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OPERACIÓN DE EMBALSES MULTIPROPÓSITO: TRADE-OFFS ENTRE PRODUCCIÓN AGRÍCOLA E HIDROELECTRICIDAD

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Embalses a nivel mundial son operados con el objetivo de satisfacer demandas de agua para diferentes usos: consumo humano, agricultura, hidroelectricidad, caudales ambientales e intereses recreacionales. Estos uso debido a periodos prolongados de sequias, generados por el cambio climático, aumento de la población, degradación del medio ambiente y aumento de la demanda energética han exacerbado diferentes conflictos en la utilización del recurso a diferentes escalas —especiales y temporales—. Por lo anterior, decisiones de asignación de agua desde embalses —y el análisis de sistemas de recursos hídricos en general— deben tener en cuenta diferentes trade-offs entre los usos que se ven beneficiados con el recurso, con el objetivo de realizar una efectiva coordinación y resolución de conflictos.

El riego y la hidroelectricidad son los principales usos en los sistemas hídricos a nivel mundial. Estos usos del agua en algunas zonas geográficas sostienen un conflicto inherente a sus requerimientos de agua debido a que son estacionalmente dispares. La hidroelectricidad tiene las mayores demandas en invierno y el uso agrícola concentra la utilización del recurso en los meses de verano. Por otro lado, la escala espacial de utilización del recurso puede transcender la cuenca, debido a la interconexión del sistema eléctrico, el cual es operado en base a intereses del operador del sistema eléctrico. Por tal, la decisión de asignar agua de un embalse puede involucrar información de disponibilidad del recurso de otras cuencas, además de información propia del sistema eléctrico, relacionada con incertidumbre de precios de combustible, estado de líneas de transmisión, demandas energéticas, entre otras. Éste trabajo plantea una propuesta metodológica para la planificación de la asignación del recurso hídrico, considerando el valor económico de los usos, integrando funciones de demanda mensual para uso agrícola, con dos representaciones del valor marginal de la generación eléctrica, inserta en un sistema eléctrico interconectado el cual transciende la cuenca. El enfoque propuesto realiza una correcta representación del uso hidroeléctrico en un modelo a escala de cuenca, lo cual alivia los conflictos entre el riego y la hidroelectricidad en presencia de escasez hídrica.

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A mis padres pilares fundamentales en mi vida y responsables de mis logros académicos y profesionales. A mis hermanos, porque siempre me han acompañado en el transcurso de mi vida.

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CAPÍTULO 1. Introducción y propuesta metodológica.

Embalses a nivel mundial son operados con el objetivo de satisfacer demandas de agua para diferentes usos, entre ellos, consumo humano, agricultura, hidroelectricidad, control de crecidas, caudales ambientales e intereses recreacionales. Estos uso del agua debido a periodos prolongados de sequias, generados por el cambio climático, aumento de la población, degradación del medio ambiente, aumento de la demanda energética y ausencia de una gobernanza pública eficaz, han exacerbados diferentes conflictos en el utilización del recurso a diferentes escalas —especiales y temporales— [*OECD*, 2011; *Grayman et al.*, 2012; *IPCC*, 2014]. Por lo anterior, decisiones de entrega de agua desde embalses —y el análisis de sistemas de recursos hídricos en general— deberían tener en cuenta diferentes trade-offs entre los diferentes usos que se ven beneficiados con el recurso, con el objetivo de realizar una efectiva coordinación, resolución de conflictos y una óptima asignación del agua [*Gleick*, 2002; *OECD*, 2011; *Grayman et al.*, 2012; *Giuliani et al.*, 2014; *Brown et al.*, 2015].

En busca de abordar los desafíos de una completa gestión del recurso hídrico (RH), en las últimas décadas han emergido modelos de simulación y optimización hidro-económicos como una herramienta común para analizar sistemas de RH [*Tilmant et al.*, 2015]. Tales modelos integran la economía y la ingeniería, enfatizando el uso de principios económicos para apoyar procesos de toma de decisión, diseño y evaluación de la operación de sistemas hídricos e integración de diferentes usuarios del agua en las cuencas [*Harou et al.*, 2009]. La importancia en la utilización de estos modelos, está dada no sólo porque brindan decisiones óptimas relativas a la operación de los sistemas, sino también porque revelan el costo de oportunidad del agua en situaciones de escasez, proporcionado bases para la toma de decisiones e internalización de externalidades a diferentes escalas [e.g. *Medellín-Azuara*, 2006; *Pulido-Velazquez et al.*, 2008; *Tilmant et al.*, 2008, 2009; *Harou et al.*, 2009; *Medellín-Azuara et al.*, 2010; *Marques and Tilmant*, 2013]. Según *Tilmant et al.*, [2015] la importancia de revelar el costo de oportunidad del agua radica en que: i) la escasez exige una buena comprensión de los flujos, usos y valores económicos para una gestión eficaz, y ii) el costo de oportunidad del recurso es, en la ausencia de mercados, el mejor indicador del precio o la disponibilidad a pagar por una cantidad de agua para mitigar la escasez.

Revelar el costo de oportunidad del agua almacenada en los embalses es de gran importancia, ya que permite identificar diferentes compensaciones entre usuarios, además compensaciones en el uso del agua en el tiempo —valor presente y futuro del agua—. Lo cual contribuye a la resolución de conflictos por el agua, parte esencial de la gestión del RH. Comúnmente existe entre el riego y la hidroelectricidad un conflicto por la utilización del recurso. Estos son los principales usos y actividades económicas en las cuencas a nivel mundial. Por ejemplo, en Chile el 73% de las extracciones de agua dulce de uso consuntivo es utilizado en el sector agrícola, el cual participa con un 22% en las exportaciones nacionales, emplea alrededor del 9% de la fuerza laboral y en el 2011 contribuyó con 3 puntos porcentuales del PIB [*MOP*, 2012]. Por el lado de la hidroelectricidad, esta participa con el 35% de la capacidad instalada en los sistemas eléctricos interconectados del país [*Delegación Presidencial para los Recursos Hídricos*, 2015] y contribuye directamente al desplazamiento de fuentes de energías costosas y de impacto negativo sobre los sistemas ambientales. Este conflicto, es inherente a los usos debido a que sus requerimientos de agua son estacionalmente dispares en algunas zonas geográficas del planeta. La hidroelectricidad tiene las mayores demandas en invierno y el uso agrícola concentra la utilización del recurso en los meses de verano [*Castelletti et al.*, 2008]. Por otro lado, la escala espacial de utilización del recurso puede transcender la cuenca, debido a la interconexión del sistema eléctrico, el cual es operado en base a intereses del operador del sistema eléctrico. Por tal, la decisión de asignar agua de un embalse puede involucrar información de disponibilidad del recurso de otras cuencas, además de información propia del sistema eléctrico, relacionada con incertidumbre de precios de combustible, estado de líneas de transmisión, demandas energéticas, entre otras.

Existe dos enfoques basados en técnicas clásicas de optimización en el área de análisis de sistemas de recursos hídricos para abordar el conflicto entre hidroelectricidad y riego en un contexto de operación de embalses: El primero considera demandas agrícolas fijas mediante restricciones [*Yeh*, 1985; *Labadie*, 2004]. Aquí, el sector agrícola es considerado como una prioridad en la operación del embalse y el despacho hidroeléctrico es restringido [*Tilmant and Kelman*, 2007]. Mientras que el segundo enfoque considera el rendimiento económico del sector agrícola —junto con el hidroeléctrico— como un objetivo integrado en un modelo hidro-económico [e.g. *Rosegrant*, 2000; *Tilmant et al.*, 2008, 2009; *Harou et al.*, 2009; *Medellín-Azuara et al.*, 2010]. Basado en este enfoque, *Goor et al.*, [2010] evalúan la distribución espacial y temporal de los beneficios económicos de los dos usos, además de los costos asociados con la operación de embalses en una cuenca en Etiopia. Para representar el sector agrícola en el modelo, los autores utilizan embalses ficticios para acumular las entregas al sector agrícola a través de la temporada de riego, y al final de esta el embalse es vaciado, debido a que en esta época los agricultores perciben el beneficio por sus cultivos.

Independientemente del enfoque utilizado para representar al uso agrícola, los beneficios del sector hidroeléctrico son calculados considerando los precios de la energía como una variable exógena. Ignorando el comportamiento estratégico que un generador hidráulico con capacidad de almacenamiento puede optar en un mercado eléctrico. Un argumento de considerar los precios de la energía como una variable exógena, está relacionado con que la participación de un generador hidráulico, es relativamente pequeña con la generación total del sistema. Como consecuencia, este no puede afectar los precios en el mercado energético. Sin embargo de acuerdo con *Vargas et al.*, [2003], un aspecto clave para ejercer poder de mercado no está completamente relacionado con la concentración de generación en el mercado, si no con la capacidad de regulación que este generador pueda realizar. Un generador hidráulico con capacidad de almacenamiento tiene la habilidad de influir en los precios del mercado eléctrico, moviendo energía —agua— entre periodos de alta a baja demanda energética [*Crampes and Moreaux*, 2001; *Bushnell*, 2003; *Førsund*, 2015]. Por lo anterior, si un generador hidráulico prefiere asignar una mayor generación hidro en periodos de baja demanda energética —altas demandas agrícolas— para incrementar sus ingresos en periodos de alta demanda energética. El sector agrícola implícitamente se vería beneficiado con este comportamiento.

Partiendo de la anterior hipótesis, el objetivo del presente estudio, es contribuir a la generación de una asignación eficiente del agua de largo plazo en sistemas de embalses multipropósito, donde los principales usos del agua son la hidroelectricidad y el uso agrícola, incorporando en un solo modelo de planificación a nivel de cuenca, información de las diferentes escalas que involucran el aprovechamiento del agua. Los objetivos específicos son: (OE1) Evaluar un esquema de modelación para asignar el recurso hídrico que aborde los conflictos espaciales y temporales entre la agricultura y la generación hidroeléctrica en un contexto de operación de embalses; y (OE2) Evaluar el impacto del comportamiento estratégico de un generador hídrico con gran capacidad de embalse, en los conflictos espaciales y temporales entre la utilización del recurso hídrico entre la agricultura y la generación hidroeléctrica.

La Fig. 1.1 presenta la propuesta metodológica que se plantea en éste estudio en la cual se proponen tres modelos. Los dos primeros —modelo agroeconómico y modelo de coordinación hidrotérmica— utilizados para la valoración del agua para el sector agrícola y el cálculo de los precios de la energía en el sistema eléctrico. Los resultados de estos, se integran en un tercer modelo utilizado para la generación de una operación óptima del embalse a escala de cuenca para ambos usos. De este último modelo se obtiene funciones de valor futuro del agua embalsada, la operación del embalse —entregas para riego e hidroelectricidad—, además de los beneficios asociados al uso del agua en la cuenca.

