment of water at different growing periods may result in varying reductions in crop yields. Particularly, a lack of water in the mid-season of rice growth will result in a greater reduction than a lack of water in the initial or late-season stages (De Datta and K. Surajit 1973). Second, high levels of water released early only positively affects fish yield in the harvest season (as explained in section 1). Consequently, a change in water release (timing and quantity) will result in changes in the income generated by the system.

The trade-offs are further complicated by the fact that decisions to release water are further affected by stochastic rainfall. In the case where rainfall comes early, and water is released early at the beginning of an irrigation season, agriculture may not benefit more than usual. However, aquaculture will benefit from this early water release. This is because crops may have enough water during two seasons and aquaculture may harvest more fish since the water level is low. Conversely, keeping water at high levels, to avoid the risks in terms of insufficient water for irrigating crops when rainfall comes late, may allow a high yield of crops to be harvested, but may limit the harvest of fish.

3. The research approach

The objectives of this study are to find the optimal paths of water release and the trade-offs in water use between irrigation and reservoir aquaculture, occurring during a year and under uncertain conditions of rainfall. The decisions to release water to different rice growing periods and fish harvest season can be considered as a process involving successive stages. Therefore, the technique suited to find the solution is dynamic programming (DP). Dynamic programming is a mathematical technique employed to deal with those problems of possessing successive stages in a process (Kennedy (1981), Kennedy (1986), and Dudley (1998)).This technique has been applied to a wide range of natural resource management (Kennedy 1986). Applications of SDP especially to water resource management can be found in the work of Kennedy (1981, 1986).

Despite acknowledging the known limitations of DP (Kennedy, 1986), DP has been used in this study for following reasons. First, the accuracy and specification of the simulation models used have been validated by many authors in a wide variety of disciplines areas. Second, the objective function of DP can be easily divided into sequential stages using a dated water production function (DWPF) and a bio-economics model. Third, ‘the curse of dimensionality’, known to be associated with DP, is overcome by incorporating both agricultural penalty and aquaculture benefit functions into a one state variable SDP model.

4. Descriptions of the model of reservoir water management

4.1 Crop response function

The water production function is a common tool used to quantify crop yield in response to different levels of applied irrigation (Rao, Sarma et al. 1988). It has been employed by many authors to different crops cultivated in different regions under varying climatic conditions (see: Reca and Roldan et al.(2001); Shangguan and Shao et al.(2002)). However, the function does not take into account the effect of when and how much water is applied to crop. In this study, consideration has been given to timing and quantifying applied irrigation, an adaptation of the approach of Paudyal and Manguerra (1990) is used to estimate the variations of crop yields in response to different levels of water supply at specified growth periods. In particular, the relative evaptransporation (AET/PET) has been replaced with the ratio of the actual water supplied (W) to the water requirement of the crop (W_0) (Paudyal and Manguerra 1990).

The DWPF can be readdressed as:

$$Y_a = Y_p \left[1 - \sum_{i=1}^{z} k_{yz} \left(1 - \frac{W}{W_0} \right)_i \right]$$

Where

W: water supplied (% of reservoir capacity)

W_0: water requirements of the crops (% of reservoir capacity)

Y_a and Y_p: actual and potential yields, respectively (ton/ha)

k_{yz}: yield response factors (parameters)

i: crop growing periods

4.2 Agricultural penalty function

DWPF can be rewritten as:

$$Y_a = \left[Y_p - Y_p \sum_{i=1}^{z} k_{yz} \left(1 - \frac{W}{W_0} \right)_i \right]$$

or

$$P_a Y_a = P_a \left[Y_p - Y_p \sum_{i=1}^{z} k_{yz} \left(1 - \frac{W}{W_0} \right)_i \right]$$

$$P_a Y_a = P_a Y_p - P_a Y_p \sum_{i=1}^{z} k_{yz} \left(1 - \frac{W}{W_0} \right)_i$$

or $TR_a = TR_p - F_a$……………(1)

where

$$F_a = P_a Y_p \sum_{i=1}^{z} k_{yz} \left(1 - \frac{W}{W_0}\right)_i \text{……………….(2)}$$

- $F_{a(s,u)} = 0$ when applied irrigation and rainfall satisfy rice water requirements
- $F_{a(s,u)} < 0$ when water deficit occurs

P_a: price of rice (mVND/ton)

i: rice growing periods

k_{yz}: yield response factors, taking values 1, 1.09, 1.31 and 0.5 for initial, development, mid-season and late-season periods of rice growth

TR_a: total return from rice (mVND/ha)

TR_p: potential return from rice (mVND/ha)

In (1) total return/ha from rice (TR_a) is measured by taking the potential return/ha from rice (TR_p) less reductions in yield (F_a) occurring because of water deficit. F_a is a function of the ratio W/W_0, crops yield response factor (k_{yz}), price of rice and potential yield. In the present study, F_a is called agricultural penalty function; and it measures losses in rice yields as water deficit occurs in each growing period. The function is mainly used for rice productions. This is because most agricultural land around the reservoirs in the south of Vietnam is devoted to rice productions (verbal communication with local authorities). Crop diversification into corn and peanuts has occurred since 2006, but to a limited degree (verbal communication with rural extension officer).

