**55th Annual AARES National Conference**

**Melbourne, Victoria**

**February 2011**

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# Managing multiple-use resources: optimizing reservoir water use for irrigation and fisheries

**Keywords:** Multiple-use resources, reservoir water management, optimization, irrigation, fisheries, and stochastic

**Topics:** Production economics

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**Abstract:**

Policy makers in Vietnam face difficult choices when deciding reservoir water management strategies between irrigation and fisheries. In this paper, an economic optimization model for water management is developed to facilitate policy makers' decision making. The model includes the response of rice and fish yields to key factors including reservoir water levels, the timing and quantity of water release, and climatic conditions. The model accounts for variation in rainfall patterns, irrigation requirements, and the demand for low water levels during the fish harvest season. The model is applied to the Daton reservoir in the south of Vietnam to maximize profits in each of three production scenarios where the reservoir's water is used for: (1) only producing rice, (2) only producing fish, and (3) producing rice and fish. Key findings are: (1) for rice production, adequate water should be released to meet rice water requirement and residual water should be stored as a source of water in the case of low rainfall; (2) for fish production, maximum water should be released prior to the fish harvest; (3) for rice and fish production, although water should be released prior to fish harvest, sufficient residual water must remain to satisfy the water requirements of rice in its remaining stages of growth. The model could be applied to other multiple-use resources such as forests, river basins, and land.

# 1 Introduction

Reservoir water is often used for several purposes such as hydroelectricity, irrigation, flood control, fisheries and recreation. Management of reservoirs to maximize their use benefits requires the amount of water to be released for each use to be specified at anytime. These water release decisions are often based on the amount of water available in the reservoir, the water requirements of the various uses, and the forecast weather conditions. As commonly observed in other cases of multiple-use resources, managing a multiple-use reservoir that attempts to achieve optimal water allocation for various uses often raises conflicts of interest (Nandalal & Simonovic 2003). Seasonal variations in water demand for these uses may also result in additional conflicts. These conflicts often centre on the quantity and timing of water distribution (Yoffe & Ward 1999).

In Vietnam, the dominant use of reservoirs is for hydroelectricity, irrigation, and flood control. However, reservoirs are also used to serve a number of secondary purposes such as the provision of drinking water, recreation, fisheries, and maintaining biodiversity. Managing reservoirs for the dominant uses often creates negative effects for the other uses; and the conflicts of interest may prevent the management of the reservoir from achieving maximum benefits. For example, to reduce the risk of low crop yields in times of drought, water is stored in reservoirs to act as buffer. However, maintaining these high levels of water in the reservoir may cause a reduction in fish yields as a result of lower fish harvest efficiencies (Tran et al. 2010). While the fish income may be a small proportion of all income derived from use of the reservoir's water, nonetheless these fish yields may play an important role in alleviating poverty and supplementing people's diet (Schilizzi 2003). For the poor people living around the reservoir whose income is mainly earned from this fish production, water storage for rice production may be problematic.

Accompanying the recent increases in the number of reservoirs in Vietnam, has been the need for policy makers to resolve problems related to the size and operations of these reservoirs. Reducing conflicts of interest in water use require reservoir operation policies to be refined and improved. The aim of this study is not to attempt to solve all these conflicts, but illustrate an approach to how the operations of a reservoir and its water release policies can be evaluated and modified. This illustration may serve as a template for how the management of other reservoirs could be assessed and improved.

Within the context of multiple-use resource management, the present study outlines the construction of a model of reservoir water management for two conflicting uses: irrigation and fisheries. The following questions are addressed: (1) What is the optimal strategy to manage a reservoir for either single or multiple -use? (2) How do these optimal management strategies respond to the variations in product prices? (3) What is the likely impact of weather conditions on these strategies?

To maximize the benefits from water use, reservoirs are often operated using a set of rules that specify the amount of water to be stored and released (Jain & Singh 2003). These operating rules are established in accordance with the water available in the reservoir, the inflows, and the demands for water. Traditionally, rule curves and storage allocation zone approaches have been the dominant tools used to develop operating rules (Nandalal & Bogardi 2007). However, these tools are often defined using historical operating practice and experience, and reservoir managers have little time to adjust water releases to reach the water levels specified by these rules. Therefore, when managers face the risk of water shortage and/or other uncertainties the rules may not be followed. Greater flexibility in operating rules is required, particularly for large scale reservoir systems which present the managers with a large number of uncertainties.

In recent years, system analysis has overtaken rule curves and storage allocation zone approaches as the most appropriate approach to derive reservoir operating rules (Nandalal & Bogardi 2007). This approach has been popularly applied to the theory and management of reservoir problems (Wurbs 1991). The advantage of this approach is that, in addition to being used for deriving reservoir operating rules in the long and short term; it can also be used for planning or managing strategies. System analysis has been applied, in theory and practice, to a number of reservoir development and management issues, including understanding the stochastic nature of hydrology (inflows, rainfall, and evaporations), socio-economic aspects, and the institutional factors involved in reservoir management.

System analysis has been commonly used to model reservoir problems. For example, Yeh (1985) provided the state-of-the-art review of system analysis using mathematical techniques to model reservoir problems. Similarly, Wurbs et al (1985) and Wurbs (1991) reviewed and provided an annotated bibliography of system analysis applied to model reservoir operation. More recently, Labadie (2004) and Rani & Moreira (2010) undertook a comprehensive review of system analysis techniques applied to reservoir operation problems. They concluded that simulation and optimization are two useful techniques to deal with reservoir problems.

Simulation has been popularly applied by reservoir management institutes/agencies to a wide range of reservoir problems such as sizing reservoirs, establishing new reservoir operation rules, and modifying operation policies for existing reservoirs. This technique is well suited to predicting reservoir system behavior under given conditions. However, while it is appropriate for evaluating and analyzing the economic performance of a large-scale reservoir system (Wurbs 1993), it is not appropriate for determining the optimal solution for reservoir operation. Even when numerous runs of a model are made with a given set of possible alternatives, this technique can only propose a near optimal solution (Jain & Singh 2003; Wurbs et al. 1985). In addition, the technique needs to account for a large number of feasible combinations of parameters in a model and therefore often requires a large amount of time to compute the near optimal solution (Wurbs 1993).

In contrast to simulation which is commonly applied in practice, optimization has been attractive to academics and some researchers. Optimization technique can be applied to decisions made in the planning and operating of a reservoir. Using optimization, reservoir problems can be formulated in terms of mathematical programming using decision variables, objective function and relevant constraints. The optimal solution defines the values of the decision variables that will maximize or minimize the objective functions. Linear programming (LP), non-linear programming (NLP), and dynamic programming (DP) are three mathematical techniques commonly applied to reservoir operation problems.