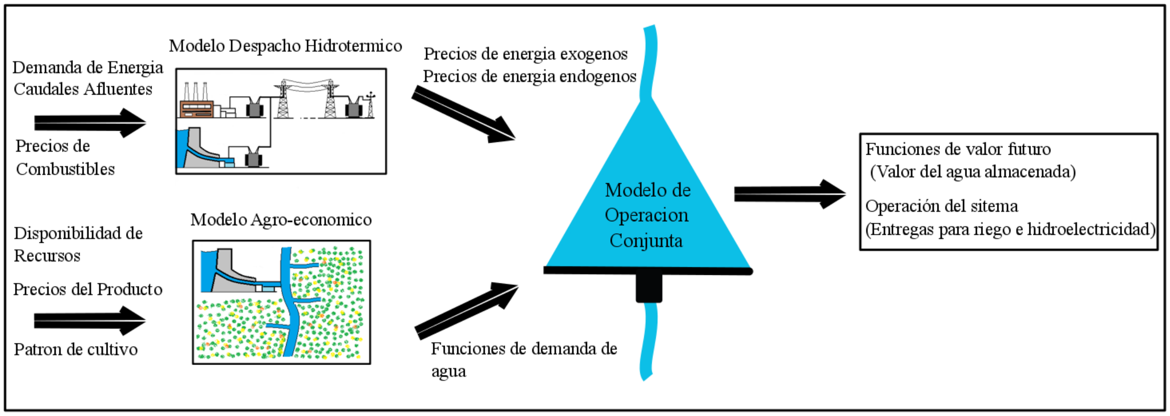

Fig. 1.1 Propuesta Metodológica

Esta Tesis se organiza en 4 capítulos. El presente capítulo corresponde al Capítulo 1, el cual busca introducir los problemas que conciernen a la gestión de los recursos hídricos y la operación de los sistemas de embalses multipropósito, presenta los objetivos en los cuales se enmarca el trabajo y además presenta la propuesta metodológica con la cual se busca cumplir los objetivos específicos del estudio. En el Capítulo 2, se presenta un primer artículo, el cual responde al OE1 y presenta una evaluación de los enfoques utilizados actualmente en el área de análisis de sistemas de recursos hídricos que abordan el conflicto entre hidroelectricidad y riego en un contexto de operación de embalses. En el Capítulo 3, es presentado un segundo artículo que responde al OE2 en el cual se evalúa el impacto de un comportamiento estratégico de un generador hidro con capacidad de almacenamiento, sobre el conflicto entre el riego y la electricidad. Finalmente en el Capítulo 4, se presentan las conclusiones generales del estudio y el trabajo futuro.

CAPÍTULO 2. Multipurpose reservoir operation: a *trade-off* analysis between hydropower generation and irrigated agriculture.

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Abstract

Reservoir operation decisions often require balancing among several objectives including water supply for human consumption and irrigated agriculture, hydropower production, flood control, environmental flows, and recreation. This study integrates two decision scales—power grid and river basin— into a hydro-economic model to assess the economically optimal operation of a multipurpose reservoir for hydropower and irrigated agriculture. Often, conflicts exist inherently between irrigated agriculture and hydropower water requirements due to a demand seasonality mismatch. Water for irrigation is usually allocated by water rights or binding contracts, represented as constraints on grid-wide power operation models. In this research, a dynamic water allocation scheme is examined, in which monthly marginal benefits of water in irrigated agriculture and hydropower are considered. Monthly demand functions for irrigation water are developed using a calibrated agricultural economic model and marginal benefits of hydropower production are derived from a cost-minimization, grid-wide power operations model. The results show that hydro-economic models provide an economically sound operation in which total benefits from water use in the basin are higher 2.5% than those obtained under a fixed allocation scheme for irrigation. Performance assessments indicate that individual solutions are better —5.4% and 1.8% for irrigated agriculture and hydropower, respectively— than those found under fixed allocation policies, alleviating the conflicts in the basin among water users.

2.1 Introduction

Hydropower reservoir operations are commonly prescribed as part of a grid-wide coordination process by an Independent System Operator (ISO), based either on a market clearing bidding scheme or on grid-wide cost minimization [*Scott and Read*, 1996; *Kirschen and Strbac*, 2004; *Steeger et al.*, 2014]. Under the latter, particularly for power systems dominated by thermal and hydropower, a key step is to determine the value of water stored in reservoirs, represented by the thermal costs avoided in the future. This avoided future cost as a function of reservoir storage is known as future value function (FVF) and allows understanding the trade-offs between present and future water use for hydropower. Often, these reservoirs have additional purposes, notably water supply and irrigated agriculture. Estimation of the FVF for multi-purpose reservoirs is challenging, particularly when water allocation decisions occur at different spatial scales. Indeed, hydropower operations involve the entire power grid, which typically includes several river basins. On the other hand, in absence of water transfers, irrigated agriculture planning takes place at the basin scale. These two water uses can be conflicting due to opposed seasonality within the year, because in some countries the power demands are highest in winter and irrigation water demand peaks during summer [*Castelletti et al.*, 2008]. In this case, water used for power generation during winter will not be available for summer irrigation.

The trade-offs for multipurpose large-scale reservoir systems are studied by *Tilmant and Kelman* [2007] and *Tilmant et al.* [2008], incorporating the irrigated agriculture use through operating constraints —using annual irrigation requirements— or economic water value to irrigated agriculture respectively, using stochastic dual dynamic programming (SDDP) in order to tackle the dimensionality of large-scale reservoirs systems. Moreover, *Tilmant et al.* [2009] evaluated the water transfers of agricultural to hydropower, incorporating the irrigation opportunity cost together to the hydropower benefits to allocate the water resources in a cascade of multipurpose reservoir in the Euphrates river basin. The authors obtain greater annual benefits with continuous allocation decisions, based on the economic benefit to both water uses and the hydrologic status of the system, compared to the water allocation by limited annual irrigation requirements. In this paper, the authors consider the spatial allocation inside at basin but not the link with the spatial scale incorporated into the power system with other basins.

Optimal allocation of water requires proper economic representation of the effects of such allocation. Hydro-economic models reveal the opportunity cost of water under scarcity, which can be the basis for decision making at various levels [e.g. *Medellín-Azuara*, 2006; *Pulido-Velazquez et al.*, 2008; *Tilmant et al.*, 2008, 2009; *Harou et al.*, 2009; *Medellín-Azuara et al.*, 2010; *Arjoon et al.*, 2014]. Sometimes, an economic representation of water use for irrigated agriculture cannot be directly included into the cost-minimization power scheduling model. This is, for example, the case in Chile, where the law establishes that only power-related costs can be considered by the ISO, leaving aside all other economic effects of scheduling [*Law N° 4/20018*, 2007]. Under these circumstances, this paper proposed an alternative strategy to balance the benefits of hydropower and irrigated agriculture at the basin scale, which relies on a multi-scale approach using three models: grid-wide power scheduling model, basin-wide agro-economic model, and a basin-wide hydro-economic model which integrates information from both other models.

The proposed strategy evaluate the trade-offs between both uses, integrating two decision scales —power grid and river basin— into a basin-wide hydro-economic model. Specifically, two pieces of information are coupled: the value of water for irrigated agriculture obtained from an agro-economic model at basin level, and the marginal benefits for power production that result from a grid-wide power scheduling model. A one-year planning horizon is considered in the hydro-economic model because it fits well both the time frame for irrigation decisions and the mid-term time horizon for grid operations scheduling. This modeling framework is compared with the common approach of fixed irrigation requirements, represented as constraints for reservoir operations. The hydro-economic model was solved using Sampling Stochastic Dynamic Programming (SSDP) [*Kelman et al.*, 1990], in order to use historical records of inflows to the evaluated system. An infinite-horizon SSDP was implemented to develop a polynomial approximation of the FVF, with the aim to generate optimal steady-state FVF and so to simulate the system operation.

In this paper, the water value for irrigated agriculture is quantified from water demand functions, which represent the marginal benefit of water used for this purpose [*Young*, 2005]. These demand functions are obtained by formulating the farmer's decision problem, which consists of allocating the available land and water to the possible crops, maximizing the net benefit [*Johansson*, 2005; *Medellín-Azuara et al.*, 2010]. This agro-economic model, solved using Positive Mathematical Programing (PMP) method [*Howitt*, 1995a, 1995b], calibrates the parameters of a production and cost function, in an optimization model by matching empirical observations, in this case, observed cropping patterns from a base year. On the other hand, the marginal value of hydropower was obtained from a grid-wide power scheduling model, using Stochastic Dual Dynamic Programming (SDDP) [*Pereira and Pinto*, 1985, 1991]. This is one of the most common methods to solve the medium- and long-term power scheduling problem at grid level in hydrothermal systems, especially those dominated by hydropower [*dos Santos and Diniz*, 2009; *Shapiro*, 2011; *Matos and Finardi*, 2012]. The main contribution of this paper is the multi-scale *trade-offs* analysis of both water uses, and the use of monthly benefit functions for irrigated agriculture sector, previous studies only incorporate an economic signal for irrigated agriculture at the end of the irrigation season, losing the monthly water distribution. Finally, the modeling framework is described in section 2.2. Operational and economic results are presented in section 2.3, while section 2.4 includes the main conclusions.

2.2 Modeling Framework

2.2.1 Conceptual framework

For conceptual purposes, the proposed methodology is applied to a hypothetical electric system constructed based on technical data from the Chilean Central Interconnected System (SIC). In this system, the power grid includes a 680-MW hydropower plant and an equivalent thermal generator with a known marginal cost function. The equivalent generator represents several thermal generators connected to the grid. Energy demand is considered deterministic using one demand profile. The conceptual system was constructed using data of the main basin in the SIC. This river basin has the largest energy storage capacity in the system with a reservoir of 5,850 Hm^3, and the water stored is used in hydropower and irrigated agriculture. Fig. 2.2 shows how the reservoir connects the two scales involved in the problem: the river basin and the power grid.

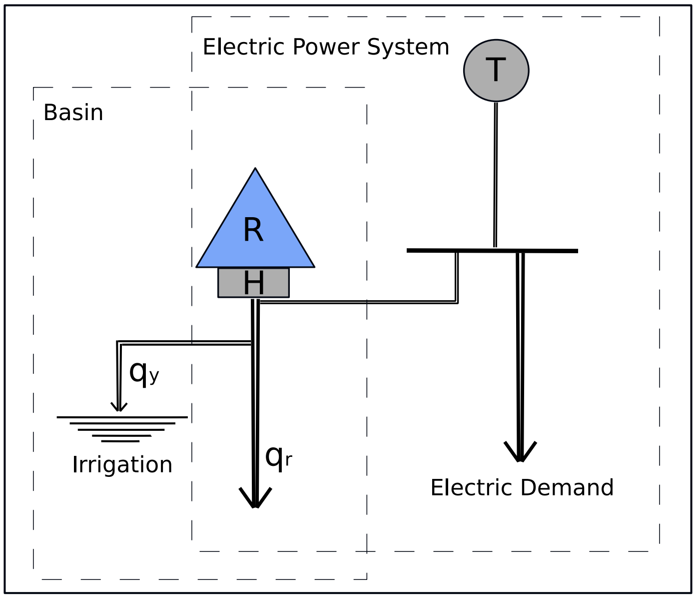

Fig. 2.2 Hypothetical system schematic, which links the different scales and water users.

The basin problem in Fig. 2.2 consists of finding the release decisions sequence (y_t, R_t for irrigated agriculture and hydropower, respectively) from the reservoir so that the joint benefit for the two uses is maximized over a planning horizon. Given the nature of immediate non-rivalry of hydropower and the irrigated agriculture, turbined flows are then available for downstream irrigation, we consider all turbined flows (R_t) can be used for irrigation (y_t).