4.3 Aquaculture benefit function

4.3.1 Returns of reservoir aquaculture

Aquaculture returns, expressed in mVND, is a function with a wide variety of inputs such as the weight and survival rates of fingerlings, labor, harvesting technique, type of species stocked, and water fluctuations in reservoirs. Of these inputs, only the latter will be considered in more detail in this study; as the other inputs have already been taken into account by Petersen et.al (2004) and Truong (2007) in the Bio-economics model of Reservoir Aquaculture- a Vietnamese Operation, commonly abbreviated to BRAVO.

In the present study, aquaculture benefits (F_f) are expressed as an increase in aquaculture returns when water levels in the reservoirs during fish harvest season become lower than usual. Specifically, aquaculture returns are first calculated by BRAVO and are then multiplied by a parameter called the physical concentration effects (PCE) (see section 4.3.2).

4.3.2 The physical concentration effects

The effects of water fluctuation on fish production have been studied by a number of researchers since the 1950s (Bernacsek 1984); but it is unlikely to ever be described by a specific model because of the complexity of the relationships among factors such as fish biology, fish migration, the natural environment, and hydrological regimes. Bernacsek (1984) clarified the factors affecting reservoir fish production into five groups namely: (1) physical concentration effects, (2) biological effects, (3) species composition or reservoir littoral ichthyomass, (4) reservoir fish yield, and (5) fishing activity. Of these five factors, only the physical concentration effect is relevant to reservoir aquaculture operations in Vietnam.

The PCE is known as a change in population density when there is a change in reservoir volume. In other words, fish production will be high when water is at low levels and vice versa. This is because the lower water level has a higher concentration of fish which are then easier to catch, resulting in a higher fish yield per unit effort (Bernacsek 1984). The effect is measured in the increase in weight of fish caught compared with the magnitude of the draw-down areas of a reservoir Marshall (1981), De Silva (1988), Nissanka (2000), and Amarasinghe (2001). However, these studies estimated fish yields at a certain level of water statically, not focusing on the PCE at different fish harvest periods. Therefore, fish harvested in terms of fluctuation of water levels over a harvest season were not considered as a dynamic process.

In Vietnam, the PCE has been primarily studied by Nguyen et al.(2001). The results of these studies indicated an exponential relationship between fish yield and reservoir size. Similarly, research by Tran (2001) in the central highland of Vietnam has shown that maximum fish yields are negatively correlated with reservoir size according to a log-log relationship. Although acknowledging the limitations of Nguyen and Tran' studies, in which fish yields were evaluated at certain levels of water and did not take into account water fluctuation in the reservoirs, these studies can be used as valuable references in the present study for choosing parameters that indicate the PCE.

In the absence of data showing fish yields harvested over a season in Vietnam and also in the literature, no research relevant to fish yield in relation to the PCE is found. This study will find an appropriate parameter to incorporate into BRAVO (Truong, 2007) in order to calculate weight of fish harvested at each period over a harvest season. Particularly, the PCE will be found from two equations:

Equation 1: $Y=0.742*A^{-0.7446}$ (Nguyen et al. 2001)

Equation 2: $A=350*s^{0.5723}$ (reservoir hypsographic curve)

⇨ $Y=259.7*S^{-0.4261}$

⇨ $\%\Delta Y = 3.0493*e^{(-0.046*s)}$

Where

Y: fish yield (ton)

%ΔY: change in fish yield (%)

A: reservoir area (ha)

s: water levels in the reservoir (% of reservoir capacity)

In the present study, the PCE is defined as the changes in fish yield harvested (%ΔY) at different water levels in the reservoirs at each harvesting period (s_{it}) as shown in equation 3.

Equation 3: $PCE_{it}=3.0493*e^{(-0.046*s_{it})}$

Where

s_{it}: water levels *t* in the reservoirs at harvesting period *i*, (% of reservoir capacity)

Once fish yields are calculated by the method described above, the aquaculture benefit function can be addressed as:

$$F_f(s,u)=\sum_{i=1}^{\alpha}\sum_{j=1}^{\beta}Y_{ij}*P_{ij}*PCE_{it}$$

Where

$\sum_{i=1}^{\alpha}\sum_{j=1}^{\beta}Y_{ij}P_{ij}$: aquaculture returns calculated by BRAVO (mVND)

PCE_{it}: the physical concentration effects

α and β: number of harvesting periods and fish species stocked, respectively *s* and *u*: water levels and water released (% of reservoir capacity) , respectively

Y_{ij}: weight of fish j harvested in period i (tones) (see Appendix 1)

P_{ij}: price of fish j harvested in period i (mVND/ton)

4.3 The stochastic dynamic programming model

To find the optimal release paths over an irrigation season for use by agriculture and reservoir aquaculture, a one state variable stochastic dynamic programming model is introduced. In this model, fish harvest occurs from February to May and two successive crops are irrigated during an irrigation season from December to July. Consequently, the time horizon considered in the model is from December to July and it is divided into eight 25-day stages as illustrated in Table 2.