Linear programming is the most popular technique applied to reservoir problems, particularly large-scale reservoir systems (Labadie 2004). The advantages of this technique are that it is applicable to a wide variety of types of reservoir problems and the solution structure is well suited to general LP computer programs (Rani & Moreira 2010). However, the requirements of LP formulation, in terms of linear objective functions and linear constraints, have limited its application. In addition, the stochastic nature of the hydrological relationships involved in reservoir problems cannot be easily accommodated in LP.

Several limitations of LP can be overcome by the application of NLP. Non-linear programming provides a more general mathematical formulation for reservoir problems and can also accommodate the non-linear characteristics of hydrological relationship. However, NLP has not been commonly applied to reservoir problem because of the large number of calculations involved in the algorithm, and the subsequent large amount of computer storage and time required to solve the problems (Jain & Singh 2003). Furthermore, it is very complicated and difficult to incorporate into NLP the stochastic nature of hydrological relationships.

Dynamic programming has been proven to be one of the most appropriate techniques for dealing with reservoir problems (Nandalal & Bogardi 2007). The formulation of this technique is flexible and applicable to the important features of reservoir problems. First, by breaking down a problem into a sequence of stages, DP can accommodate very complex problems. On this basis, it can deal with time-sequential decision problems such as defining the optimal operation policies for a reservoir. Second, it can accommodate non-linear relationships and the stochastic nature of hydrological relationships in a model. Finally, DP is well suited to solve "stock effects" problems that are often involved in reservoir operations.

The application of DP to reservoir operation, particularly to irrigation, has been investigated by several authors (Dudley 1971a; Dudley 1971b; Vedula & Mujumdar 1992; Reca et al. 2001a; Reca et al. 2001b; Abdallah et al. 2003). In their studies reservoir release policies were based on crop water demand also known as crop evapotranspiration. While soil moisture balance equations were often employed to calculate crop water demand, the application of these equations significantly increased the complexity without producing reliable irrigation strategies (Paudyal & Manguerra 1990). In addition, calculating crop water demand by this way was not very applicable to irrigation decisions where the reservoir managers needed to know how much water should be released based on (1) the actual water demand in the field, (ii) the actual water supplied, (iii) the available water in the reservoir and (iv) the demands of other uses.

In the present study, a stochastic DP (SDP) model is developed for reservoir water management for irrigation and fisheries that takes into considerations the limitations mentioned above. The model builds on previous work (Tran et al. 2010) which outlines the development of a SDP model for reservoir water management. Tran et al.'s model includes eight stages, one state variable (the amount of water availability in the reservoir at the beginning of each stage), and one decision variable (the amount of water released at each stage). The objective function is to maximize the expected net present value (ENPV) of net changes in total income when there are water release changes.

By considering the net changes in total income, this model implicitly assumes that the total production cost does not affect the objective function. In addition, the model assumes that reservoir inflows do not affect reservoir operation policies, as these inflows were subsequently ignored in the state transition equation. In the present study, we revise and extend Tran et al.'s model to define optimal strategies for reservoir management. In particular, stochastic inflows and total production costs are considered in the model. Other elements, such as the stages, state variable and decision variable, remain unchanged.

# 2 A dynamic optimization model for reservoir water management

## 2.1 Water release and the returns of rice and fish

The profits obtained from rice and fish production depend on the timing and quantity of water released from reservoirs. For rice production, the amount of water to be released determines the rice yield. The rice crop achieves its potential yield if the release satisfies the water requirements of the rice during its growth periods. Any water deficits result in profit losses. For fish production, when there is less water in the reservoir the concentration of fish is higher and it is cheaper and easier to harvest fish. Therefore, increases in water release result in profit gains.

### 2.1.1 Rice profit function

To account for the response of rice yield to applied irrigation, a water production function (Rao et al. 1988) was adapted from the method proposed by Paudyal & Manguerra (1990).

$$Y_r = Y_p \left( 1 - \sum_{n=1}^{N} ky_n \left( 1 - \frac{W}{W_0} \right)_n \right) \quad (1)$$

where $Y_r$ is the rice yield (ton/ha); $Y_p$ is the potential yield of rice (ton/ha); $ky_n$ is the yield response factor at stage $n$; $N$ is the number of rice growing periods; $W_0$ is the rice water requirements measured in percentage of reservoir capacity (%RC); and

$$W_n = u_n + q_n \quad (2)$$

where $W_n$ is total water supply at stage $n$, including the water release ($u_n$) and rainfall ($q_n$); all are measured in %RC.

The profit obtained from rice productions in stage $n$ is defined as:

$$V_{rn} = P_r Y_r - C_r \quad (3)$$

where $P_r$ is the price of rice measured in million Vietnamese Dong[5] (mVND) per ton; $C_r$ is the total rice production cost at stage $n$ (mVND)

### 2.1.2 Fish profit function

Fish yields harvested at each stage are estimated using a bio-economic model for reservoir aquaculture (Truong & Schilizzi 2010)

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1 $A = 20,000 Vietnamese Dong (price in January 2011)

$$Y_f = \sum_{n=4}^{N-1}\sum_{j=1}^{\beta}(Y_{f_{nj}} P_{f_{nj}}) \quad (4)$$

where $Y_f$ is the fish yield harvested at stage $n$ (tonnes); $Y_{f_{nj}}$ is the weight of fish $j$ harvested at stage $n$ (tonnes); $P_{f_{nj}}$ is the price of fish $j$ harvested at stage $n$ (mVND/ton); $\beta$ is the number of fish species.

To measure fish yields harvested in response to the fluctuation of reservoir water levels, the physical concentration effect (PCE) coefficient (Tran et al. 2010) is used.

$$PCE_n = \left(\lambda\theta\omega A_0^{(\theta+1)} s_t^{(\lambda\theta-1)}\right)\left(\frac{s_t}{Y_f}\right)(\%\Delta s) \quad (5)$$

where $\lambda$ is the parameter obtained from the reservoir hypsographic curves; $\theta$ and ω are the parameters obtained from Nguyen et al (2001) which indicate the relationship between fish yields and reservoir surface area; $A_0$ is the reservoir surface area at full level of water (ha); $s_t$ is reservoir water level at the harvest stage (%RC)

$$s_t = \frac{s_n + s_{n+1}}{2} \quad (6)$$

where $s_n$ and $s_{n+1}$ are water levels at the beginning of fish harvest at stage $n$ and $(n+1)$ (%RC)

$$s_{n+1} = s_n - u_n - e_n + q_n + i_n \quad (7)$$

where $u_n$ 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. $i_n$ is defined as follows:

$$i_n = q_n Rc \quad (8)$$

where $Rc$ is reservoir catchment area ($km^2$)