2.3 Basic models: Grid-wide power scheduling and basin-wide agro-economic

2.2.3 Grid-wide power scheduling model

The hydropower marginal value in the system was evaluated with a grid-wide power scheduling model. In this case, we assumed that there is an ISO that plans the energy resources —water and fuel— in a planning horizon T, satisfying an energy demand profile at a minimum cost. In this paper, the main result of this model is the energy price, this is given as the dual —marginal value— of the demand constraint in the economic dispatch in the grid-wide power scheduling model [*Steeger et al.*, 2014]. The energy price in each stage of the planning horizon is the marginal value of water use in hydropower, this piece of information is crucial as it links the electric power system scale with the basin scale.

In this paper is used the typical ISO formulation for an electrical power system, which consists in minimizing the power system cost —related to the use of thermal generation—, satisfying the energy demand in each stage of the planning horizon, see [*Pereira and Pinto*, 1985]. We used Stochastic Dual Dynamic Programming (SDDP) [*Pereira and Pinto*, 1985, 1991] to solve the power scheduling model. This is one of the most common methods to solve the medium- and long-term power scheduling problem at grid level in hydrothermal systems, especially those dominated by hydropower [*dos Santos and Diniz*, 2009; *Shapiro*, 2011; *Matos and Finardi*, 2012]. The inflow uncertainty is incorporated into the model through a 50-scenarios tree, and the planning horizon contains 3 years with monthly steps (T = 3-years), with two extra years to avoid the emptying the reservoir at the end of the 3rd year, like in *Kelman et al.* [2001].

2.2.2 Basin-wide agro-economic model

The river basin data used in the model correspond to the Laja basin, located in the Bio-Bio region in Chile. This is one the main river basin due to the existence of the largest reservoir in the country, which satisfies water demands for hydropower and irrigated agriculture, this last use with more of 100.000 ha. With aiming to evaluate the water value in irrigated agriculture in the zone, we group all the irrigation sectors in the basin and implemented a basin-wide agro-economic model. Of this model, we obtain monthly water demand functions for irrigation which represent the farmer's willingness to pay for varying quantities of water for their crops [*Harou et al.*, 2009].

The agro-economic model implemented is solved using PMP, method proposed by *Howitt* [1995a, 1995b]. PMP is a deductive approach to simulating the effects of policy changes on cropping patterns at the extensive and intensive margins [*Medellín-Azuara et al.*, 2010; *Howitt et al.*, 2012]. This method calibrates the parameters of a production and cost function, in an optimization model by matching empirical observations, in this case, observed cropping patterns from a base year. In the following table, we can see the main crops in the zone, and the used data to calibrate the agro-economic model. Details of the model and the method used in this paper can be found in *Medellín-Azuara et al.* [2007] and *Howitt et al.* [2012] respectively.

Table 1. Input data to calibrate the Agro-economic model

Basin	Crops	Area Planted (ha)	Total production (qqm)	Performance (qqm/ha)	Land Costs $USD/ha	Water Costs $USD/ha	Price to Producer $USD/qqm	Water Requirement m3/s-ha
Laja	Corn	22,028	3,304,257	150	2,113	833	20	0.0047
	Oats	37,520	1,800,972	48	434	339	21	0.0045
	Potato	10,487	3,146,062	300	3,175	2,041	29	0.0023
	Bean	5,400	69,662	13	2,318	812	261	0.0042
	Wheat	102,391	6,143,462	60	522	266	28	0.0046

Once calculated the monthly water demand functions are integrated to obtain the monthly benefit functions for using the water in the irrigated agriculture sector like in *Medellín-Azuara* [2006]. These functions are those that are finally used in the basin-wide hydro-economic model.

2.4 Basin-wide hydro-economic model.

The hydro-economic model is represented by Eqs. (2.1) to (2.1d). The value economics of the power grid is contained in the marginal value of hydropower, whereas monthly irrigation benefit functions represent the value economics of water use in the irrigated agriculture sector.

$$\underset{R_t, y_t}{\text{Max}}\ Z = \underset{q_t}{E}\left[\sum_{t=1}^{T} B_t(S_t, R_t, y_t) + \nu(S_{T+1})\right] \tag{2.1}$$

$$S.t. \quad S_{t+1} = S_t + q_t - R_t - Sp_t - ev_t(S_t) \qquad \forall t = 1, \dots, T \tag{2.1a}$$

$$g_t^h \leq g_{max}^h \qquad \forall t = 1, \dots, T \tag{2.1b}$$

$$g_t^h = \gamma R_t \qquad \forall t = 1, \dots, T \tag{2.1c}$$

$$y_t \leq R_t + Sp_t \qquad \forall t = 1, \dots, T \tag{2.1d}$$

$$\boldsymbol{B_t\left(S_t, R_t, y_t\right) = p'_t g_t(S_t, R_t) + B_{ir_t}(y_t) + \xi'_t Sp_t} \tag{2.1e}$$

The Eq. (2.1) represents the objective function which maximizes the expected value of total benefit $B_t(\cdot)$ from water uses over the time horizon T, plus the value $\nu(\cdot)$ of ending storage. The Eq. (2.1a) represents the water balance in the reservoir, where Sp_t is the spill, $ev_t(\cdot)$ is the evaporation, S_t is the storage at the beginning of stage t, q_t is the natural inflow during the stage t and R_t is the release to hydropower decision at the beginning of stage t. Eq. (2.1b) is the constraint of maximum capacity of the hydropower plant with g_t^h and g_{max}^h being the hydro generation and the maximum hydro generator capacity, respectively. Eq. (2.1c) relates the optimal hydro generation (g_t^h) in each stage t, with the reservoir releases R_t at the beginning of stage t. Eq. (2.1d) represents the irrigation releases. Eq. (2.1e) defines the total benefit as the sum of hydropower and irrigation benefits, where $\boldsymbol{p_t'}$ is the marginal value of energy from the grid-wide power model, and $B_{ir_t}(\cdot)$ is the monthly irrigation benefit function, y_t is the irrigation release at the beginning of stage t, and ξ_t' a vector of penalty coefficients.

In order to compare the proposed modeling framework, we evaluated the irrigated agriculture objective, incorporating fixed irrigation requirements. If these fixed irrigation requirements are not meet, the irrigation deficits are penalized in the objective function. The change in the problem formulation is given by the next equations.

$$Ir_t \leq R_t + Sp_t + DIr_t \qquad \forall\, t = 1, \dots, T \tag{2.2}$$

$$B_t\big(S_t, R_t, DIr_t\big) = p_t' g_t(S_t, R_t) + \xi_t' Sp_t + \xi_t' DIr_t \tag{2.3}$$

The Eq. (2.2) represents the new irrigation constraint, where Ir_t is the fixed irrigation requirement at stage t and DIr_t is the irrigation deficits, which occur when releases cannot meet the irrigation requirements. The Eq. (2.3) is the new objective function where the deficits (DIr_t) are penalized.

2.4.1 Solution strategy

In this paper, we used SSDP combined with a polynomial interpolation, with the aim to solve the hydro-economic and the fixed-irrigation model to generate optimal monthly steady-state FVFs. Then this FVFs are used to simulate the system operation through a re-optimization process [*Tejada-Guibert et al.*, 1993]. We used a Chebyshev interpolation like in *Miranda and Fackler* [2004] in order to reduce the problem dimensionality and computational effort [*Johnson et al.*, 1993]. The SSDP formulation of the hydro-economic basin-wide model is as follows:

$$\max_{R_t^*, y_t^*} \left[\frac{1}{L}\sum_{l=1}^{L}\left[B_t\left(S_t^j, R_t, q_t^l, y_t\right) + \alpha f_{t+1}^i(S_{t+1}, l)\right]\right] \quad \forall\, S_t^j,\ and\ t = 1, \dots T \tag{2.4}$$

S.t.

$$S_{t+1} = S_t + q_t - e_t(S_t, S_{t+1}) - R_t - Sp_t \qquad \forall\ t = 1, \dots, T \tag{2.4a}$$

$$g_t^h \ \le \ g_{max}^h \qquad \forall t = 1, \dots, T \tag{2.4b}$$

$$g_t^h = \gamma\, R_t \qquad \forall\ t = 1, \dots, T \tag{2.4c}$$

$$y_t \le R_t + Sp_t \qquad \forall\ t = 1, \dots, T \tag{2.4d}$$

The Eq. (2.4) is the Bellman equation for the optimization problem Eqs. (2.4-2.4d), Where q_t^l is the reservoir inflow in the stage $\boldsymbol{t}$ under the l-th inflow scenario; S_t^j is $\boldsymbol{j}$-th discrete reservoir storage volume at the beginning of stage t, with $S_t^1 = S_{min}$ and $S_t^J = S_{max}$, and $\boldsymbol{i}$ is the iterations number makes by the model until the FVFs converge. The model optimizes over 50 historical inflow scenarios ($\mathrm{L} = 50$) with monthly stages over an annual planning horizon (T =12-month); therefore, each inflow scenario corresponds to 12-month and each iterations $\boldsymbol{i}$ is a moved by $t = T, T-1, \dots, 1$, solving the bellman equation (Eq. 2.4) in each stage $\boldsymbol{t}$.

The optimization model (Eqs. 2.4 to 2.4d) is solved for an annual infinite horizon, for each discretization of the state variable $\boldsymbol{j}$ and for each stage $\boldsymbol{t}$. The solution for each stage is a target releases for each water use R_t^* and y_t^*. These targets are then corrected for feasibility under each hydrologic scenario $\boldsymbol{l}$ through Eqs. 2.4e to 2.4g, respectively. The adjusted releases (R_t^l, y_t^l) are then used to update the value function $\boldsymbol{f_t^i}(\cdot)$ (Eq. 2.4h), which reflects the total –present and future- value of release decision at each stage $\boldsymbol{t}$, under each inflow scenario $\boldsymbol{l}$. This procedure is repeated for each stage $t = T, T-1, \dots, 1$, and for each discretization of the state variable $j = 1, \dots, J$, until the functions $\boldsymbol{f_t^i}(\cdot)$ converge. In the first iteration $\boldsymbol{i}$ for the stage T, $f_{T+1}^1(\cdot) = 0$ are performed for all $\boldsymbol{j}$ reservoir discretizations, and then in the second iteration the FVFs —$f_{T+1}^2(\cdot)$— for all $\boldsymbol{j}$ reservoir discretizations is updated such that $f_{T+1}^2(\cdot) = f_1^1(\cdot)$, and so on at each iteration $\boldsymbol{i}$.

$$R_t^l = min\begin{Bmatrix} max[R_t^*, S_t + q_t^l - R_t - Sp_t - ev_t(S_t) - S_{max}], \\ S_t + q_t^l - R_t - Sp_t - ev_t(S_t) - S_{min} \end{Bmatrix} \tag{2.4e}$$

$$g_t^{h,l} = \gamma R_t^l \tag{2.4f}$$

$$y_t^l = \begin{Bmatrix} R_t^l & if & R_t^l \leq Ir_t, \\ Ir_t & if & R_t^l > Ir_t \end{Bmatrix} \tag{2.4g}$$

$$f_t^i(S_t^j, l) = B_t(S_t^j, g_t^{h,l}, q_t^l, y_t) + \alpha f_{t+1}(S_{t+1}^j, l) \qquad \forall j, l \; and \; t = 1, \dots, T \tag{2.4h}$$

In the Eq. 2.4g, Ir_t is the irrigation requirement at stage t. Once the stationary FVFs for each inflow scenario $\boldsymbol{l}$ converge these are used in the re-optimization. This process uses the same 50-scenarios tree and the same planning horizon (T = 3-years) used in the grid-wide power scheduling model, so that the same marginal value of hydropower —from the power scheduling model— are used in the basin-wide hydro-economic model. Moreover, the simulation process is run with 25% of initial storage, with the aim to evaluate the system performance with an unfavorable initial storage. The model with fixed irrigation requirements is solved through SSDP like the model Eqs. 2.4-2.4d.

