Incorporating CO_2 net flux in multipurpose reservoir water allocation optimization

J. Lopes de Almeida
Department of Civil Engineering, Coimbra University, Portugal

Abstract

Multipurpose hydropower plants play an important role in water resources management throughout the world. In many cases the water stored in the reservoir dam can be used for agricultural irrigation or for hydroelectricity production. From a planning point of view this conflicting, mutually exclusive, water use can be remedied by judicious water allocation. This can be computed by a decision model that maximizes global return from both electricity and agricultural production, as we showed in previous papers. However, the increasing importance of environmental constraints, especially CO_2 emission targets, demands new approaches in order to incorporate these aspects in the decision model. This paper describes a mathematical model that computes optimum water allocation taking into account the returns from hydroelectricity and agricultural production and also the corresponding CO_2 net fluxes, in order to achieve a sustainable multipurpose hydropower management. After formulation the problem is solved using nonlinear programming.
Keywords: multipurpose hydropower reservoir management optimization, irrigation, CO_2 net flux, nonlinear programming.

1 Introduction

Reservoir dams are hydraulic structures used pretty well all over the world. Their multipurpose character, combined with the natural scarcity of water resources, often leads to complex water management problems. This problem can arise when multipurpose reservoirs are committed to the two main tasks of agricultural irrigation, by diverting upstream water, and electricity production. From a sustainable planning point of view, water sharing should be established, taking into account both the revenue from the production activities and the

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environmental aspects. After the Kyoto Protocol [1], several signatory nations embarked on an extraordinary effort to reduce their CO_2 emissions to slow down global warming. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), released in Paris on 5th February 2007, pointed out that carbon dioxide is the most important anthropogenic greenhouse gas and that the global atmospheric concentration of carbon dioxide has increased 35% since the pre-industrial period.

It is known that hydroelectric power plants can help reduce CO_2 emissions by replacing fossil fuel electricity production. The CO_2 emitted during construction is a small fraction of the CO_2 savings during the lifetime of the hydroelectric power plant. This environmental importance of hydropower was recognized at the World Water Forum hosted by the World Water Council, 16-23 March 2003, in Japan. The Forum culminated in the ratification of a formal declaration, which includes a specific reference to hydropower: "We recognize the role of hydropower as one of the renewable and clean energy sources, and that its potential should be realized in an environmentally sustainable and socially equitable manner." In the Portuguese electricity system, D-L No. 33-A/2005 of 16th February states that for each kWh of independent hydroelectricity production 370 g of CO_2 is avoided.

The irrigation of farmland seems to be another way of reducing atmospheric CO_2, if suitable agricultural management practices are adopted. Extensive research is presently being done to evaluate the potential of sequestering carbon by increasing soil organic carbon (SOC) using appropriate agricultural management practices [2–4]. West and Marland [2] analysed the full carbon cycle in corn crops, computing the CO_2 emissions associated with agricultural activities, which included: tillage, seed production and application, planting, fertilizer production and application, herbicide production and application, and harvesting. The net carbon flux (NCF) was evaluated considering the carbon emitted into the atmosphere as a positive flux, while carbon sequestered from the atmosphere into the soil is represented as a negative flux. Several fertilizer application rates were considered as well as two tillage practices: conventional till and no-till. According to these authors [2] the conventional till continuous corn crop in Kentucky is a net contributor to the atmospheric CO_2 pool (positive NCF). However if conventional till is replaced by no-till (when only a narrow band of earth is disturbed where the seed is to be planted and fertilized) the NCF can become negative if adequate fertilization is used. If we disregard CO_2 emissions associated with farm construction (farm infrastructures last for decades and are very small compared to the extensive corn fields) we can compute the following indicative values of CO_2 sequestration in topsoil per kg of corn yield from [2]:

- CO_2 net flux to the atmosphere for conventional till with conventional fertilization rate : + 146 g of CO_2 per kg of corn yield;
- CO_2 net flux to the atmosphere for no-till with increased fertilization rate: - 53 g of CO_2 per kg of corn yield. This carbon sequestration can be expected to last from 20 to 50 year according to [3] and [5].

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We would like to stress that West and Marland [2] focused exclusively on CO_2 emissions. Yet other greenhouse gases emissions like N_2O and CH_4 may have a considerable impact on global warming [4].