*%Δs is* the percentage change in water levels in each harvest stage compared with full reservoir

$$\%\Delta s = \frac{s_t - s_{\max}}{s_{\max}} \tag{9}$$

where $s_{\max}$ is the maximum reservoir capacity (%RC)

The profit obtained from fish productions at stage *n* is defined as:

$$V_f = Y_f\left(1 + PCE_n\right) - C_f \tag{10}$$

where $V_f$ is the fishery profit (mVND); $C_f$ is the total cost of fish production at stage *n* (mVND)

## 2.2 The objective function of SDP model

Total profit generated by the system at stage *n*, ($V_n$), is defined as:

$$V_n\{s_n,u_n,q_n,i_n\} = V_{rn}\{s_n,u_n,q_n\} + V_{fn}\{s_n,u_n,q_n,i_n\} \tag{11}$$

where $V_{rn}\{s_n,u_n,q_n\}$ and $V_{fn}\{s_n,u_n,q_n,i_n\}$are the profits obtained from rice and fish production at stage *n*, respectively. Total profits $V_n\{s_n,u_n,q_n,i_n\}$ is the function of reservoir water levels at the beginning each stage ($s_n$), water release ($u_n$), rainfall ($q_n$), and reservoir inflows ($i_n$).

## 2.3 State transition

The state transition is defined as:

$$s_{n+1} = s_n - u_n - e_n + q_n + i_n \tag{12}$$

## 2.4 Economic optimization

The model finds a sequence of water releases ($u_n$) that maximizes the ENPV of the profits generated from the system. The optimization problem for an *N*-stage planning horizon is as follows:

$$V_n\{s_n\} = \underset{u_n}{Max}\left[E\left[\sum_{k=1}^{m} p_n\{q_n^k\}\left(V_n\{s_n, u_n, q_n^k, i_n^k\} + \alpha V_{n+1}\{s_n, u_n, q_n^k, i_n^k\}\right)\right]\right] \tag{13}$$

*(n=N,……,1)*

$$\sum_{k=1}^{m} p_n\{q_n^k\} = 1 \tag{14}$$

Where $V_n\{s_n\}$ is total the profit generated by the system at stage $n$; $E$ is the mathematical expectation operator; $p_n\{q_n^k\}$ is the probability that rainfall at stage $n$ $(q_n)$ takes the *k-th* value in a domain which is limited to $m$ values; $\alpha$ is the discount factor $(1+r)^{-1}$ for the given discount rate $r$ (%/stage); and $V_{n+1}$ is the total profit generated by the system at stage $(n+1)$.

Equation (13) is solved subject to state transition equation (12) and the following constraints:

$$s_{min} <= s_n <= s_{max} \tag{15}$$

$$u_{min} <= u_n <= u_{max} \tag{16}$$

$$u_n <= s_n \tag{17}$$

$$((u_n + q_n^k)/W_0) <= 1 \tag{18}$$

$$V^*\{s_n, u_n, q_n^k, i_n^k\} = 0 \tag{19}$$

Where $s_{max}$ and $s_{min}$ are the maximum and minimum reservoir capacity (%RC); $u_{min}$ and $u_{max}$ are the minimum and maximum release (%RC); $V^*$ is value function at the terminal stage.

Equation (13) shows that the stage profits $(V_n)$ are affected by reservoir water levels, water release, and rainfall in stage n. The recursive solution is executed from $n = N$ to $n = 1$ subject to the state transition equation (12).

A solution for this system for a range of values of the state variable from $s_{min}$ to $s_{max}$ yields optimal decision rules. These rules are used to retrieve the optimal release path for any given initial state, expected rainfall, evaporation and expected inflows. Following the optimal release path, the amount of water to be released at each stage is specified so that the maximum ENPV generated by the system can be determined.

## 3 Case study

A case study of the Daton reservoir in the South of Vietnam is presented in this section. This is a multiple-use reservoir where its water capacity is much greater than the irrigation requirements. This case study shows how the SDP model developed can be applied to determine the optimal strategies for managing the reservoir for either single-use or multiple-uses.

Construction of the Daton reservoir began in 1987 and was completed in 1989. The reservoir is located in Dong Nai province in the southeast region of Vietnam, and is about 150 km from Ho Chi Minh City. The reservoir has a surface area of more than 350 hectares and reaches a maximum depth of 20 metres. Its maximum capacity is 19.6 million cubic metres (MCM) and its minimum capacity is 0.4 MCM. The reservoir is replenished by rainfall and inflows during the wet season (from July to November) and water is regularly released for irrigation during the dry season (from December to June). Water availability in the reservoir varies throughout year depending on the rainfall and the amount of water released for irrigation.

Daton reservoir water is used predominantly for irrigating two consecutive rice crops of approximately 1000 hectares each. These crops are cultivated during the dry season and each crop is about 100 days long. The first crop is grown from December to March and the second crop extends from April to July. These two crops must be irrigated during the period from December to June because of low rainfall at this time of year. To avoid crop water deficits that may occur if rainfall is late or if there has been drought, as much water as possible is maintained in the reservoir.

Since 2000, the reservoir has also been used by the Daton Aquaculture Cooperative for fish production. The reservoir fishery operates on an annual cycle. Stocking the fingerlings into the reservoir 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 silver carp and mrigal make up 40%-50% of the stocked fingerlings (Nguyen et al. 2001). Harvesting of fish occurs when the reservoir water is at low levels, often from February to May. However, at this time of a year, water is often stored for irrigation purposes.

As commonly observed in many Vietnamese reservoirs, the purpose of using the Daton reservoir for fish production is to help the people living around the reservoir to earn an income. Most of these people were displaced from their land when the reservoir was constructed. However, provincial government regulations stipulate that the use of the reservoir for fisheries must not interfere with the use of the reservoir for irrigation. Therefore, although reservoir fisheries are an important source of income for the people disadvantaged by the reservoir construction, there are a number of conflicts of interest between irrigation and fisheries in the relative use of the water (Tran et al. 2010). To manage the reservoir for both irrigation and fisheries, there is a need to define a water release strategy that is able to maximize the profits generated by the system.

## 3.1 Data

The model is validated for the Daton reservoir using input data gathered by the survey of rice and fish production at the reservoir. All costs and income are measured mVND. All hydrological parameters were initially measured in millimetres (mm). In the model they are converted into %RC, which allows the model to be applied to different reservoirs.

During a three-month fieldtrip to the reservoir from January to March 2009 this data was collected, including climatic and hydrologic data, rice and fish production data, and economic data. Primary data was obtained by surveying rice and fish farmers. The Board of the Daton Aquaculture Cooperative and a sample of 80 rice farmers in the area surrounding the reservoir were interviewed. All rice and fish production data was collected for the 2008 production year. Secondary data was collected from the Daton irrigation branch, local authority, and the Sub-Institute of Hydrometeorology and Environment of South Vietnam (SHESV).