2.5 Results and Discussion

Results will focus on comparing the simulation of the system operations, in terms of reservoir releases and benefits obtained by each water user in the hydro-economic model respect to the fixed-irrigation model. The monthly water demand functions for the agricultural sector and the hydropower marginal value presented in the Fig. 2.3 and Fig. 2.4, respectively. Represents an intermediate result, which are used as an input for the hydro-economic and the fixed-irrigation models.

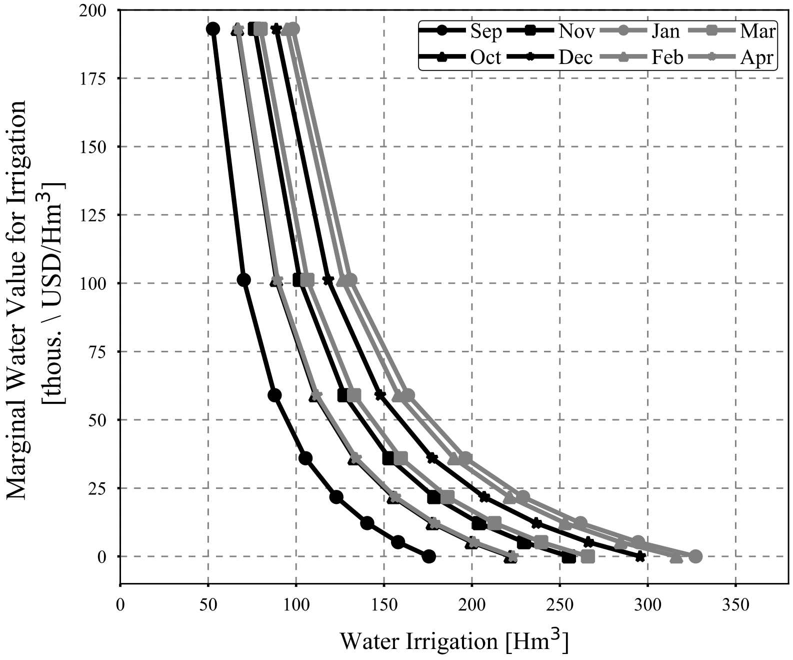

Fig. 2.3 Monthly water demand functions

In Fig. 2.3 we can see that the monthly willingness to pay for irrigation water, is consistent with monthly water requirements. The highest marginal values for water are estimated from Dec through Feb, when water requirements are highest in the southern hemisphere. Moreover, in Fig. 2.4 we can see how the hydropower marginal value results represent correctly the intra-annual seasonality of the energy price, which are greater in winter due to the higher energy consumption.

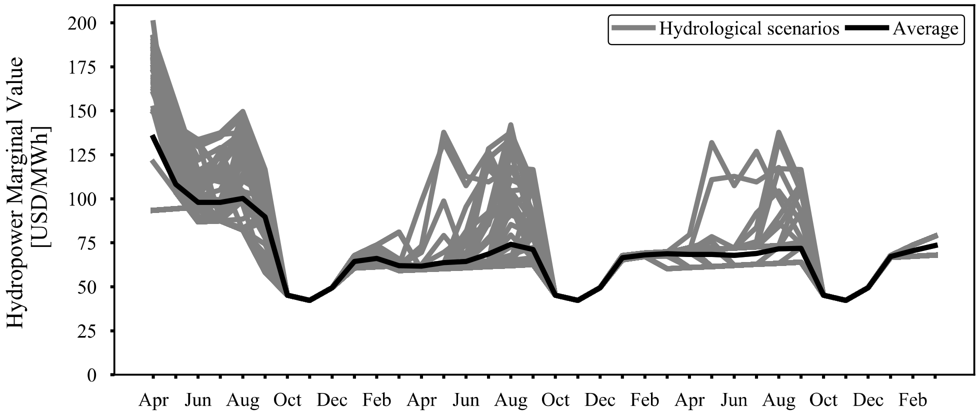

Fig. 2.4 Hydropower Marginal Value

A frequency analysis of reservoir releases for irrigated agriculture is shown in Fig. 2.5. These are presented as a percentage of the maximum requirement. The irrigation season is divided into two periods: the sum of releases from Sep-Dec and sum of releases form Jan-

Apr, for observing the main differences in the irrigation seasonality released from both models. We can observe in Fig. 2.5a that in the first half of the irrigation season, the fixed-irrigation model releases more water than the hydro-economic model. Irrigation demand is fully met with a 55% cumulative frequency, while in the hydro-economic model only 79% of demand is satisfied with the same probability. The above is explained because the fixed-irrigation model is forced to cover the irrigation requirements not to incur a large penalty, which results in releases meeting the demand unless it is not feasible. In the second half of irrigation season (Fig. 2.5b) this behavior changes, the hydro-economic model show larger releases for irrigation for a cumulative frequency higher than 10%, until the irrigation releases are equal in both model —cumulative frequency 95%—. Demand is almost never fully met in the second half of irrigation season due for the unfavorable water availability in the system —only with a cumulative frequency less than 5% in the fixed-irrigation model—. A greater cumulative frequency in the Fig. 2.5 correspond to dry hydrologic scenarios. Interestingly in these scenarios, the reservoir releases in both model are same, the main difference in the reservoir releases are in wet and normal hydrologic scenarios.

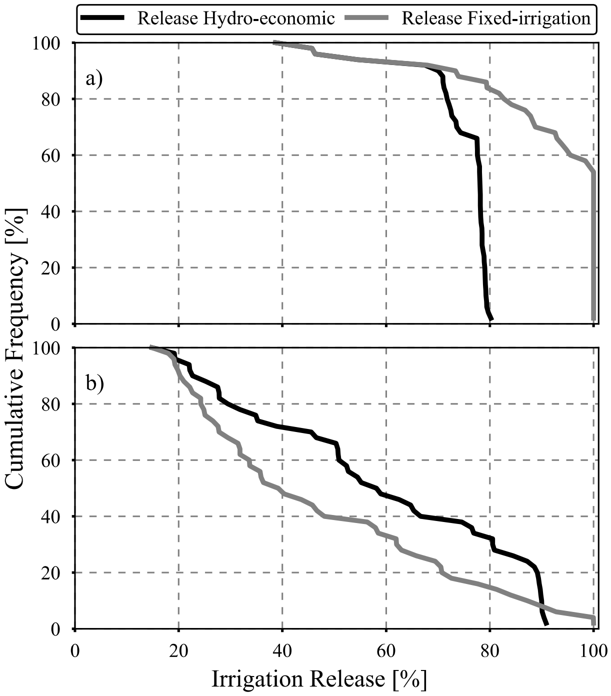

Fig. 2.5 Frequency analysis of irrigation releases. a) Total Release Sep-Dec. b) Total Release Jan-Apr.

In Fig. 2.6 we show reservoir releases and the hydro-economic to fixed-irrigation benefits ratio for normal hydrologic scenarios. As expected, we can see that the water allocated for irrigation tends to follow the demand pattern under the fixed-irrigation model until water availability makes it infeasible. Under the hydro-economy model, the reservoir fails to meet the requirements during the entire irrigation season. However, the worst monthly deficits are milder than those observed for the fixed-irrigation model in the second half of the irrigation season. The reservoir release in the non-irrigation season is the same in both models, differences are only observed during the irrigation season when the releases are affected by the irrigated agriculture requirements. We can see that the greater deficits incurred in the fixed-irrigation model in the second half of irrigation season, make a big difference between the benefits in the basin. For example, in March the benefit is 150% greater in the hydro-economic model than in the fixed-irrigation model. While the worst deficit observed in the hydro-economic model —December— generates a decrease in the basin benefits of 18% with respect to the fixed-irrigation model. In total, the annual benefits in the basin in this normal scenario is greater 3% in the hydro-economic model compared to the fixed-irrigation model. We can see in Fig. 2.6 that the hydro-economic model distributes the deficits along the irrigation season. This contributes to generating greater benefits in the irrigated agriculture sector and can alleviate the conflicts in the basin between the water users.

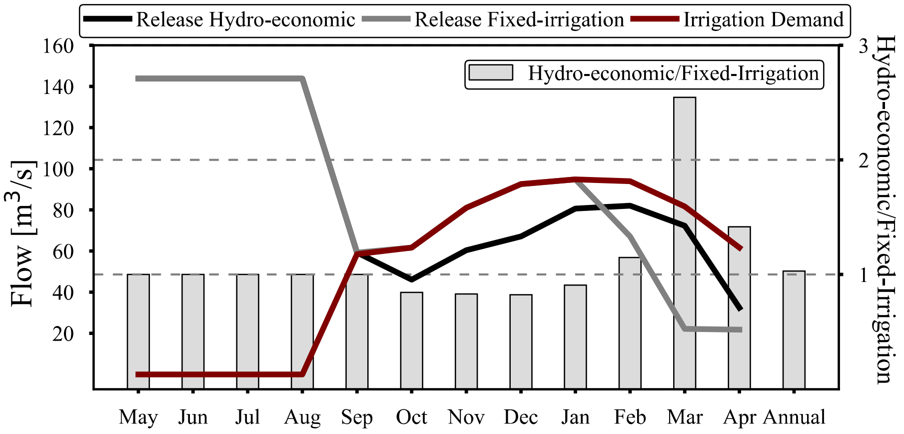

Fig. 2.6 Reservoir releases and ratio of basin-wide benefits.

In Fig. 2.7 a frequency analysis of the annual benefits for both users is presented. In the hydropower case, normalized with the maximum annual benefit observed in the fixed-irrigation model, while the irrigated agriculture benefits were normalized by the annual benefits obtained if the irrigations requirements are supplied. Is possible observed a slight increase in the annual hydropower benefits (Fig. 2.7a), but the main difference in the benefits is shown for the agricultural sector (Fig. 2.7b). For example with a cumulative frequency of 80% in the hydro-economic model, the agricultural benefit is 70% of the benefits obtained if the irrigations requirements are supplied completely, while in the fixed-irrigation model the benefits are 65% with the same cumulative frequency.

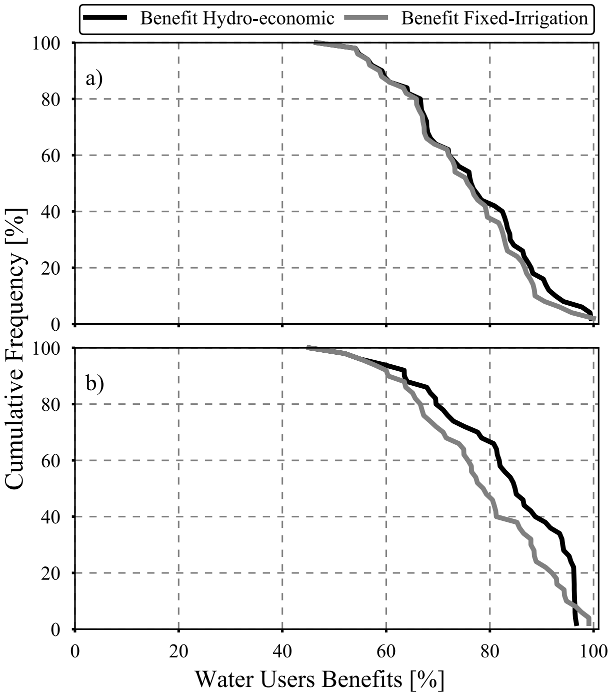

Fig. 2.7 Frequency analysis of water users' benefits. a) Hydropower. b) Irrigation.