Table 2 Dynamic programming stages incorporate rice growing periods and fish harvest season

Time horizone	**December**							**July**
Stages of dynamic programming	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Rice practices	Sowing in December		Harvesting in March		Sowing in April		Harvesting in July	
	First crop				Second crop			
	Initial	Development	Mid-season	Late-season	Initial	Development	Mid-season	Late-season
Aquaculture operations				February			May	
				Fish harvest duration				
				Harvest 1	Harvest 2	Harvest 3	Harvest4	

4.3.1 The structure of the SDP model

4.3.1.1 Objective function

The objective function is to maximize the expected net present values (ENPV) generated by both rice and fish. The ENPV are measured specifically in terms of penalties to rice production and gains in fish production. In the model, the ENPV depends on both how much water is available in the reservoir at the beginning of each stage (s_n) and how much water is released in each stage (u_n), regardless of other input factors. This assumes all production inputs other than water do not limit yields of rice and fish.

The objective function: $\text{Max } E[V_{(s,u)}] = \text{Max } E[Fa_{(s,u)} + Ff_{(s,u)}]$

Where

E: mathematical expectation operator

V: the net present values (mVND)

s and *u*: water levels and water released (% of reservoir capacity), respectively

$Fa_{(s,u)}$: agricultural penalties (mVND) expressed in reductions in crop yield when water deficit occurs.

$Ff_{(s,u)}$: aquaculture benefits (mVND) expressed in increases in aquaculture returns when water in the reservoirs in each harvesting period become lower than usual.

4.3.1.2 State variable

State variable is water availability in a reservoir at the beginning each stage, measured in percentage of reservoir capacity. This is a continuous variable in reality. However, in the model, it takes a number of discrete levels range in [s%, ss%]. The lower bound (s%) satisfies the lowest level of water remaining in a reservoir as a safety level required by reservoir manager; and the upper bound (ss%) is the maximum reservoir capacity.

Table 3 Capacity and surface areas of Daton reservoir

	Unit	Minimum	Maximum	Increment
Reservoir water levels (state variable)				
- Million cubic metres of water	MCM	0.4	19.6	0.2
-Percentage of reservoir capacity	%	2	100	1
Reservoir surface areas	ha	37	350	na

4.3.1.3 Stochastic variable

Rainfall, stochastic variable *k*, is an unknown factor in the model but it is described by a set of discrete probability distributions. Rainfall amount and its probability distribution are obtained from daily data of an eight year period from 2000 to 2008. Daily data about rainfall amount is observed in mm/day; however, in the model it is transferred into the percentage of reservoir capacity (see Appendix 2).

4.3.1.4 Decision variable

The decision variable, taken as a number of discrete values, is the volume of water released u, expressed as the percentage of reservoir capacity. It is assumed that at any period if water release u is specified, it should be made even if crop water requirement (CWR) is fully supplied by rainfall. In that case, a part of water released may be abandoned. This assumption is applicable to cases where water is managed for the two users. For example, if reservoir is considered for the prior use of aquaculture, the amount of water released during fish harvest season can take the higher amount compared with the amount of water released to satisfy CWR at any periods.

The value of the decision variable is defined by the following process. First, CWR for every rice growing period is calculated using the Cropwat 8.0 model (Swennenhuis 2006)[4]. These values are deterministically calculated using the average values of climatic conditions, humidity, rainfall, evaporation, and radiation. CWR is then used as a standard to measure the water deficit at different levels of applied irrigation or water released. Second, the amount of water released to each rice growing period is set up at different discrete values which can be higher or lower than the CWR. These chosen values are defined after CWR has been obtained from Cropwat 8.0. In

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[4] A computer program for calculating crop water requirements and irrigation requirements under given climatic conditions and crop data

the case where these chosen values are lower than CWR, a crop water deficit will occur and cause a reduction in crop yields at that stage. This reduction can be calculated by the agricultural penalty function. Conversely, if the chosen values of water released are higher than CWR, there is a surplus of water, this surplus is assumed to have gone into rivers without a negative effect on rice yields. The argument for setting these chosen values higher than CWR is based on two reasons. Firstly, an over release may reasonable when considering the water release for fish harvesting. Secondly, in reality, this over release will not affect crop yields because the rice producers can control how much water is taken into their farms.