## Climatic and hydrologic data

Climatic data of the area was collected from the local irrigation branch and the SHESV including an eight-year period of daily rainfall from 2000 to 2008. This data was used to calculate the amount of water replenishing the reservoir, inflows of the reservoir, and the amount water that the rice fields received from rainfall. The average rainfall in each stage is shown in Appendix 5. A thirty-year period of monthly climatic data for the research area, from 1976 to 2006, including rainfall, evaporation, wind speed and hours of sunshine was obtained from the SHESV. This monthly data was used to calculate the rice water requirements.

Hydrologic data of the reservoir from 2000- 2008 was obtained from the local irrigation branch, including daily observations of water levels, reservoir capacity, and releases. The relationship between reservoir capacity and reservoir surface areas and the relationship between reservoir surface areas and water levels were determined using the hypsographic curves provided by local irrigation branch. These relationships were used to calculate the PCE on fish yields.

## Rice and fish production data

A seasonal calendar for rice production and the actual cultivated area of rice were obtained from the 2000-2008 annual reports of the local authority. The potential yields of rice, obtained from the survey in the research area over this eight-year period, were considered to be the maximum value of the historical yields. Rice water requirements and extra irrigation amounts were calculated using the Cropwat model  (Swennenhuis 2006), a computer program for calculating crop water requirements and irrigation requirements, using crop data and given climatic conditions.

The BRAVO model (Truong & Schilizzi 2010) was employed to estimate fish yields at the Daton reservoir. All input data required for this model, including date of stocking the fingerlings, fish harvest periods, and fish productions costs were obtained from the 2000-2008 annual reports of the Daton cooperatives.

### Economic data

The average cost and return per hectare for rice production used in the case study was obtained from the survey. The average production cost includes seeding, weeding, fertilizing, chemical, labor, and harvesting costs. The average cost per hectare for the first and second rice crop was mVND 8.82 and 6.72, respectively. The returns from the two rice production seasons were estimated by multiplying the price of rice by the rice yield obtained from the dated-water production function. Total returns and costs for the cultivated area were estimated by multiplying these average values by the cultivated areas. Total fish production cost was mVND 615 (from the 2008 annual report of the Daton cooperative).

## 3.2 Results and discussion

The optimal water management strategy for the Daton reservoir is analyzed in three scenarios. These scenarios are the water management for maximum profits: firstly solely from rice production (Scenario 1), secondly solely from fish production (Scenario 2), and thirdly for both rice and fish production (Scenario 3). It is assumed that if the reservoir is managed for rice production, there is no fisheries and *vice versa*. If the reservoir is used for rice production, as much water as possible will be retained in the reservoir in case of drought; consequently, water will be at very high levels during the fish harvest season. This results in a very low fish yield and may cause net loss. This risk will prevent fish famers from operating fisheries in the reservoir. In contrast, if water is used for fish production, the reservoir will have its lowest water levels early. This may cause a water deficit for rice crops and may reduce rice yield. As a result, rice farmers may not cultivate rice crops because of the risk of low rice profit. This is a reasonable assumption for the reservoirs in the south of Vietnam where storing water for the dominant use of rice often causes a net loss in fish production.

The optimal release strategies of three scenarios, calculated for a range of the initial water levels from 10%RC-100%RC, are illustrated using three representative initial water levels: 100%RC, 70%RC and 50%RC. Policy implications are also discussed for either single-use (Scenario 1, 2) or multiple-uses (Scenario 3). The ‘break event point’ (BEP) between two single-use scenarios

(Scenario 1, 2) is found; and the maximum irrigated area for the multiple-use (Scenario 3) is outlined.

**Scenario 1**

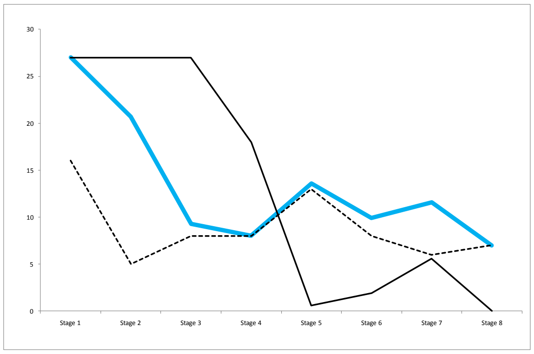
The optimal strategy for the single-use of rice production (Scenario 1) indicated that adequate water (Figure 1 a, c, e) should be released to meet the rice water requirements to achieve maximum yields. The optimal release path (16, 5, 8, 8, 13, 8, 6, and 7 %RC for stages 1-8, respectively) is unchanged in response to different initial water levels ranging from 100%RC - 70%RC. This is because this range of water is always sufficient to satisfy rice water requirements. Supplying sufficient water to rice always results in the maximum ENPV being obtained from rice production (Figure 2). The optimal storage (Figure 1 b, d, f) requires residual water to be stored as a source of water for use as additional irrigation in case of low rainfall. Because the reservoir capacity is much greater than irrigation requirements, for any initial water level (100%RC to 70%RC) the reservoir management strategy always retains high levels of water at stage 8.

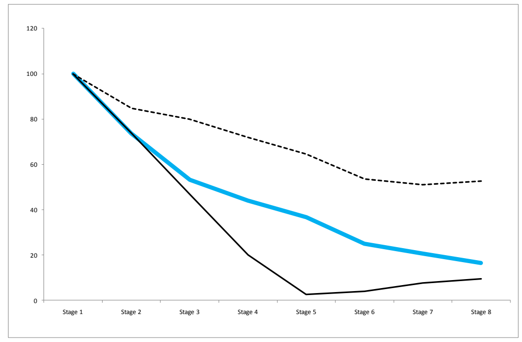
**Scenario 2**

The optimal strategy for solely producing fish (Scenario 2) is presented in Figure 1 (a, c, e). For any initial reservoir water level, maximum amount of water should be released from stage1- 4 (prior to fish harvest). This brings the reservoir to low water levels to increase fish concentration that facilitates the harvest of fish and achieves maximum yield of fish. For example, when the initial water levels are at 100%RC the optimal releases were the maximum (27%RC) from stage 1-3 and 18%RC at stage 4. This brought the reservoir to its lowest level (approximately 2%RC) at stage 5 (Figure 1b). The maximum ENPV obtained from these releases was mVND 2505.8 (Figure 2). Although maximum releases were made from stage 1-3, the maximum ENPV obtained from the initial water level at 100%RC was lower than those ENPV obtained from the initial water levels were at 70%RC and 50%RC (Figure 2). This is because when the initial water levels at 70%RC and 50%RC the lowest water levels occurred earlier in stage 4 and stage 3, respectively (Figure 1 d, f) instead of later in stage 5 (Figure 1b); and therefore fish were harvested at higher yields. For any initial water level, the optimal release strategy always results in low water levels during the fish harvest season from stage 4 to stage 7 (Figure 1 b, d, f).