Finally in average, the Fig. 2.8 show that the basin annual benefits are higher 2.5% in the hydro-economic model respect to the fixed-irrigation model. In the same way, the benefits for irrigated agriculture are higher 5.4% and the hydropower benefits 1.8% under the hydro-economic model. Therefore, is achieved a better joint system performance, but also every user is better off separately. This is due to a better water distribution in the irrigation season, which in the case of the fixed-irrigation model, it cannot be done by the reservoir operation myopic.

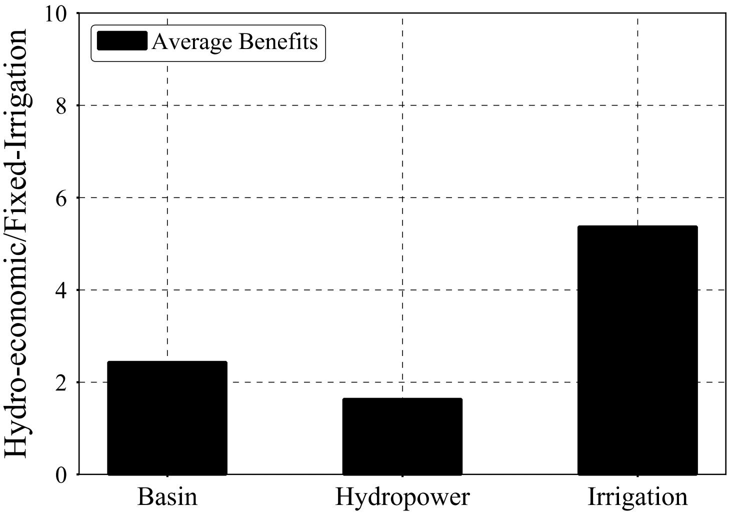

Fig. 2.8 Benefit associated with the use of water

2.6 Conclusions

A hydro-economic model to evaluate the multi-scale *trade-off* between hydropower and irrigated agriculture is presented. The system performance is compared with a scheme wherein the agricultural sector is represented through fixed irrigation requirements. Where the objective function is penalized if irrigation deficits are incurred. Is possible observed that the reservoir releases for irrigation tend to follow the demand pattern under the fixed-irrigation model. However, the system fails to meet those demands in the second half of irrigation season. While in the hydro-economic model, the reservoir fails to meet the requirements during the entire irrigation season, but the worst deficits are milder than those observed for the fixed-irrigation model. For example, with a cumulative frequency of 55%, the irrigation requirements are covered 100%, while in the hydro-economic model with the same cumulative frequency is covered the 79% of requirements in the first half of the irrigation season. While in the second half, with a cumulative frequency of 60% the hydro-economic model covered the 50% of irrigation requirements, while the fixed-irrigation model covered the 33%. This better water distribution in the irrigation season generates in average, an increase of 2.5% in the benefits in the basin, 5.4% in the irrigated agriculture benefits and 1.8% in the hydropower benefits. Moreover, alleviating the conflicts in the basin between the water users.

CAPÍTULO 3. A *trade-off* analysis between irrigated agriculture and hydropower under market power by hydropower reservoirs operators.

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Water resources systems, multi-purpose reservoir, sampling stochastic dynamic programming, hydropower and agricultural water conflicts, market power.

Abstract

In power systems organized such as a centralized mandatory pool, hydropower reservoirs are dispatched by an Independent System Operator (ISO) following a system-wide cost minimization criterion. This operation could be cost- or bid-based, both reported by the power operators to the ISO. In non-competitive power systems, the operation dispatched by the ISO could not converge in both schemes, since hydropower reservoirs operators could impact the operation in order to maximize their revenues with their bids, affecting the market-clearing price. Therefore, to influence in a different way the water management in the reservoirs and the interaction with the reservoir stakeholders. This paper assesses the hydropower reservoir operator strategic behavior on the *trade-offs* in the water requirements temporal conflict between irrigation and hydropower, compared to the cost-based operational approach. Using two models i) Power System Operational model and ii) Hydropower Strategic Bidding model, we consider both users interests and show how the hydropower reservoir operators strategic behavior can alleviate the users' conflicts. Results demonstrate that under strategic behavior, water volumes to the agricultural sector increase 4.3% in the irrigation season, representing a revenue increase 6.8% to this sector. The power system cost increases 7.3% in the non-irrigation season and decreases 5.9% in the irrigation season, respect to the cost-based ISO operational approach. Regardless the power system costs, this paper seeks to highlight the impact on the water resources systems of two power system operational approaches, incorporating to the analysis the particularity that the hydropower reservoir operator, may exert market power.

3.1 Introduction

In power systems organized as centralized mandatory pool, all power generators are dispatched by an Independent System Operator (ISO) following a system-wide cost minimization criterion [*Stoft*, 2002; *Kirschen and Strbac*, 2004], among these hydropower reservoir plants. This ISO operation could be cost- or bid-based, both reported by the power operators to the ISO [*Pereira and Pinto*, 1985; *Steeger et al.*, 2014]. Operation dispatched by the ISO in both schemes must converge in competitive power systems. Nevertheless, the different system conditions make those power generators that have an opportunity cost greater than their variable operating cost, have the perverse incentive to impact the market-clearing price seeking to maximize their revenues with the bids [*Puller*, 2000; *Kelman et al.*, 2001; *Borenstein et al.*, 2002; *Bushnell*, 2003; *Førsund*, 2015]. This could generate different operations of the hydropower reservoir plants, impacting the water management in the reservoirs and involves the different users who benefit from the stored water. Since the reservoir systems often supply water requirements for several uses including human consumption, irrigated agriculture, and environmental flows.

Hydropower reservoir operators —with large water storage capacity— have many advantages compared to other technologies, these advantages may provide incentives to impact the market-clearing price resulting from the ISO economic dispatch process with their bids [*Crampes and Moreaux*, 2001; *Bushnell*, 2003; *Vargas et al.*, 2003; *Flach et al.*, 2010; *Steeger et al.*, 2014]. The main advantage is the ability to store and move water at zero operating cost that could be used in future periods [*Førsund*, 2015]. Therefore, reservoir hydropower plants operators may consider the opportunity cost —represented by future expected market-clearing prices— of selling energy today or selling it in future periods [*Scott and Read*, 1996; *Flach et al.*, 2010; *Steeger and Rebennack*, 2015], preferring to reduce hydro generation in periods of high-energy demand and allocating them in low-energy demand periods [*Crampes and Moreaux*, 2001; *Bushnell*, 2003; *Førsund*, 2015]. In order to impact the market-clearing prices and thus maximize their revenue, impacting the water management in the reservoir and the interaction with the reservoir stakeholders.

Irrigated agriculture and hydropower are the main economic water uses in multi-purpose reservoir systems, irrigated agriculture represents more than two-thirds of human water withdrawals [*Gleick*, 2002] and the 71% of all renewable electricity worldwide is supplied by hydropower [*World Energy Council*, 2016]. These water uses sometimes have a conflict due to an inherent seasonal mismatch between their water requirements: hydropower has highest energy demand in winter and irrigated agriculture requirements peak during the summer season [*Castelletti et al.*, 2008]. Therefore, the water available at the beginning of winter in the reservoirs may not be available in summer for irrigated agriculture. This temporal conflict has been exacerbated due to periods of prolonged drought associated with climate change, environmental degradation and water demand increases [*OECD*, 2011; *Grayman et al.*, 2012; *IPCC*, 2014]. Whereby, this water conflict may be moderated by the strategic behavior adopted by the hydropower reservoir plants operators, which may vary depending on the operational scheme adopted in the power system, as we presented previously.

In this paper, we assess the hydropower reservoir operator strategic behavior on the *trade-offs* in the water requirements seasonal mismatch conflict, between irrigation and hydropower. Compared to the cost-based operational approach. We used two models i) Power System Operational model and ii) Hydropower Strategic Bidding model. In both cases, the irrigated agriculture user interests are incorporated into the problem formulation through monthly irrigation benefit functions. Furthermore, the economic effects that the hydropower reservoir operator strategic behavior could produce on the power system is assessed. The paper is structured as follows: Section 3.2 presents the methodology framework. In Section 3.3 the model results are presented and discussed. Finally, Section 3.4 contains the main conclusions.

3.2 Methodology framework

3.2.1 Methodology Overview

The proposed methodology is applied to a single node representation of a power system, built based on the relevant technical data from the Chilean Central Interconnected System. Here, the power grid includes a 680-MW hydropower reservoir plant and equivalent thermal generation with a known variable operating cost function that resembles the spot prices observed in the Chilean market. We use an equivalent generator with a cubic cost curve (i.e. quadratic marginal cost) to represent several thermal generators connected to the grid. Energy demand is considered deterministic while inflows are stochastic. The only reservoir in the system is used for hydropower and irrigation, with a storage capacity of 5,850 Hm^3. The reservoir in analysis corresponds to the main reservoir in the Chilean Central Interconnected System with interannual regulation.

Fig. 3.1 shows the proposed methodology, where we implemented as a base a Power System Operational model, which represents the cost-based minimization approach. From this model, we obtained the reservoir operation and the hydropower reservoir power production value, represented by the residual demand curves (RDCs). These curves combine the market-clearing prices as a function of the optimal output level of hydropower reservoir power production, and reflects the interaction of a hydropower reservoir operator with others competitors, fuel prices, and the uncertainty of energy demand and the reservoir inflows [*Scott and Read*, 1996; *Baillo et al.*, 2004; *Flach et al.*, 2010; *Baslis and Bakirtzis*, 2011; *Cruz et al.*, 2016].