Table 4 The decision variable and the range of discrete values for each stage

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Rice water requirements								
- Million cubic metres of water	2.35	0.76	1.23	1.25	2.82	2.74	0.00	0.00
-Percentage of reservoir capacity	12	3.9	6.3	6.4	14.4	14	0	0
Yield response factors	1	1.09	1.32	0.5	1	1.09	1.32	0.5
Applied irrigation(*) (decision variable)								
Minimum	7	0	3	3	9	7	0	0
Maximum	15	8	11	11	17	15	8	8
Increment	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

(*) expressed as the percentage of reservoir capacity

4.3.1.5 Transition equation

The transition equation for the system describe how state of the system changes overtime

$s_{n+1} = s_n - u_n + k_n$

Where

s_{n+1} and s_n: water availability in reservoirs at the beginning of stage (n+1) and stage n, respectively (%of reservoir capacity)

u_n: the amount of water released at stage n (% of reservoir capacity)

k_n: the amount of rainfall during stage n, (% of reservoir capacity)

The backward recursive equation employed to solve the problem is

$$V_n\{s_n\} = \underset{u=n,\ldots 1}{Max}\left[\sum_{k=1}^{m} p\ \{k_n\}\left(F_a\{s_n, u_n, k_n\} + F_f\ \{s_n, u_n, k_n\} + \alpha V_{n+1}\{s_n, u_n, k_n\}\right)\right]$$

$$\sum_{k=1}^{m} p\{k_n\} = 1$$

Where

$p\{k_n\}$: probability of rainfall amount in stage n (%)

m: number of random values of rainfall amount

$\alpha = 1/(1+r)$: discount factor

r : discount rate (%/stage)

$F_a\{s_n, u_n, k_n\}$: agricultural penalty function

$F_f\{s_n, u_n, k_n\}$: aquaculture benefit function

$V\{s_n\}$and $V_{n+1}\{s_n, u_n, k_n\}$: the value of the function at the stage n and (n+1), respectively

The backward recursive equation can be solved subject to the following constraints

- $s_{min} <= s_n <= s_{max}$
- s_{min}= 2% (~ 0.4 MCM)
- s_{max}=100% (~19.6 MCM)
- $s_n >= u_n$
- $0.5 <= [(u_n+k_n)/w_{0n}] <= 1$ (W_{0n}: CWR in stage n, derived by Cropwat 8.0)
- $V_9\{s_n,u_n,k_n\}=0$

4.3.2 Solution algorithm

Since water levels at the beginning of each stage are given and the amount of water released are defined, the optimal release paths can be found by using Bellman's principle of optimality which states that "An optimal policy has the property that, whatever the initial state and optimal first decision may be, the remaining decisions constitute an optimal policy with regard to the state resulting from the first decision" (Bellman 1957) (p.83). In other words, the solution to find the optimal release paths can be divided into two main steps. First, a set of optimal decision rules can be determined using a backward process. Second, the optimal decision rules can then be used to determine the optimal paths for a given initial condition of state variable.

More specifically, in the eight 25-day stages of the SDP, instead of first finding the optimal decision rules for the initial stage, the process starts at stage 8 and moves back to the initial stage. Instead of simulating losses in rice yields and gains in weight of fish harvested chronologically through the stages of the season, these losses and gains are calculated from the last stage back to the first stage. The solution is obtained by starting at stage 8 and finding the optimal amount of water released and maximum of the expected net present value for this stage. These results from stage 8 can then be used to determine the optimal decision for stage 7, which in turn is employed in stage 6. This process is repeated until the optimum is found for the initial stage.

The optimal release paths can be found by a forward tracking process. In this process, all feasible combinations of optimal decisions are first shown in the output of the SDP. Based on the water level at the beginning of stage 1 (the initial value of state variable) and the expected value of rainfall, an optimal decision will be chosen for stage 1. This decision can then be used to find the levels of water at the beginning of stage 2 (the value of state variable). Using a set of optimal decision rules in stage 2 obtained from the backward process indicated above, an optimal decision can then be selected for stage 2. This optimal manner continues till stage 8 reached.

The results of the forward tracking process determine the optimal release path for whole process. In other words, by following the optimal release path, the optimal amount of water released in each stage is determined so that the expected net present value (ENPV) generated from the system is maximized.

4.4 Model parameters

In the present study, the model described above has been used to find the optimal paths of water release and dynamic trade-offs in water uses between irrigation and aquaculture at Daton reservoir in the south of Vietnam. Descriptions of the parameters used in the model are given in Table 5.

Table 5 Parameter values used in the SDP model

		Unit	Value
Price of fish (*)			
	Common Carp	mVND /ton	16
	Silver Carp	mVND /ton	6
	Grass Carp	mVND/ton	8.5
	Bighead Carp	mVND/ton	6
	Mrigal	mVND/ton	8.5
Price of rice paddy (*)		mVND/ton	2.5
Potential yield of rice (**)			
	First rice crop	Ton/ha	6.5
	Second rice crop	Ton/ha	6
Irrigation areas		ha	1000
Discount rate (*)		%/stage	0.56

(*) average *price in 2009*

(**) *The highest rice yield in the region obtained by surveys in 2009*

5. Results and discussions

5.1 Estimating the Expected Net Value (ENPV) generated by the system

Estimation of the ENPV is shown in Figure 2. The ENPV is affected by water availability in the reservoir at the beginning of an irrigation season. For example, if the reservoir is full (s=100% ~ 19.6 MCM) the ENPV is mVND 491 (~ A$ 28,882)[5]. This value increases up to the maximum value at mVND 1389 (~ A$ 81,705) when water levels reduce to 66% (~ 10.97 MCM). This is because as water is released early it creates low levels for fish harvesting and also supply enough water to the rice; resulting in increasing fish yields harvested and no losses in rice yields. After reaching the maximum value, the ENPV slightly increases while water levels continue to go down to 47% (~ 9.2 MCM). This is because if water levels are from 47% to 66% in the first stage, it will then be very low in the fish harvest season due to the use of irrigation and also supply enough water to rice. Therefore, most fish are likely to be harvested in the first harvesting period. Consequently, aquaculture benefits will increase slightly during the later periods of the fish harvest season. This slight increase in aquaculture benefit together with no agricultural penalties will result in a slight increase of the ENPV.