**Scenario 3**

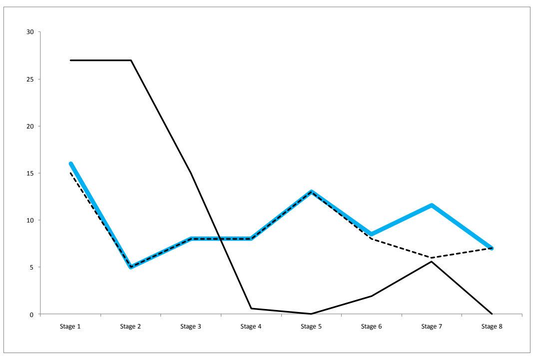
Modeling was also applied to the Daton reservoir to determine the optimum strategy for reservoir management when the water is required for both the irrigation of rice and the production of fish (Scenario 3). The optimal strategy is different depending on the initial water levels. In the case where the initial water level is from 100%RC to 80%RC, maximum release can be made from stage 1-4 for fish production subject to satisfying rice water requirements at any stage. For example, Figure 1a indicates that when the initial water level is at 100%RC maximum water is released from stage 1 to stage 4 (27, 20.7, 9.3, and 8 %RC) to bring the reservoir to low water levels prior to the fish harvest season and also to satisfy the minimum water demands for rice production. These releases are lower than or equal to the releases for fish production alone (Scenario 2) and higher than the releases for rice production; this is because water must be retained to satisfy the high demand for water for rice production at stage 5-8. In the other case when the initial water level is lower than 70%RC, the release policy gave priority to rice production regardless of the demand for water release for fish harvest. As rice contributes approximately 85% to the total profits derived from the reservoir's water use, insufficient irrigation for rice crops is likely to cause a reduction in rice yield and a significant loss in total profits. For example, when the initial water level is at 70%RC, the optimal releases are made just equal or slightly higher than the rice water requirement during the irrigation season (Figure 1e).

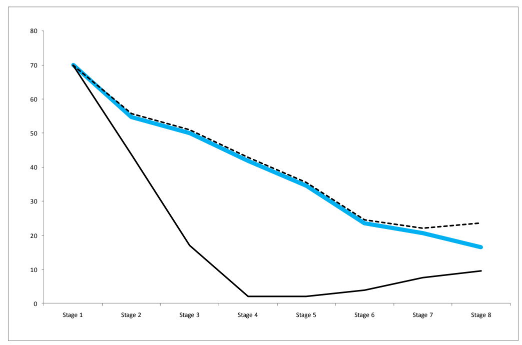



(a) (b)

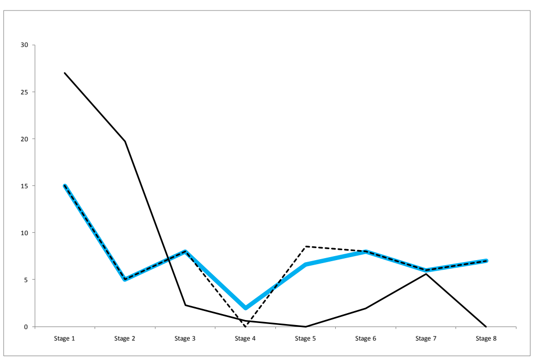
The initial water level at 100%RC

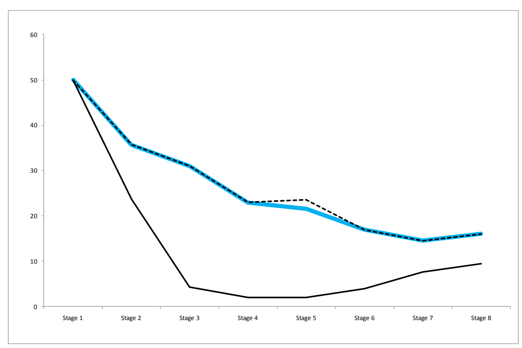



(c) (d)

The initial water level at 70%RC




(e) (f)

The initial water level at 50%RC

Figure 1 The optimal release (%RC) (a,c,e) and the optimal storage (%RC) (b,d,f) for the Daton reservoir used for Scenario 1-Rice (..........); Scenario 2-Fish (———); Scenario 3- Rice and Fish (━━━━)

The maximum ENPV obtained from each of three scenarios was calculated for the initial water levels ranging from 20%RC to 100%RC. For single-use fish production (Scenario 2) the maximum ENPV shows an inverse relationship to the initial water levels (Figure 2). In particular, fish profits increased substantially when the initial water levels decrease from 100%RC to 80%RC. The ENPV peaks when the initial water level is at 50%RC. This is because when initial water levels is lower than or equal to 50%RC, the optimal release for fish production results in the lowest water levels which coincide with the beginning of the fish harvest season (Figure 1d, f). For Scenarios 1 and 3, where profits are largely determined by rice productions, the maximum ENPVs are obtained when the initial water levels ranged from 100%RC to 70%RC. When the initial water levels are lower than 70%RC these ENPVs significantly decline due to insufficient water to irrigate rice.