The production of a given type of plant depends on many different factors, like the soil characteristics, the climate, and particularly on the availability of water during the vegetative life cycle.

In order to reproduce the agricultural production of a corn crop analytically, Cunha *et al.* [6] developed an agricultural production function based on models taken from, Doorenbos and Kassam [7],

$$\left(1 - \frac{Ya_i}{Ym_i}\right) = Ky_i \left(1 - \frac{ETa_i}{ETm_i}\right) \tag{1}$$

Ya_i=actual production in period i; Ym_i=maximal production (when no factor limits production) in period i; Ky_i=yield response coefficient in period i; ETa_i=actual evapotranspiration in period i; ETm_i=maximal evapotranspiration in period i (if there is not an irrigation deficit), and Bowen and Young [8],

$$\frac{Ya}{Ym} = \prod_{i=1}^{N} \left(\frac{Ya_i}{Ym_i}\right) \tag{2}$$

Ya=actual production ; Ym=maximal production (when no factor limits production). This agricultural production function was applied to a corn crop in Turkey.

If we combine the agricultural production function with the indicative values of CO_2 net flux per kg of corn yield, we will get a simplified model for carbon dioxide sequestration estimation. It should be pointed out that this model derived from different data obviously cannot reproduce a specific situation. However, it analytically reproduces a simplified mechanism linking irrigation policy to CO_2 sequestration, allowing the mathematical development and computation of a decision model that can later be adapted to specific data.

In order to achieve sustainable multipurpose hydropower management we should try to maximize the monetary return and minimise CO_2 emissions. This is typically a multiobjective problem. According to Revelle and McGarity [9], these problems can be solved by two approaches:

- A multiobjective approach. In this case we can maximize the tangible monetary return from hydroelectricity and agricultural production and at the same time minimise the intangible monetary value of CO_2 emissions.

- A single objective approach. If it is possible to reduce all tangible and apparently intangible aspects to monetary values (benefits and costs), we can transform a multiobjective problem in to a single objective problem that maximizes overall net benefit function. “This is the basic logic behind benefit-cost analysis, which has been the dominant analytical tool for civil and environmental problems for 60 years” [9: 515].

At the moment CO_2 emissions tend to have a very precise monetary value. The European Union Emission Trading Scheme (EU ETS), the largest multi-national greenhouse gas emissions trading scheme in the world, came into operation on 1 January 2005, although a forward market has existed since 2003.

Other countries like Canada and Japan will establish their own internal markets in 2008 and may well link up with the EU ETS. Even in the countries like the USA that have not ratified the Kyoto Protocol, voluntary organizations are establishing CO_2 credits markets.

Since a tangible monetary value can be attributed to the CO_2 emitted or avoided, the problem can be formulated as a single objective optimization decision problem.

2 Formulation of the problem

Figure 1 gives a schematic layout of the multipurpose reservoir.

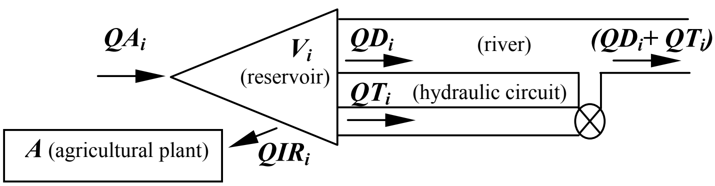

Figure 1: Schematic layout of inflows and outflows.

The problem can be stated as follows:

For each of the *i=1 to 12* fortnights of the 6 month crop period: how much water shall be allocated to agriculture production (QIR_i), to hydroelectric production (QT_i) and released downstream (QD_i) in order to maximize global return, taking in to account the CO_2 net flux and satisfying the problem constraints.
Inflows are represented by QA_i, stored reservoir volume by V_i, agricultural area by A, and the downstream required outflows are represented by $(QD_i + QT_i)$.