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[5] The exchange rate is: A$1=VND 17,000

Another interesting point found here is that the ENPV will be significantly lower or reduced if water in the reservoir at the beginning of an irrigation season is lower than 47%; and it will reduce to zero when the water reaches 11% (~ 2.15 MCM). This is because if water remains at levels lower than 47% there is a lack of water available to rice which will reduce in rice yields. In addition, keeping water at low levels at the beginning of an irrigation season will result in a very low level of water for growing of fish; this may negatively affect the fish growth rate. A key conclusion here is that to maximize the ENPV water availability in the reservoir at the beginning of an irrigation season should be maintained at levels between 47% and 66%. If reservoir water levels are kept at greater than 66% or smaller than 47%, the ENPV is not maximized.

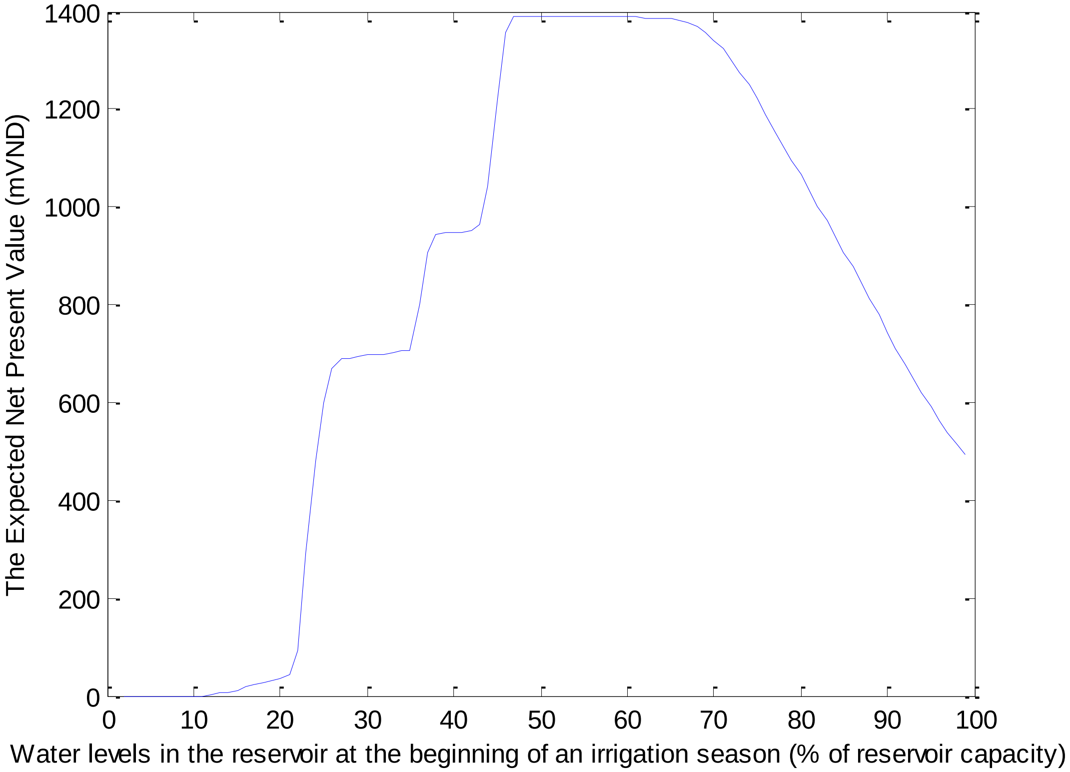

Figure 2 The Expected Net Present Value (ENPV) obtained from different water levels in the reservoir at the beginning of an irrigation season

5.2 The optimal paths of water release

The optimal paths of water release were found by forward tracking process using the optimal release rules resulting from the SDP model and the expected values of rainfall in each stage. The optimal paths are counted for different initial values of water levels in the reservoir at the beginning of an irrigation season. For example, if the initial water level is 47%, the optimal path counted for stage 1 to stage 8 is 10.8; 2.8; 5.2; 5.4; 13.1; 10.5; 3.5; and 0 MCM. Similarly, if reservoir is full the optimal path is 15; 9; 11; 11; 17;15; 8; and 0 MCM (see Figure 3).