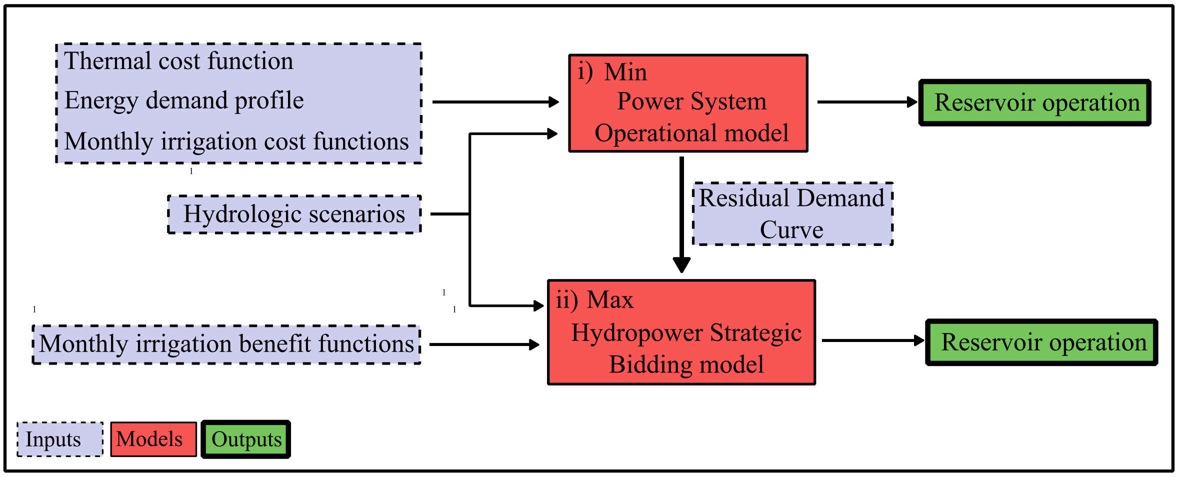

Fig. 3.9 Methodology overview

The Power System Operational model is executed five times modifying the reservoir initial storage —0, 25, 50, 75 and 100 % of capacity— to obtain the optimal hydropower reservoir power production and the market-clearing prices throughout a range of water availability values, and thus build the RCDs through the model results. Once the RCDs are built, these are incorporated in a Hydropower Strategic Bidding model along with the irrigation benefit functions. In this model, the hydropower reservoir operator decides, on based its power production value, the agriculture benefits, the water stored available and the hydrologic uncertainty, their power production and the bid price reported to the ISO. The power system costs that may be imposed by the strategic behavior of hydropower reservoir operator, were computed exogenously with the optimal power production and the bid price reported to the ISO.

3.2.2 Power system operational model

The Power System Operational model schedules the hydropower reservoir and the thermal plants to supply the energy demand at minimum cost within the planning horizon. In this paper, in addition to the thermal costs, the cost of failing to meet the irrigation water requirements is added to the ISO problem. This ISO-Irrigation problem is constrained by the capacity of the generators plants (Eq. 3.1c and 3.1d) and two balance equations (Eq. 3.1a and 3.1b). The first balance equation represents the energy demand supplied through the hydro and thermal generation, and the second one represents the water balance in the reservoir. Eq. 3.1e corresponds to the water-energy conversion. Additionally, one last constraint is included, and it represents the irrigation releases (Eq. 3.1f). We consider all turbined flows (R_t) can be used for irrigation (y_t). The inflow uncertainty is incorporated into the model through a 50-scenarios tree. The Power System Operational model is formulated as follows:

$$\underset{g_t^h, g_{t,j}, y_t}{\text{Min}} \; Z = \underset{q_t}{E}\left[\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j} g_{t,j} + C_{ir_t}(y_t)\right] \tag{3.1}$$

$$S.t. \; \sum_{j=1}^{J} g_{t,j} + g_t^h = d_t \qquad \forall t = 1, \dots, T; \qquad dual\ variable\ (\pi_t^d) \tag{3.1a}$$

$$S_{t+1} = S_t + q_t - R_t - Sp_t - ev_t(S_t) \qquad \forall t = 1, \dots, T \tag{3.1b}$$

$$g_{t,j} \leq g_{max} \qquad \forall j, t = 1, \dots, T \tag{3.1c}$$

$$g_t^h \leq g_{max}^h \qquad \forall t = 1, \dots, T \tag{3.1d}$$

$$g_t^h = \gamma R_t \qquad \forall t = 1, \dots, T \tag{3.1e}$$

$$y_t \leq R_t + Sp_t \qquad \forall\, t = 1, \dots, T \tag{3.1f}$$

Where $\boldsymbol{t}$ represents the stages —monthly time periods— in the model and $\boldsymbol{j}$ the thermal generators in the system; $C_{t,j}$ is the vector of variable operating costs of thermal generators; $C_{ir_t}(\cdot)$ are the monthly cost functions for not meeting the irrigation water requirements, $g_{t,j}$ and g_t^h are vectors of the optimal thermal and hydro generation in each stage $\boldsymbol{t}$. d_t is the vector of energy demand in each stage $\boldsymbol{t}$; S_t is the vector of storage volumes at the beginning of stage $\boldsymbol{t}$; R_t is the vector of releases at the beginning of stage $\boldsymbol{t}$; y_t is the vector of irrigation releases at the beginning of stage $\boldsymbol{t}$. q_t is the vector of natural inflows during of stage $\boldsymbol{t}$; Sp_t is the vector of spill; and ev_t is the vector of evaporation. Finally, g_{max}, g_{max}^h, and γ are the maximum thermal generator capacity, the maximum hydro generator capacity and a factor to convert water flow to energy, respectively, and E is the conditional expectation operator for water flow q_t. The planning horizon contains 3 years with monthly steps (T = 3-years), with two extra years to avoid the emptying the reservoir at the end of the 3rd year, like in *Kelman et al* [2001].

We used Stochastic Dual Dynamic Programming (SDDP) method to solve the Power System Operational model. This is a popular method for solving the planning problem of hydrothermal power systems, due to the ability to tackle the dimensionality issues related to the uncertainty and the large-scale of the power system [*Pereira and Pinto*, 1985, 1991]. The SDDP is based on building a piecewise linear outer approximations of the future value function (FVF) in two phase: a backward optimization and forward simulation [*Shahidehpour and Fu*, 2005; *Shapiro et al.*, 2013]. More details of the SDDP method can be found in *Pereira and Pinto*, [1985, 1991].

The optimal hydropower reservoir power production and market-clearing prices are used to build the RCDs for each stage $\boldsymbol{t}$, coupling each hydropower reservoir power production with the market-clearing prices observed in the system in the same stage. For each set of points by stage $\boldsymbol{t}$, we fit a quadratic function in order to have a functional form of the RCDs.

3.2.3 Hydropower strategic bidding model

The RCD curves obtained for each stage are then integrated into a Hydropower Reservoir Strategic Bidding model to evaluate the operation of the multi-purpose reservoir. In this model, the irrigated agriculture use is incorporated into the model through monthly irrigation benefit functions, which were used to obtain the monthly cost functions for not meeting the irrigation water requirements in the Power System Operational model. The Hydropower Strategic Bidding model is formulated as follows:

$$\underset{R_t, y_t}{\text{Max}}\ Z = \underset{q_t}{E}\left[\sum_{t=1}^{T} B_t(S_t, R_t, y_t) + \nu(S_{T+1})\right] \tag{3.2}$$

$$S.t. \quad S_{t+1} = S_t + q_t - R_t - Sp_t - ev_t(S_t) \qquad \forall t = 1, \dots, T \tag{3.2a}$$

$$g_t^h \le g_{max}^h \qquad \forall t = 1, \dots, T \tag{3.2b}$$

$$g_t^h = \gamma R_t \qquad \forall t = 1, \dots, T \tag{3.2c}$$

$$y_t \le R_t + Sp_t \qquad \forall t = 1, \dots, T \tag{3.2d}$$

$$\boldsymbol{B_t(S_t, R_t, y_t) = \left(\vartheta_t\left(g_t^h(S_t, R_t)\right) * g_t^h(S_t, R_t)\right) + B_{ir_t}(y_t) + \xi_t' Sp_t} \tag{3.2e}$$

Where $B_t(\cdot)$ is the benefit function of the water use in the multi-purpose reservoir, for the hydropower reservoir and irrigated agriculture (Eq. 3.2e). $\vartheta_t(\cdot)$ are the RDCs of the hydropower reservoir; g_t^h is the vector of optimal hydro generation in each stage $\boldsymbol{t}$; $B_{ir_t}(\cdot)$ are the monthly irrigation benefit functions; y_t is the vector of irrigation releases at the beginning of stage $\boldsymbol{t}$; Sp_t is the vector of spill and ξ_t' a vector of penalty coefficients. $\nu(\cdot)$ is a terminal value function; and E is the conditional expectation operator for water flow q_t. Eq. 3.2a represents the water balance in the reservoir, where S_t is the storage volumes at the beginning of stage $\boldsymbol{t}$; R_t is the vector of hydropower releases at the beginning of stage $\boldsymbol{t}$; q_t is the vector of natural inflows during the stage $\boldsymbol{t}$; ev_t is the vector of evaporation; g_{max}, g_{max}^h, γ and are the maximum thermal generator capacity, the maximum hydro generator capacity, and a factor to convert water flow to energy respectively.

3.2.3.1 Hydropower strategic bidding model solution strategy

In this paper, we used Sampling Stochastic Dynamic Programing (SSDP) [*Kelman et al.*, 1990], combined with a polynomial interpolation, with the aim to generate optimal monthly steady-state future value functions (FVFs). Then these FVFs are used to simulate the multi-purpose reservoir operation through a re-optimization process [*Tejada-Guibert et al.*, 1993]. We used a Chebyshev interpolation like in *Miranda and Fackler* [2004] in order to reduce the problem dimensionality and computational effort [*Johnson et al.*, 1993]. The SSDP formulation of the Hydropower Strategic Bidding model is as follows:

$$\operatorname*{Max}_{R_t^*, y_t^*}\left[\frac{1}{L}\sum_{l=1}^{L}\left[B_t\left(S_t^j, R_t, q_t^l, y_t\right) + \alpha f_{t+1}^i(S_{t+1}, l)\right]\right] \qquad \forall j, and\ t = 1, \dots, T \qquad (3.3)$$

$$S.t. \qquad S_{t+1} = S_t + q_t - R_t - Sp_t - ev_t(S_t) \qquad \forall t = 1, \dots, T \qquad (3.3a)$$

$$g_t^h \leq g_{max}^h \qquad \forall t = 1, \dots, T \qquad (3.3b)$$

$$g_t^h = \gamma R_t \qquad \forall t = 1, \dots, T \qquad (3.3c)$$

$$y_t \leq R_t + Sp_t \qquad \forall\, t = 1, \dots, T \qquad (3.3d)$$

Eq. (3.3) is the Bellman equation for the optimization problem Eqs. (3.3-3.3d), where q_t^l is the reservoir inflow in the stage $\boldsymbol{t}$ under the l-th inflow scenario; $\boldsymbol{f_{t+1}^i}$ are the FVFs; S_t^j is $\boldsymbol{j}$-th discrete reservoir storage volume at the beginning of stage t, with $S_t^1 = S_{min}$ and $S_t^J = S_{max}$, and $\boldsymbol{i}$ is the iterations number makes by the model until the FVFs converge. The model optimizes over 50 historical inflow scenarios ($\mathrm{L} = 50$) with monthly stages over an annual planning horizon (T =12-month); therefore, each inflow scenario corresponds to 12-month and each iterations $\boldsymbol{i}$ is a moved by $t = T, T-1, \dots, 1$, solving the bellman equation (Eq. 3.3) in each stage $\boldsymbol{t}$.