The objective function is:

$$\max R = \prod_{i=1}^{N} \frac{Ya_i}{Ym_i} Ym \cdot A \cdot (Py + CAF \cdot P_{CDA}) + \sum_{i=1}^{N} \eta_i \cdot \gamma \cdot QT_i \cdot H_i \cdot (Pe_i + CHF \cdot P_{CDH}) \tag{3}$$

R=global remuneration; N=number of time steps (ex.: fortnights); i=integer that represents the time step period; Py=unit price of agricultural production; CAF= CO_2 net flux per unit of corn yield; P_{CDA}=unit price of CO_2 in agriculture; η_i=overall efficiency of the hydropower plant during period i; γ=constant that depends on the water density; QT_i=volume of water to be used by the turbines during period i; H_i=Gross head during period i; Pe_i=tariff price of the hydroelectricity production during period i; CHF= CO_2 net flux per kWh; P_{CDH}=unit price of CO_2 in hydroelectric production.

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The constraints of the problem can be divided into four main types:

- The constraints associated with agricultural production that give corn yield as a function of the irrigation policy. Figure 2 shows minimum and maximum corn yield associated with the least and most efficient distribution of total irrigation by the three bimonthly vegetative periods of the agricultural production function. This function, reproduced by equations (1) and (2), was adopted in the application examples.
- The constraints associated with hydroelectric production that provide the physical and technical restrictions of the hydroelectricity generation process, as well as the tariff for production remuneration. In Figure 2 we can see an arbitrated tariff based on the Portuguese tariff for independent producers. According to D-L No. 33-A/2005 of 16th February, each ton of avoided CO_2 is worth 20 €. Hydroelectricity is paid taking in to account the peak and average consumption hours, the off-peak consumption hours, as well as the average monthly hydroelectric power. Figure 2 was computed by arbitrating a management policy to transfer inflows from low consumption hours to peak and average consumption hours.
- The constraints associated with water use that provide minimum and maximum limits for: reservoir water surface levels, outflows, required energy production, and initial and final stored reservoir volumes, throughout the 12 fortnights.
- The constraints associated with the hydraulics of the problem, such as the mass balance equation in the reservoir, the elevation-storage curve at the reservoir, the elevation-flow curve at the end of the hydraulic circuit, and the stationary condition for initial and final reservoir stored water volumes.

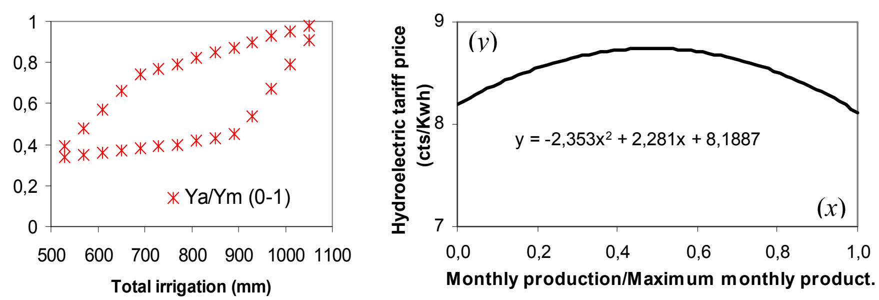

Figure 2: Production functions: Agricultural production (*Ya/Ym*) versus most efficient (upper values) and least efficient (lower values) irrigation policy, and hydroelectric tariff as a function of monthly production.

The analytical expressions that reproduce these constraints can be found in Almeida and Cunha [10].

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The nonlinear character of the objective function and some constraints indicated that nonlinear programming was the appropriate method to use. The model was solved using the GAMS/MINOS software [11, 12].

3 Examples

The computational feasibility and the dynamic behaviour of the decision model were analysed by means of several tests. Real data was mixed with artificial data to create extreme illustrative situations. The agricultural area was A=600 ha and the maximum agricultural production per hectare was Ym=6 t/ha. Three bimonthly vegetative periods were considered with $Ky_1=0.4$, $Ky_2=1.1$ and $Ky_3=0.4$. Based on information from Portuguese regional agriculture market we adopted a unit base price for corn yield of Py=182 €/t. Irrigation, with a hydraulic efficiency of 70%, occurs during the 6 month crop period from March to August. Further data associated with the agricultural production function presented in Figure 2, like for instance, soil moisture conditions, effective precipitation and evapotranspiration, can be found in Cunha *et al*. [6].