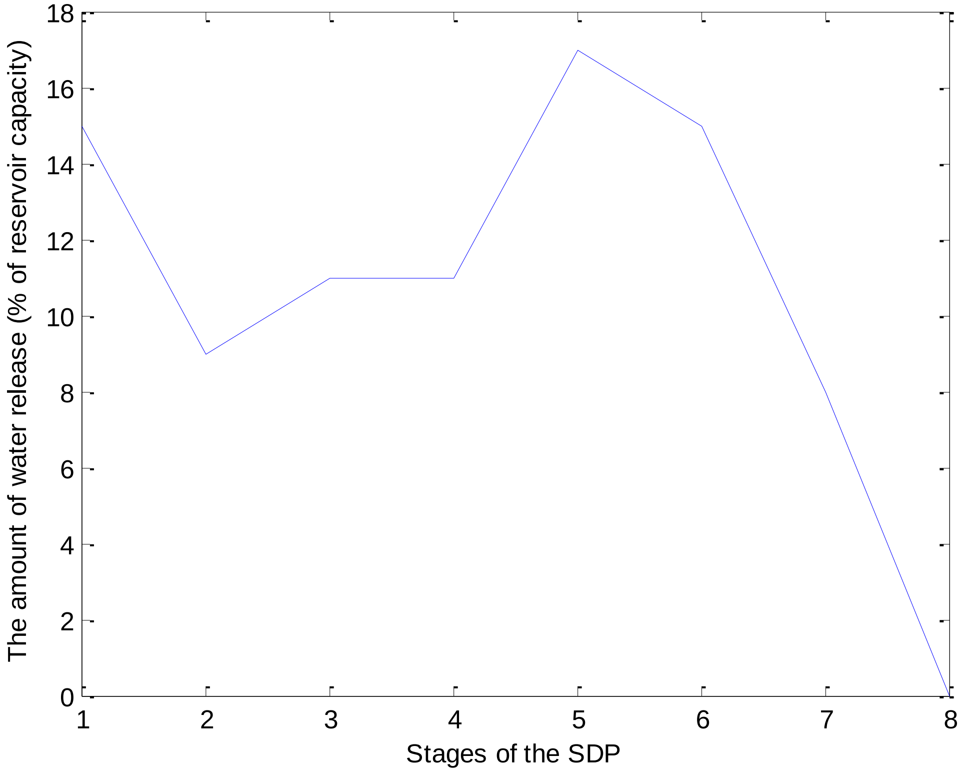

Figure 3 The optimal path of water release for a full reservoir

5.2 The optimal water levels in the reservoir throughout an irrigation season

The optimal water levels in the reservoir throughout an irrigation season are shown in Figure 4. It is clear that the maximum and minimum values of the initial levels of water can vary from 100% and 47%, respectively. In the case where the initial water levels in the reservoir are lower than 47%, there is not enough water available for the whole irrigation season. Because of this reason, the trade-offs in water use between irrigation and reservoir aquaculture will be found for those initial levels of reservoir water ranging from 100% to 47% (as further explained in section 5.4). From Figure 4 if the reservoir is full, following the optimal paths indicated in section 5.2, the amount of water availability in the reservoir at the end of an irrigation season is 26.21% (~5.13 MCM). Similarly, if the initial reservoir water is at 47%, the amount of water available in the reservoir at the end of an irrigation season is 5.83% (~ 1.14 MCM). The results derived from the model are consistent with Daton reservoir where the actual average value of minimum water levels in the reservoir (in June) from 2001 to 2008 was 18.36% (~ 3.6 MCM) (See appendix 3).

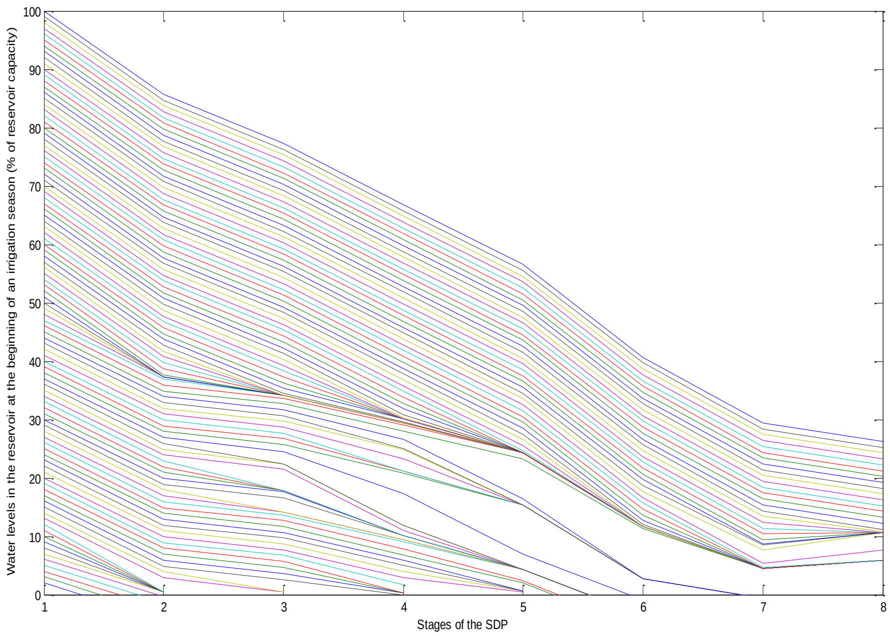

Figure 4 The optimal storage levels of the reservoir throughout an irrigation season

These results have significance for reservoir management. When considering water release for aquaculture, the amount of water released to rice at the beginning of an irrigation season can take those values greater than CWR. Under these conditions, rice yields are not penalized and harvested fish yields will increase.