The optimization model (Eqs. 3.3 to 3.3d) is solved for an annual infinite horizon, for each discretization of the state variable $\boldsymbol{j}$ and for each stage $\boldsymbol{t}$. The solution for each stage is a target releases for each water use R_t^* and y_t^* . These targets are then corrected for feasibility under each hydrologic scenario $\boldsymbol{l}$ through Eqs. 3.3e to 3.3g, respectively. The adjusted releases (R_t^l, y_t^l) are then used to update the value function $\boldsymbol{f_t^i}(\cdot)$ (Eq. 3.3h), which reflects the total —present and future— value of release decision at each stage $\boldsymbol{t}$, under each inflow scenario $\boldsymbol{l}$. This procedure is repeated for each stage $t = T, T-1, \dots, 1$, and for each discretization of the state variable $j = 1, \dots, J$, until the functions $\boldsymbol{f_t^i}(\cdot)$ converge. In the first iteration $\boldsymbol{i}$ for the stage T, $f_{T+1}^1(\cdot) = 0$ are performed for all $\boldsymbol{j}$ reservoir discretizations, and then in the second iteration the FVFs —$f_{T+1}^2(\cdot)$— for all $\boldsymbol{j}$ reservoir discretizations is updated such that $f_{T+1}^2(\cdot) = f_1^1(\cdot)$, and so on at each iteration $\boldsymbol{i}$.

$$R_t^l = min\left\{\begin{matrix} max[R_t^*, S_t + q_t^l - R_t - Sp_t - ev_t(S_t) - S_{max}], \\ S_t + q_t^l - R_t - Sp_t - ev_t(S_t) - S_{min} \end{matrix}\right\} \tag{3.3e}$$

$$g_t^{h,l} = \gamma R_t^l \tag{3.3f}$$

$$y_t^l = \left\{\begin{matrix} R_t^l & if & R_t^l \leq Ir_t, \\ Ir_t & if & R_t^l > Ir_t \end{matrix}\right\} \tag{3.3g}$$

$$f_t^i(S_t^j, l) = B_t(S_t^j, g_t^{h,l}, q_t^l, y_t) + \alpha f_{t+1}(S_{t+1}^j, l) \qquad \forall j, l \; and \; t = 1, \dots, T \tag{3.3h}$$

In the Eq. 3.3g, Ir_t is the irrigation requirement at stage t. Once the stationary FVFs for each inflow scenario $\boldsymbol{l}$ converge these are used in the re-optimization. This process uses the same 50-scenarios tree and the same planning horizon (T = 3-years) used in the Power System Operational model. Moreover, the simulation process is run with 25% of initial storage, with the aim to evaluate the system performance with an unfavorable initial storage.

3.3 Results and discussion

We focused on comparing reservoir releases, reservoir storage, water user revenue and power system cost from both models. Fig. 3.10 shows the monthly hydropower reservoir RDCs. Each point on the curve corresponds to the optimal combination of the hydropower reservoir production and the market-clearing prices for specific initial storage, hydrologic scenario, and energy demand. We can see that these curves adequately represent the energy demand seasonality. Highest energy prices are observed during non-irrigation season —Apr-Aug—, whereas during Oct-Mar are observed lower energy prices. These results are consistent because the energy demand is higher in non-irrigation seasons and thus more costly thermal energy is used to supply the demand.

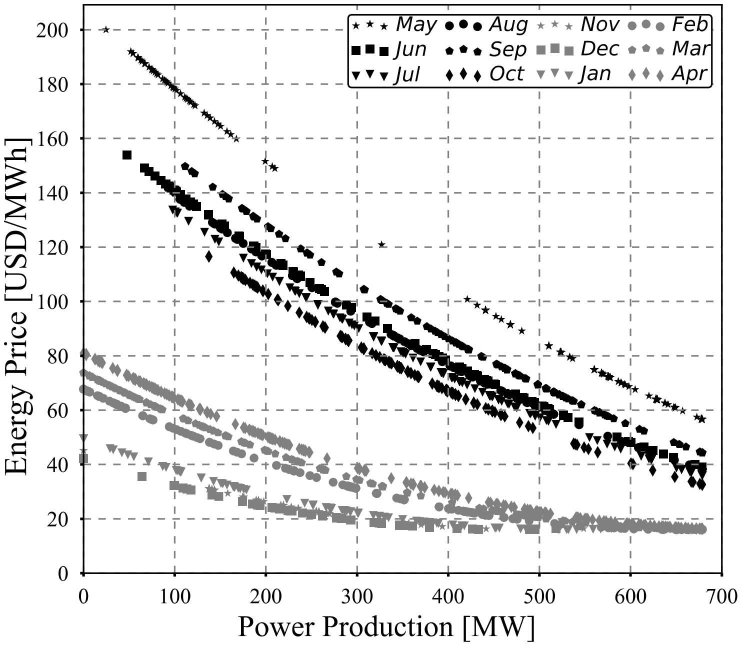

Fig. 3.10 Residual Demand Curve

Regarding the reservoir operation, Fig. 3.11 shows cumulative frequency curves over reservoir releases results of hydropower reservoir and irrigated agriculture uses in both models over hydrologic uncertainty. Hydropower reservoir releases are normalized with the maximum release of the Power System Operational model (Fig. 3.11a-b) and the irrigated agriculture releases by the irrigation water demand in the whole irrigation season (Fig. 3.11c). Results are shown for the monthly sum of releases of irrigation and non-irrigation season for the planning horizon. We can see that in the non-irrigation season (Fig. 3.11a) reservoir releases from the Hydropower Strategic Bidding model are smaller in those optimal releases under Power System Operational model —for cumulative frequencies below 60%—. This is concordant with the strategic behavior because the hydropower reservoir operator withholds —stores— water in the months when energy is most valuable —non-irrigation season— to drive prices further up and increase revenue. The withheld water is later used during the irrigation season (Fig. 3.11b). For example, with 20% of cumulative frequency, the hydropower reservoir operator in the strategic bidding model allocates 47% of water in the non-irrigation season, while in the irrigation season allocates 68%. Interestingly, under strategic behavior, the hydropower reservoir operator allocation is quite stable. For example, releases vary only 3% and 6% for cumulative frequencies below 80%, for the non-irrigation (Fig. 3.11a) and irrigation season (Fig. 3.11b), respectively. In the Power System Operational model, optimal solutions perceive more variable releases, with changes of 70% and 50% for cumulative frequencies below 80%, in the non-irrigation (Fig. 3.11a) and irrigation season (Fig. 3.11b), respectively.

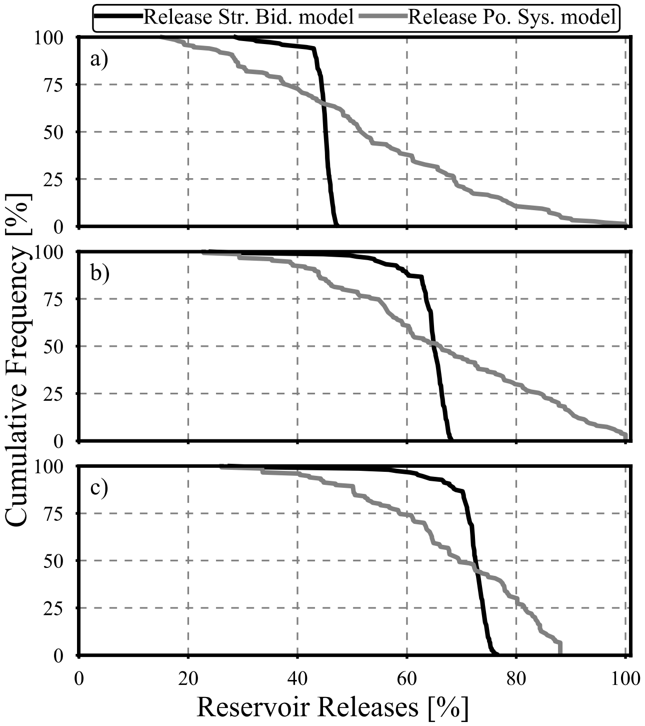

Fig. 3.11 Cumulative frequency of reservoir releases. a) Total hydropower releases non-irrigation season b) Total hydropower releases irrigation season c) Total irrigated agriculture releases.

Furthermore, in Fig. 3.11c we can see that under most hydrologic scenarios, with strategic behavior irrigated agriculture releases are higher to supply the irrigation demand. For example, 70% of the irrigation demand is satisfied with 80% of cumulative frequency from the strategic bidding model, whereas only 52% of irrigation demand is met with the same cumulative frequency in the optimal Power System Operational model. On average, the Hydropower Strategic Bidding model releases 4.3% more water volume to the agricultural sector than the optimal Power System Operational model solution.

Fig. 3.12 shows that water users' revenue improves in most scenarios under the optimal Hydropower Strategic Bidding model solution. With cumulative frequency higher than 41% with respect to the revenues perceived in the Power System Operational model, the irrigated agriculture revenues are higher in the strategic bidding model (Fig. 3.12a), while the hydropower reservoir operator revenues are higher for cumulative frequency higher than 19% in the strategic bidding model (Fig. 3.12b). On average, the revenues that are perceived by each user is greatest in the Hydropower Strategic Bidding model, where the irrigated agriculture user increases their revenue 6.8% and hydropower reservoir operator increases 10.8%, compared to the Power System Operational model.

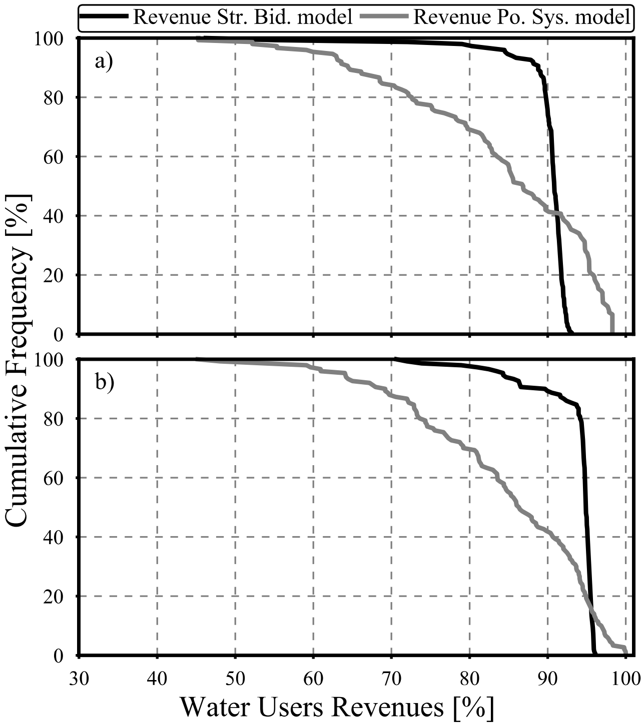

Fig. 3.12 Cumulative frequency of water users' revenues. a) Irrigated agriculture b) Hydropower.

The power system operational costs in the two seasons —non-irrigation and irrigation— is shown in Fig. 3.13. We can see that the system costs are higher in the Hydropower Strategic Bidding model for a cumulative frequency higher than 59% in the non-irrigation season and 39% in the irrigation season with respect to the maximum cost observed in the Power System Operational model. On average, the cost in the non-irrigation season is 7.3% higher in the strategic bidding model due to water withhold. In the irrigation season, the cost tendency is reversed, on average in the Power System Operational model, the system operation is 5.9% more costly with respect to strategic bidding model solutions. This is so because a large part of the water withheld is stored and then used during the irrigation season. An interesting point related to the system costs is that regardless of which model increases or decrease the costs, in the Hydropower Strategic Bidding model the system costs holds slight variations in most hydrologic scenarios. With higher than 20% of cumulative frequency, the costs variations are less than 5% in both seasons, while in the Power System Operational model with the same cumulative frequency the costs variations are 59% in the non-irrigation season (Fig. 3.13a) and 57% in the irrigation season (Fig. 3.13b).