Table 1 gives the inflows to the hydropower plant reservoir. The installed capacity was $PINST$=10 MW, reservoir bottom altitude was 500m, and bottom altitude at the end of the hydraulic circuit was 234.5m. The hydroelectric tariff was given by the expression from Figure 2 where maximum price is 8.9 cts/kWh. As mentioned above, the base formulation of the problem allows the imposition of several multipurpose constraints. However, given that we are interested in analyzing the full impact of CO_2 emission in the water allocation, we will adopt illustrative examples with minimum constraints in order to provide a high degree of freedom to the decision model. The minimum and maximum surface water levels in the reservoir were set to 517 m and 536 m respectively. Outflows were not limited by minimum or maximum values. No obligatory hydroelectric power production was imposed. Further data can be found in Almeida and Cunha [13].

Table 1: Inflows to the hydropower plant reservoir.

i	1	2	3	4	5	6
$QA_i\ (m^3)$	2443890	2118140	1624010	1513950	1234500	671630
i	7	8	9	10	11	12
$QA_i\ (m^3)$	259130	76570	122200	39550	28390	30830

We considered 3 illustrative scenarios:

1) In scenario 1, water allocation optimization is computed without any considerations about the monetary evaluation of the CO_2 net flux. In this case, the application of D-L No. 33-A/2005 of 16th February leads to a mean depreciation of about 45%. The corn yield is evaluated with the base unit price of Py=182 €/t.

2) In scenario 2, the water allocation optimization is computed considering the hydroelectric tariff presented in Figure 2, and considering a conventional till corn crop. As a conventional till corn crop is a net contributor to CO_2 emissions, the unit price is depreciated to a final value of *Py*=179 €/t. To compute this price, the +146 kg of CO_2 per ton of corn yield are multiplied by the 20 € per ton of CO_2. A final depreciation value of 3 € per ton of corn yield was adopted.
3) In scenario 3, the water allocation optimization is computed considering the hydroelectric tariff presented in Figure 2, and considering a no-till corn crop. As a no-till corn crop is a non conventional technique, we estimated the monetary value of the avoided CO_2 emissions using exactly the same criterion as for the independent hydroelectric producers. This criterion basically increases the monetary value of the ton of CO_2 by a factor of 4.5. Using the -53 kg of CO_2 per ton of corn yield, a final increase of 5 € per ton of corn yield was adopted, which gives us the final price of *Py*=187 €/t.

Examples were computed with a monthly time steep. Figure 3 and 4 present results in each scenario.

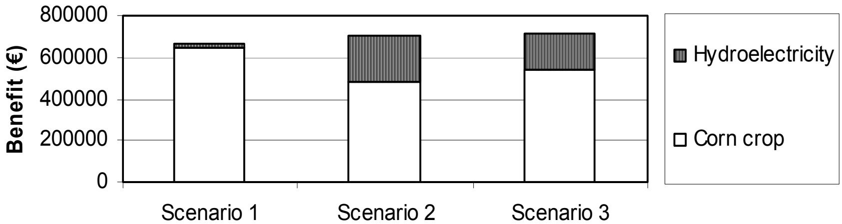

Figure 3: Benefit in each scenario.

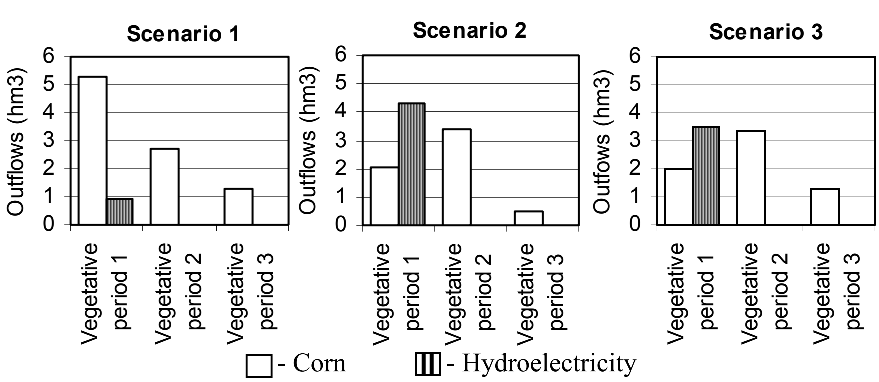

Figure 4: Water allocation in each scenario.