5.4 Trade-offs in water use between irrigation and reservoir aquaculture

Trade-offs in water use between irrigation and reservoir aquaculture were found after obtaining the optimal release paths and the optimal storage levels of the reservoir. As indicated in section

5.3, trade-offs need to be made at every stage in which the initial water level varies from 47% to 100%. Figure 5 shows that if the reservoir is full at the beginning of each stage the more water is released the higher the trade-offs are. For example, if the reservoir is full at the beginning of stage 1, a 5% increase in water release will result in an increase in the ENPV mVND 127.18 (~A$7,481); while mVND 897.33 (~A$ 52,784) is gained if 50% of water is released (Table 6).

In addition, the earlier water is released the higher the ENPV becomes. In general, the more water released at the first four stages will result in the higher ENPV than at the later four stages. Particularly, in terms of the same amount of water released at every stage during an irrigation season (from 0% to 52%), the ENPV is at highest values in stage 4, lowest values in stage 7 and zeros at stage 8 (see Table 6). This is because fish are first being harvested at stage 4 and are not being harvested in stage 8; additionally, rice is not being irrigated in stage 8.

Table 6 Trade-offs (mVND) at every stage of the SDP.

Water release	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**Stage 7**	**Stage 8**
0%	0	0	0	0	0	0	0	0
5%	127.18	127.57	128.06	128.65	112.62	90.166	51.966	0
10%	286.91	287.94	289.23	290.57	254.36	203.65	117.37	0
15%	447.45	450.98	453.97	456.35	397.52	318.31	199.69	0
20%	602.74	608.01	612.46	616.71	527.37	404.17	210.46	0
25%	757.52	763.45	768.65	773.59	644.07	468.34	140.99	0
30%	864.8	872.78	879.26	884.31	705.62	472.62	142.66	0
35%	893.68	901.56	907.79	912.58	705.62	472.62	142.66	0
40%	896.85	902.73	907.85	912.58	705.62	472.62	142.66	0
45%	897.31	902.78	907.85	912.58	705.62	472.62	142.66	0
52%	897.33	902.78	907.85	912.58	705.62	472.62	142.66	0

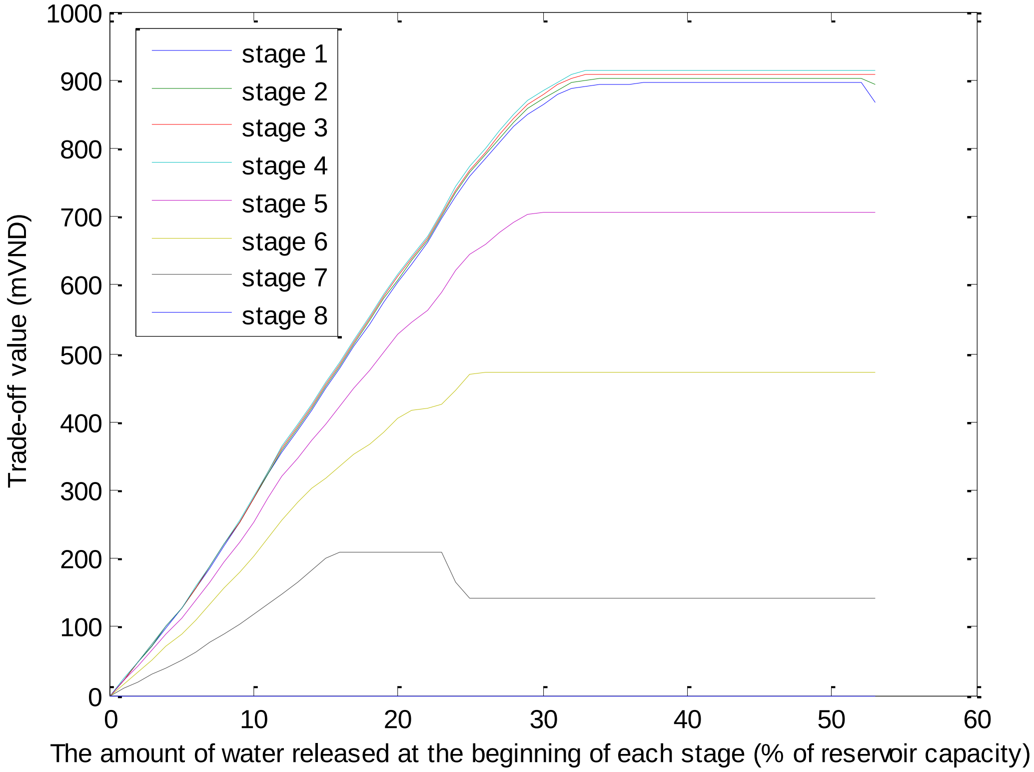

Figure 5 Trade-off curves

6. Conclusions and implications for further research

Conflicts of interest between irrigation and aquaculture in water use from reservoirs are one of the challenges for managing reservoirs tending to develop rural areas in the south of Vietnam. The aims of this paper are first to find the optimal paths of water release and then to evaluate the trade-offs in water use between irrigation and aquaculture. The constructed model is first applied to Daton reservoir. This model will be then explored with other parameter configurations.