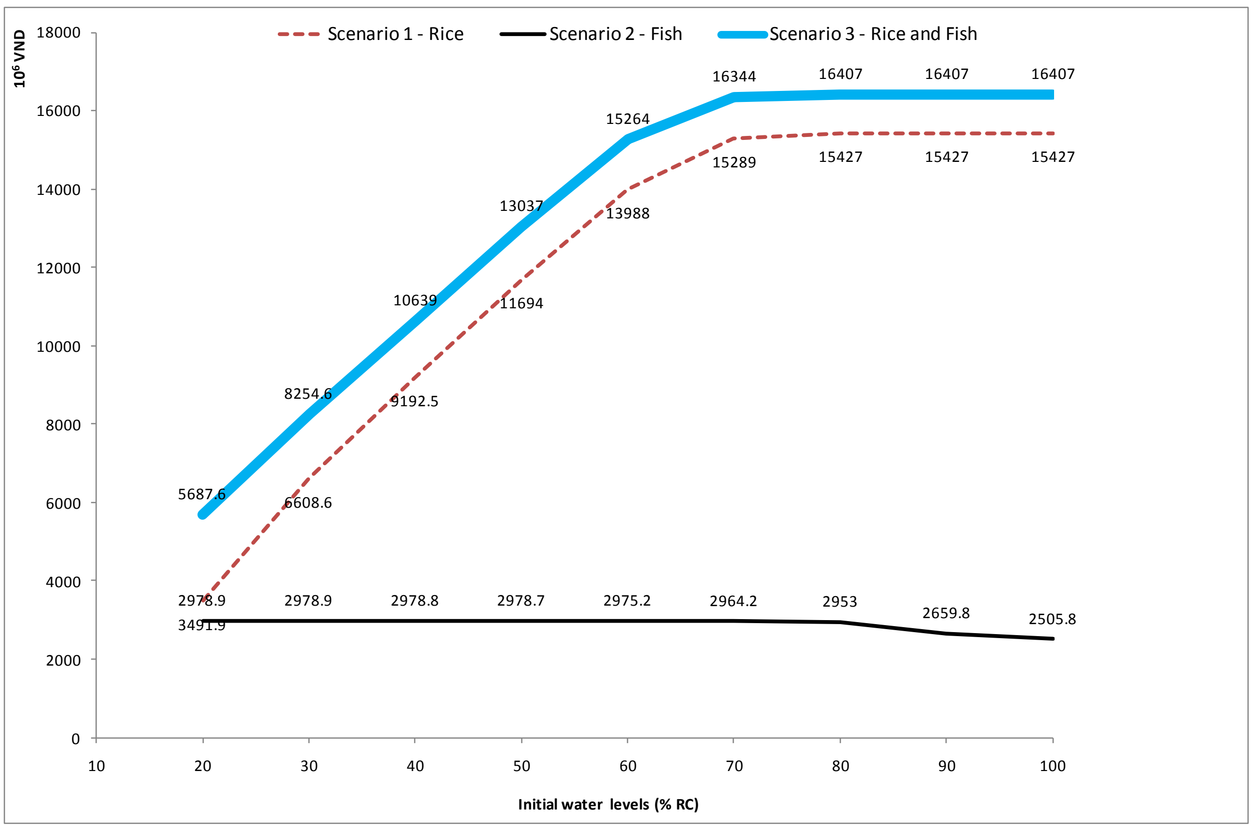



Figure 2 The ENPV (mVND) obtained from three scenarios. Data is showed at the initial water levels ranging from 20%RC-100%RC

Of the three scenarios, the multiple-use management (Scenario 3) which optimizes water use for rice and fish production produces the highest ENPV. However, this ENPV is smaller than the sum of the maximum ENPV obtained from the two single-use operations: rice production (Scenario 1) and fish production (Scenario 2) (Figure 2).

For multiple-use resource management, the results obtained from the present study are similar to those found by Klemperer (1996) in managing public forestland. Klemperer concluded that policy makers cannot optimize the use of multiple-use resources by maximizing each individual use; they should instead aim at maximizing the value obtained from the system by optimizing the combined output levels.

Besides examining the impact of the initial water levels on the maximum ENPV obtained from the three strategies, the impact of weather conditions was also analyzed (see Table 1). For reservoir initial water level at 100%RC, changes in weather conditions did not affect the optimal release strategy for rice production. As the water capacity of the Daton reservoir is much greater than the irrigation requirements, there is always sufficient water available in the reservoir to satisfy water requirements of rice even when the weather is very dry, or the initial water level is low (e.g. lower than 50%RC). Weather conditions are more likely to affect the optimal management strategy of a reservoir for rice production where its maximum capacity is smaller than or equal to the irrigation requirements. For fish, and rice and fish production, the releases in a wet year are likely higher than or equal to the release in a dry year. In a wet year, reservoir water inflows and rainfall are high; and reservoir water levels during the fish harvest season are often higher than in the dry season. This requires increases in the release to make fish more concentrated.

Table 1 Comparing the optimal release obtained from three scenarios in the dry and the wet year-outcomes are shown for initial water levels at 100%RC

| Scenarios | The optimal release (%RC) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 | Stage 7 | Stage 8 |
| 1. Rice | | | | | | | | |
| Dry year | 16.0 | 5.0 | 8.0 | 8.0 | 13.0 | 8.0 | 6.0 | 7.0 |
| Wet year | 16.0 | 5.0 | 8.0 | 8.0 | 13.0 | 8.0 | 6.0 | 7.0 |
| 2. Fish | | | | | | | | |
| Dry year | 27.0 | 27.0 | 27.0 | 17.1 | 1.7 | 0.0 | 11.4 | 0.0 |
| Wet year | 27.0 | 27.0 | 27.0 | 17.9 | 2.2 | 0.4 | 16.0 | 0.0 |
| 3. Rice and Fish | | | | | | | | |
| Dry year | 27.0 | 20.4 | 8.9 | 8.0 | 13.0 | 9.6 | 17.4 | 7.0 |
| Wet year | 27.0 | 21.2 | 8.9 | 8.0 | 15.0 | 8.4 | 22.0 | 7.0 |

Although the optimal releases for fish and rice and fish produciton in a wet year are found to be higher than in a dry year, they are not very big different. This results in no difference in the ENPV between the dry year and the wet year.

For single-use management, water use for rice production is more lucrative than for fish. Although the ENPV obtained from fish production is smaller, it will increase if fish prices[6] and fish harvest efficiency increase. As a result of these increases, if they are sufficiently large, then water use for fish production may be considered as the best choice. In the case where fish prices increase, the policy makers need to be aware of BEP between fish and rice production if they wish to maximize the profits generated from the reservoir. The BEP is a point where the choice of managing water for rice or for fish results in an equal ENPV. Figure 3 indicates that the BEP occurs when the prices of fish increase approximately 5.5 times. Such a massive and sustained increase in the price of fish is highly unlikely. Hence, the preferable use of the water for rice production is destined to continue.

[6] Fish prices $P_f$ is a vector (1x5) including prices of 5 fish species (see Appendix 2)