3.1 Scenario 1

We can observe that in scenario 1 the decision model gives priority to agricultural production because the hydroelectric tariff is low. The optimum solution implements an irrigation policy without water deficits that leads to a maximum agricultural production of *Ya/Ym*=1.00. Irrigation during each bimonthly vegetative period, next to the plants, is I_1=615mm, I_2=314mm, I_3=151mm (which corresponds do the upstream diversion from the reservoir of QIR_1=5.269hm^3, QIR_2=2.688hm^3 and QIR_3=1.292hm^3 respectively). The agricultural yield is 644400 €.

The optimum solution only implements hydroelectric production when surplus water is available after priority agricultural use. The outflow to the turbines is QT_1= 0.914hm^3. The hydroelectric production benefit is 25221 €.
Global benefit in scenario 1 is 669621 €.

3.2 Scenario 2

In scenario 2, the hydroelectric production tariff increases and the unit price of corn yield slightly decreases relative to the corresponding values of scenario 1. The decision model correctly identifies that hydroelectric production becomes more lucrative and responds to this modification by reallocating considerable volumes of water from agricultural use to hydroelectric use. The optimum solution implements an irrigation policy with water deficits which reduces agricultural production to *Ya/Ym*=0.74. The irrigation during each bimonthly vegetative period, next to the plants, is I_1=236mm, I_2=392mm, and I_3=57mm (which corresponds do the upstream diversion from the reservoir of QIR_1= 2.022hm^3, QIR_2= 3.364hm^3 and QIR_3= 0.488hm^3 respectively). Since the yield response coefficient in the second vegetative period is almost triple the yield response coefficients in the remaining vegetative periods, the decision model adopts an irrigation policy that favors this period. The agricultural yield is 482463 €.

The optimum solution implements a hydroelectric production policy that allocates the initial high natural inflows to hydropower production, rather than to ensuring a no-deficit agricultural irrigation in the first vegetative period, as occurred in scenario 1. The outflow to the turbines is QT_1= 4.290hm^3.

The hydroelectric production benefit is 221378 €.

Global benefit in scenario 2 increased to 703841 €.

3.3 Scenario 3

In scenario 3, the hydroelectric production tariff and the unit price of corn yield increase relative to the corresponding values of scenario 1. The decision model correctly identifies that hydroelectric production becomes more lucrative and responds to this modification by reallocating considerable volumes of water from agricultural use to hydroelectric use.

The optimum solution implements an irrigation policy with water deficits that reduces the agricultural production to *Ya/Ym*=0.80. The irrigation during each bimonthly vegetative period, next to the plants, is I_1=236mm, I_2=392mm, I_3=151mm (which corresponds do the upstream diversion from the reservoir of QIR_1=2.022hm^3, QIR_2=3.364hm^3 and QIR_3=1.292hm^3 respectively). The agricultural production in scenario 3 is higher than in scenario 2 because an increase of irrigation in the third and driest vegetative period occurs. The agricultural yield is 538560 €.

The optimum solution implements a hydroelectric production policy that allocates the initial high natural inflows to hydroelectric production, rather than to ensuring a no-deficit agricultural irrigation in the first vegetative period, as occurred in scenario 1. The outflow to the turbines is QT_1= 3,485hm^3.

The hydroelectric production benefit is 179332 €.

Global benefit in scenario 3 increased to 717892 €.

With respect to scenario 2, it is clear that the adoption of the no-till corn crop increased the competitiveness of the agricultural production relative to the hydroelectric production. Consequently, the decision model slightly rearranged the water allocation increasing agricultural water use and decreasing hydroelectric water use.

4 Conclusions

Comparing scenario 1 with scenarios 2 and 3 we can conclude that the incorporation of the monetary evaluation of the CO_2 net flux can have a considerable impact on optimum multipurpose water allocation.

From scenarios 2 and 3 we can conclude that the replacement of a conventional till by a no-till corn crop has a low impact on optimum multipurpose water allocation, when a CO_2 net flux monetary evaluation approach is adopted.

From a conceptual, mathematical and computational point of view, the approach presented above was able to incorporate the CO_2 net flux in a multipurpose reservoir water allocation optimization model for agricultural production and hydroelectric production.

In the examples presented above the decision model showed a logical response, from a dynamic point of view, to the modifications made to the data.

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