Although the results are preliminary, they can be used as a benchmark for those who work in managing natural resources for alleviating rural poverty in Vietnam.

The results presented in this paper highlight two things. First, at the moment to avoid risk, in terms of insufficient water available for irrigation in case rainfall comes late, the decisions to store water for irrigation in the current rice season are not optimal. The results showed that if the reservoir is full at the start, the leftover final amount is 26.2% on average; and it is 5.8% if it starts at 47% is capacity. This implies that if greater amount of water is released earlier to increase fish yield harvested, the ENPV generated by the system will be higher than if water is stored. Second, the trade-offs value in the first four stages are higher than they are in the later stages. This implies that a unit of water will create higher values if it is released early.

Due to lacking information about the stochastic inflows and stochastic surface evaporation in the reservoir, these variables are not considered in the SDP model. This limitation prevents the model from giving completely valid results. Another limitation is that the ENPV were estimated using (1) the expected rainfall in each of the 8 stages and (2) the average prices of fish and rice. This use implicitly assumed the farmers are risk neutral and regardless of the sensitivity of the ENPV as the price of fish and rice change. Finally, the proposed model has not yet produced clearly the trade-offs in water use between agriculture and reservoir aquaculture. Further works need to be done to overcome these limitations.

Appendixes

Appendix 1 Weight of fish harvested at Daton reservoir (ton) resulting from BRAVO

Species	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Common Carp	0	0	0	3.506	3.026	2.636	2.262	0
Silver Carp	0	0	0	8.861	7.666	6.693	5.758	0
Grass Carp	0	0	0	7.043	6.239	5.573	4.887	0
Bighead Carp	0	0	0	4.477	3.93	3.479	3.027	0
Mrigal	0	0	0	4.154	3.584	3.121	2.678	0

Appendix 2 Rainfall amount (% of reservoir capacity) and its probability (%) in each stage

Stage 1		Stage 2		Stage 3		Stage 4		Stage 5		Stage 6		Stage 7		Stage 8	
Rain	Prob	Rain	Prob	Rain	Prob	Rain	Prob	Rain	Prob	Rain	Prob	Rain	Prob	Rain	Prob
0.44	0.96	0.44	0.98	0.44	0.98	0.44	0.95	0.44	0.87	1.33	0.79	1.33	0.71	1.33	0.60
1.56	0.01	1.56	0.00	1.56	0.01	1.56	0.00	1.56	0.02	3.34	0.01	3.34	0.04	3.34	0.04
2.45	0.00	2.45	0.00	2.45	0.01	2.45	0.00	2.45	0.01	4.24	0.01	4.24	0.01	4.24	0.04
3.34	0.01	3.34	0.01	3.34	0.00	3.34	0.02	3.34	0.03	5.13	0.01	5.13	0.02	5.13	0.02
4.24	0.01	4.24	0.00	4.24	0.01	4.24	0.00	4.24	0.03	6.02	0.01	6.02	0.02	6.02	0.03
5.13	0.00	5.13	0.00	5.13	0.00	5.13	0.00	5.13	0.01	6.91	0.02	6.91	0.01	6.91	0.03
6.02	0.00	6.02	0.00	6.02	0.00	6.02	0.01	6.02	0.00	7.81	0.01	7.81	0.01	7.81	0.01
6.91	0.01	6.91	0.00	6.91	0.00	6.91	0.01	6.91	0.01	8.70	0.02	8.70	0.02	8.70	0.03
7.81	0.01	7.81	0.01	7.81	0.00	7.81	0.02	7.81	0.00	11.38	0.04	11.38	0.04	11.38	0.11
8.70	0.00	8.70	0.01	8.70	0.00	8.70	0.00	8.70	0.01	15.84	0.03	15.84	0.03	15.84	0.02
11.38	0.01	11.38	0.00	11.38	0.00	11.38	0.00	11.38	0.02	20.31	0.02	20.31	0.03	20.31	0.02
13.83	0.00	13.83	0.00	13.83	0.00	13.83	0.01	13.83	0.01	22.76	0.04	22.76	0.08	22.76	0.06

Appendix 3 Minimum and maximum water levels in Daton reservoir from 2001 to 2008

Descriptions	2001	2002	2003	2004	2005	2006	2007	2008	Average
Minimum water availability (MCM)	7.2	2.13	2.9	4.98	0.24	6	3.8	1.8	3.63
Maximum water availability (MCM)	21.1	18.6	21.41	19.59	21.91	20.91	21.1	17.44	20.26

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