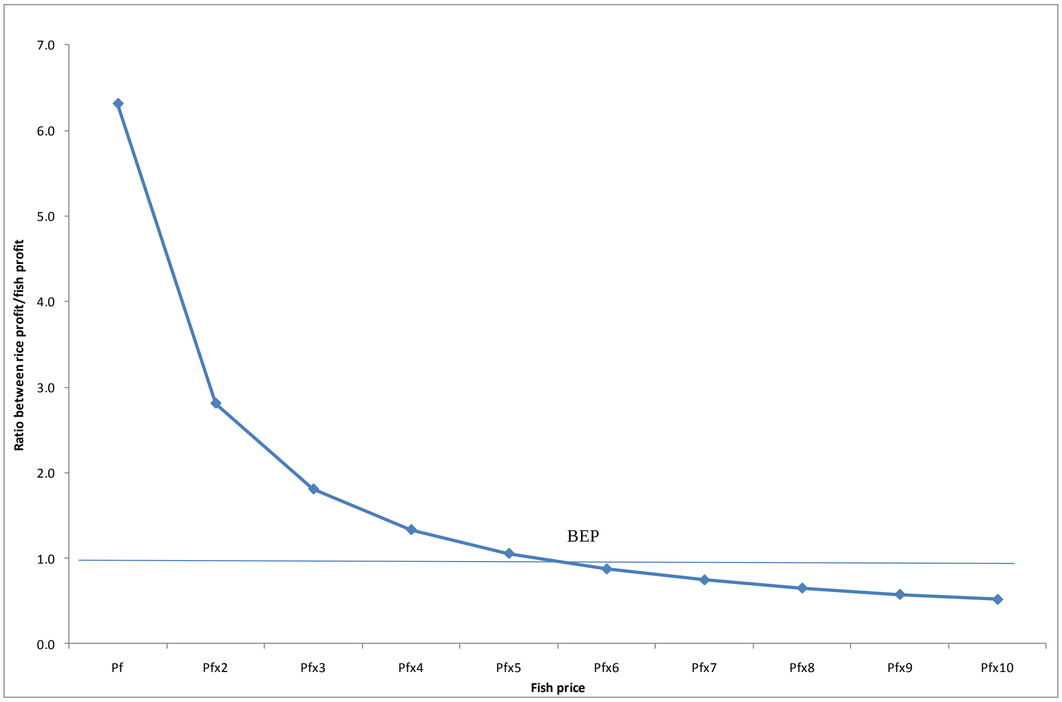



Figure 3 Break event point between rice and fish production. Data is shown at 100%RC and expected rainfall

Table 2 Comparing the outcomes of three scenarios. Outcomes are shown only for the initial water level at 100%RC using expected rainfall

| Scenarios | Maximum ENPV (mVND) | Total amount of water release (MCM) |
|---|---|---|
| Scenario 1-Rice | 15,427 | 13.9 |
| Scenario 2-Fish | 2,505 | 21 |
| Scenario 3-Rice & Fish | 16,407 | 21 |
| + Rice | 15,427 | 13.9 |
| + Fish | 980 | 7.1 |

Multiple-use management (Scenario 3) not only produces the highest ENPV but also generates benefits for the use of rice and fish (Table 2). However, the additional releases for harvesting fish (7.1 MCM) are useless for irrigation as the rice water requirements are already satisfied. This implies that when the reservoir is managed simultaneously for rice and fish, the ENPV may be further increased if extensions of the cultivated area are considered. These extensions require increases in water releases for rice and also bring the reservoir to the low water level in the fish harvest season. This will enhance the fish harvest yield. Figure 4 indicates that if the reservoir is full (100%RC) at the beginning of the irrigation season, the maximum irrigated area can be extended to 2,000 hectares to achieve the maximum ENPV at mVND 24,968. The irrigated area can be extended to 1,600 hectares when the initial water level is at 70%RC.

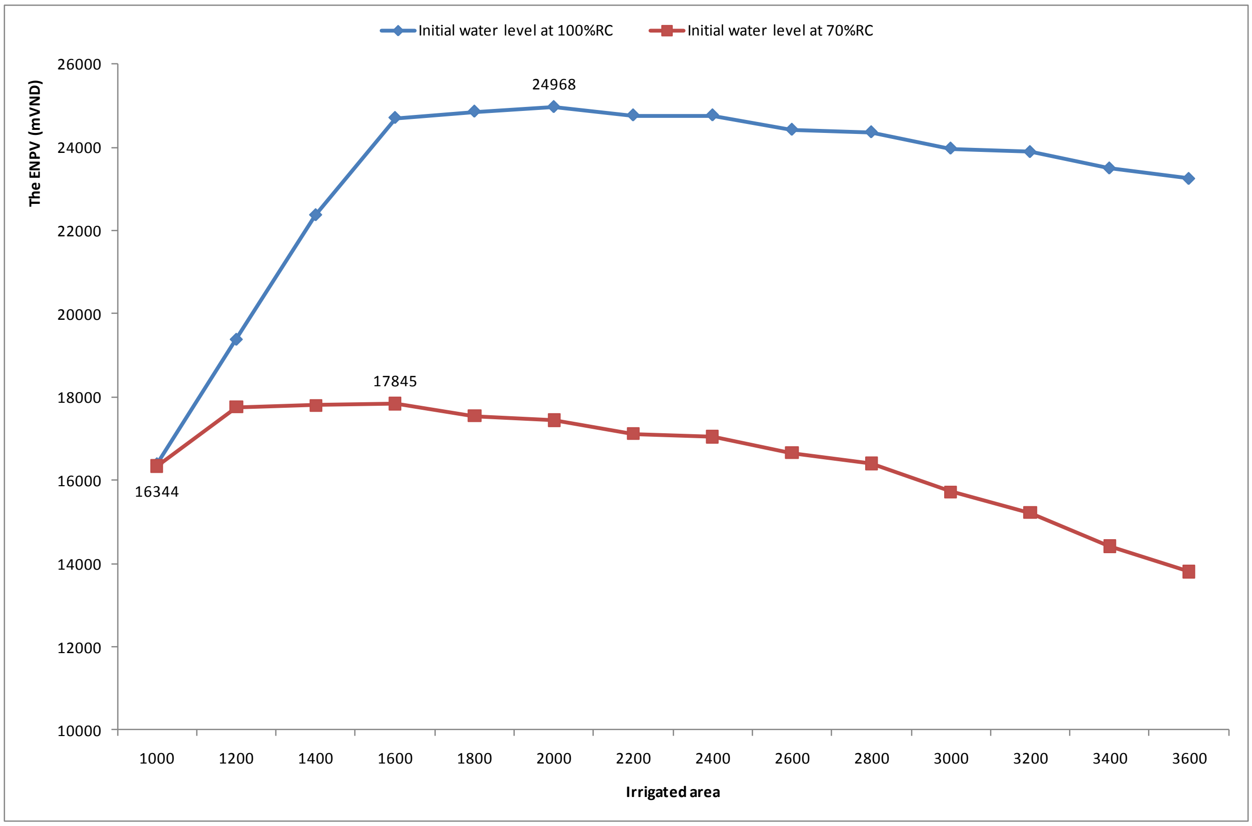



Figure 4 Variation of the ENPV (Scenario 3) corresponding to the extensions of irrigated area

## 4 Conclusions

An optimization model is used to determine the optimal management strategy for use of reservoir water for either sole production of rice or fish, or their joint production. The impacts of the initial water levels on the strategies for managing the reservoir's water are examined. For any initial water level from 100%RC to 70%RC, the optimal releases for rice production remain unchanged. For fish production, at any initial water level maximum releases should be made prior to fish harvest season. For rice and fish production, when initial water level is higher (e.g. 100%RC to 80%RC) maximum release can be made prior to fish harvest season but the residual water should be store to satisfy the demands for rice in its growth stages. Conversely, when initial water level is low (e.g. lower than 70%RC), the release policy gives priority to rice production regardless of the demand for water release for fish harvest.

The affects of weather conditions on the optimal release strategy and the profits obtained from the system are also examined. Although weather conditions do not affect the expected net present value (ENPV) of profits from rice, fish, and rice and fish production, they do affect the optimal release strategies of the reservoir, when the reservoir is used solely for fish, or for both rice and fish.

Managing the reservoir solely for fish production generates the smallest ENPV, and it is unlikely to ever be chosen as best option for use of reservoir's water when compared against rice production. The break event price for fish, that makes managing the reservoir for fish production as profitable as for rice production, is 5.5 times the usual price of fish.

The results of this study suggest that when constructing a new reservoir, the relationship between the irrigated area and reservoir capacity should be determined in order to maximize the ENPV. For existing reservoirs where the irrigation requirements are greater than their maximum capacity, switching the irrigated crops area to dry crops area can be considered. Conversely, where reservoirs have a maximum capacity far greater than the irrigation crop area's requirements, then enlargement of the irrigated area should be extended.

Overall, the results of this study show that the SDP model developed here can facilitate reservoir management and could potentially be applied to other reservoirs in the south of Vietnam to facilitate there management. The modeling approach could even be employed to develop optimal management strategies for other multiple-use resources other than reservoirs, such as forests, river basins, and land.

## Appendices

Appendix 1 Parameters used in the model

| Parameters | Unit | Value | Descriptions |
|---|---|---|---|
| $N$ | | 8 | Stages of SDP |
| $P_a$ | mVND/ton | 2.5 | The price of rice |
| $\beta$ | | 5 | Number of fish species |
| $A_0$ | ha | 350 | Reservoir surface area at full level of water |
| $Rc$ | $Km^2$ | 21 | Reservoir catchment area |
| $\lambda$ | | 0.5732 | Hypsographic coefficient |
| $\theta$ | | -0.7446 | Coefficient obtained from Nguyen et al (2001) |
| $\omega$ | | 0.7422 | Coefficient obtained from Nguyen et al (2001) |
| $s_{min}$ | MCM | 0.4 | Minimum reservoir capacity |
| $s_{max}$ | MCM | 19.6 | Maximum reservoir capacity |
| $u_{min}$ | %RC | 0 | Minimum release |
| $u_{max}$ | %RC | 27 | Maximum release |
| $r$ | %/stage | 0.05 | Discount rate |

Appendix 2 The prices and yields of fish

| Fish species | Price (mVND/ton) | Fish yields (ton) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 | Stage 7 | Stage 8 |
| 1 | 16 | 0 | 0 | 0 | 3.506 | 3.026 | 2.636 | 2.262 | 0 |
| 2 | 6 | 0 | 0 | 0 | 8.861 | 7.666 | 6.693 | 5.758 | 0 |
| 3 | 8.5 | 0 | 0 | 0 | 7.043 | 6.239 | 5.573 | 4.887 | 0 |
| 4 | 6 | 0 | 0 | 0 | 4.477 | 3.93 | 3.479 | 3.027 | 0 |
| 5 | 8.5 | 0 | 0 | 0 | 4.154 | 3.584 | 3.121 | 2.678 | 0 |

Appendix 3 The value of the potential yield of rice *($Y_p$)*; yield response factor *($k_y$)*; crop water requirements *($W_0$)*, and evaporation *($e_n$)*

| Parameter | Unit | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 | Stage 7 | Stage 8 |
|---|---|---|---|---|---|---|---|---|---|
| $Y_p$ | Ton/ha | 6.5 | 6.5 | 6.5 | 6.5 | 6 | 6 | 6 | 6 |
| $k_y$ | | 1 | 1.09 | 1.32 | 0.5 | 1 | 1.09 | 1.32 | 0.5 |
| $W_0$ | mm | 252.5 | 80.3 | 124.6 | 132.1 | 209 | 131.7 | 85.1 | 103.7 |
| $e_n$ | mm | 5.34 | 6.85 | 8.30 | 9.30 | 8.3 | 5.59 | 3.99 | 3.59 |

Appendix 4 Rainfall $q_n^k$ (m) and rainfall probability $p_n\{q_n^k\}$

| | Rainfall $q_n^k$ | Rainfall probability $p_n\{q_n^k\}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $k$ | (mm) | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 | Stage 7 | Stage 8 |
| 1 | 0 | 0.955 | 0.98 | 0.98 | 0.95 | 0.865 | 0.745 | 0.635 | 0.545 |
| 2 | 37.5 | 0 | 0 | 0 | 0 | 0.005 | 0.005 | 0.015 | 0.03 |
| 3 | 87.5 | 0.005 | 0 | 0.01 | 0 | 0.015 | 0.01 | 0.035 | 0 |
| 4 | 137.5 | 0 | 0 | 0.005 | 0.015 | 0.01 | 0.03 | 0.025 | 0.025 |
| 5 | 187.5 | 0.01 | 0.005 | 0 | 0 | 0.025 | 0.01 | 0.035 | 0.04 |
| 6 | 237.5 | 0.005 | 0 | 0.005 | 0 | 0.03 | 0.005 | 0.01 | 0.035 |
| 7 | 287.5 | 0 | 0 | 0 | 0.005 | 0.005 | 0.01 | 0.015 | 0.02 |
| 8 | 337.5 | 0 | 0 | 0 | 0.01 | 0 | 0.01 | 0.02 | 0.03 |
| 9 | 387.5 | 0.005 | 0 | 0 | 0.015 | 0.005 | 0.02 | 0.005 | 0.03 |
| 10 | 437.5 | 0.01 | 0.01 | 0 | 0 | 0 | 0.01 | 0.01 | 0.005 |
| 11 | 487.5 | 0 | 0.005 | 0 | 0 | 0.01 | 0.02 | 0.02 | 0.03 |
| 12 | 537.5 | 0 | 0 | 0 | 0.005 | 0 | 0.005 | 0.01 | 0.02 |
| 13 | 587.5 | 0.005 | 0 | 0 | 0 | 0.005 | 0.005 | 0.015 | 0.015 |
| 14 | 625.0 | 0.005 | 0 | 0 | 0 | 0.025 | 0.115 | 0.15 | 0.175 |

Appendix 5 Rainfall (mm) at the Daton reservoir (from 2000 to 2008)

| | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 | Stage 7 | Stage 8 |
|---|---|---|---|---|---|---|---|---|
| **Average** | 16.13 | 7.63 | 2.56 | 15.31 | 44.88 | 177.56 | 272.75 | 316.00 |
| **Min** | 0 | 0 | 0 | 0 | 7 | 48 | 57 | 64 |
| **Max** | 47 | 35 | 10.5 | 46.5 | 105 | 289 | 515 | 623 |

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