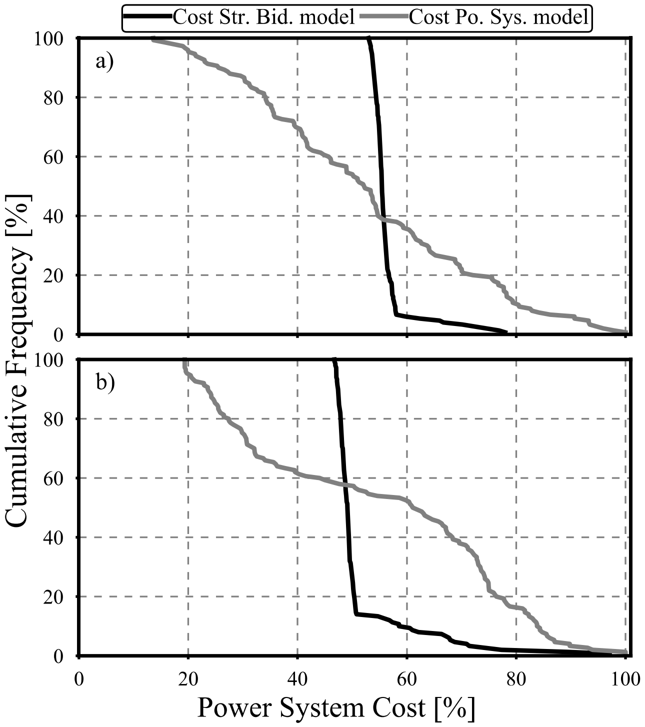

Fig. 3.13 Cumulative frequency of power system costs. a) Total cost non-irrigation season b) Total cost irrigation season.

In the strategic bidding model, the hydropower reservoir operator regulates the system inflows taking advantage of the storage capacity. As we can see in Fig. 3.14, although the re-optimization starts with a storage capacity of 25%, the average storage in the planning horizon —normalized with the maximum capacity— in the Power System Operational model is never large than 10%. While in the Hydropower Strategic Bidding model, more water is stored in both seasons. We can see that on average with 50% cumulative frequency in the non-irrigation season the water stored is 14% in the strategic bidding model, while in the power system model is 5% of the maximum reservoir capacity (Fig. 3.14a). In the irrigation season, both models stored slightly more water, where with 50% cumulative frequency the water stored is 18% in the strategic bidding model and 7% in power system model (Fig. 3.14b).

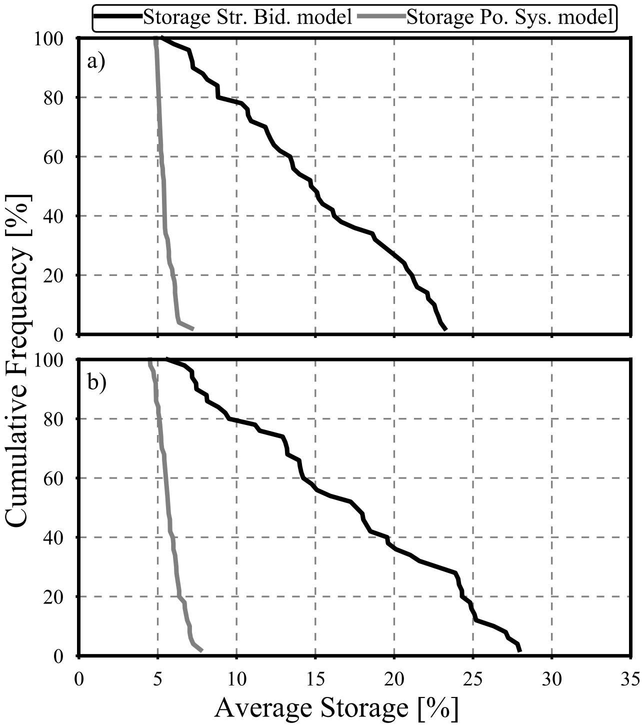

Fig. 3.14 Cumulative frequency of average storage in the planning horizon. a) Storage non-irrigation season b) Storage irrigation season.

Finally, Fig. 3.15 shows the reservoir releases for two hydrologic scenarios —normal and dry—. Furthermore, this figure also shows the irrigation demand and the ratio for both models of the system costs —Hydropower Strategic Bidding/Power System Operational— for the two scenarios in one year of simulation. We can see slight differences in the turbined flow in the strategic bidding model in both scenarios. This is consistent with the results in Fig. 3.11 where reservoir releases in both seasons remained almost constant over the hydrologic scenarios, and this is explained by the regulation of the system inflows in the reservoir. On the contrary, in the Power System Operational model, the releases are large if volumes of water are available, with the aim of minimizing the present system costs. We can see differences in the reservoir releases in the Power System Operational model in both hydrologic scenarios and in the dry scenario it is possible to observe that the irrigated agriculture sector is strongly affected.

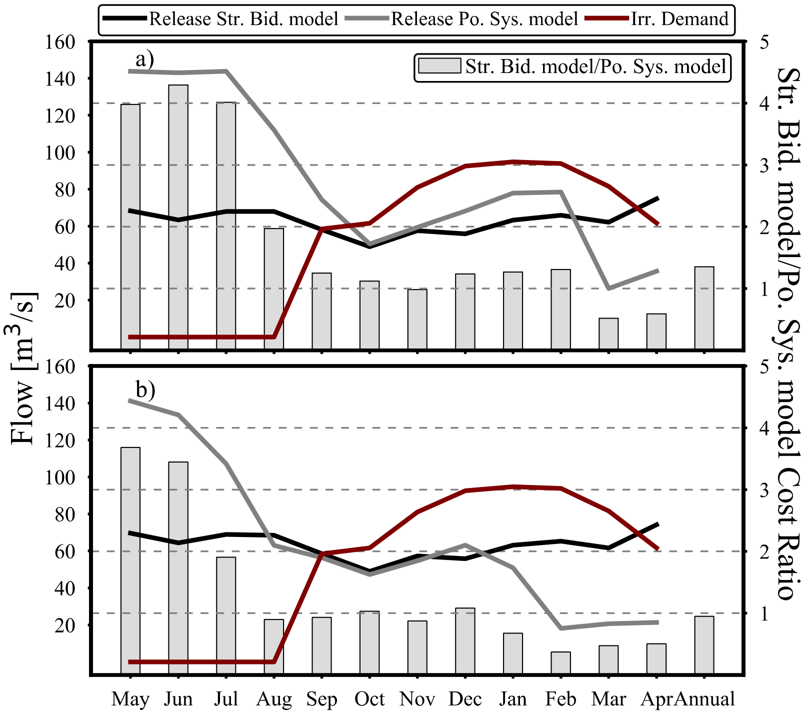

Fig. 3.15 Reservoir operation and system cost of one year of simulation. a) Normal inflow hydrologic scenario b) Dry inflow hydrologic scenario.

In the Hydropower Strategic Bidding model, as we can see, although the irrigation demand is never met under both inflow scenarios, the reservoir releases are closer to irrigation demand compared to Power System Operational model releases. Evidently, higher turbined flows imply lower power system costs, and this can be seen in Fig. 3.15. In the normal hydrological scenarios, the annual system cost is 35% higher in strategic bidding model, compared to the Power System Operational model. Nevertheless, this is reversed in the dry scenario where the annual system cost is 5% higher in Power System model.

3.4 Conclusions

We contribute with an analysis of the water requirements seasonal conflict, between irrigation and hydropower, incorporating into the problem the strategic behavior that could have a hydropower reservoir operator in a power system. Residual demand curves were used together with monthly irrigation benefit functions in a Hydropower Reservoir Strategic Bidding model. In this model, the hydropower reservoir operator decides, on based its power production value, the agriculture benefits, the water stored available and the hydrologic uncertainty, their power production and the bid price reported to the ISO. Results demonstrate that under strategic behavior, water volumes to the agricultural sector increase on average 4.3% in the irrigation season, respect to the cost-based ISO operational approach. This water volume increase represents a revenue increase on average 6.8% to this sector, which could smooth the water conflicts between these water users. Evidently, the power system costs are higher in the non-irrigation season if the hydropower operator exerts market power —on average 7.3% respect to the cost-based approach—. Although, in the irrigation season this cost tendency is reversed because a large part of the water withheld is stored during the non-irrigation season and then used in the irrigation season reducing the system costs. Regardless the power system costs, this paper seeks to highlight the impact on the water resources systems of two power system operational approaches, incorporating to the analysis the particularity that the hydropower reservoir operator, may exert market power.

CAPÍTULO 4. Conclusiones y trabajo futuro

Se presentó una propuesta metodológica donde se vinculan dos escalas espaciales de utilización del recurso hídrico; escala de cuenca y escala de sistema eléctrico, en un horizonte de planificación de mediano y largo plazo. Además se evaluó mediante dos enfoques el conflicto temporal entre la hidroelectricidad —con capacidad de almacenamiento— y agricultura. Para resolver el OE1, se implementó dos modelos de optimización, i) modelo hidro-económico, el cual incorpora el valor económico del agua para los dos usos del agua, y ii) modelo de riego fijo, el cual incorpora los requerimientos hídricos del uso agrícola mediante restricciones al problema. De los resultados del modelo de riego fijo se observa que la asignación de agua desde el embalse para el sector agrícola tiende a seguir el patrón estacional de los requerimientos hídricos, sin embargo el sistema falla y no satisface los requerimientos al final de la temporada de riego, generando pérdidas al sector agrícola. Mientras que en el modelo hidro-económico, el embalse no satisface los requerimientos hídricos del sector agrícola durante toda la temporada de riego, pero los déficits son más leves que los observados en el modelo de riego fijo. Por ejemplo, con una frecuencia acumulada del 55% los requerimientos de riego se satisfacen al 100% en la primera mitad de la temporada de riego en modelo de riego fijo, mientras que en el modelo hidro-económico con la misma frecuencia acumulada se cubre el 79% de los requerimientos en esta primera mitad de la temporada. En la segunda mitad de la temporada de riego se invierte la tendencia de entrega de agua desde el embalse. Con una frecuencia acumulada del 60%, el modelo hidro-económico cubre el 50% de los requerimientos del sector agrícola, mientras que el modelo de riego fijo cubre solo el 33% de los requerimientos. Esta mejor distribución de agua en la temporada de riego genera en promedio, un incremento del 2,5% en los beneficios económicos en la cuenca, un 5,4% en los beneficios económicos del sector agrícola y un 1,8% en los beneficios económicos del sector hidroeléctrico, disminuyendo los conflictos en la cuenca entre los usuarios del agua en presencia de escasez hídrica.

En el OE 2 se contribuye al análisis del conflicto estacional de los requerimientos hídricos entre los usos agrícola e hidroeléctrico, incorporando en el problema el comportamiento estratégico que podría tener el operador de las centrales hidroeléctricas —con capacidad de almacenamiento— en un sistema de energía. En este caso, se utilizaron curvas de demanda residual para el uso hidroeléctrico junto con funciones mensuales de beneficios de riego en un modelo hidro-económico. Los resultados demuestran que bajo el comportamiento estratégico del generador hidro, los volúmenes de agua al sector agrícola aumentan en promedio 4,3% en la temporada de riego, respecto a un enfoque donde el operador hidro no actúa estratégicamente. Este aumento de volumen de agua representa un aumento de los beneficios económicos del 6,8% para el sector agrícola, lo cual generaría una disminución los conflictos de agua entre el riego y la hidroelectricidad. Evidentemente el comportamiento estratégico del operador hidro, impacta los costos del sistema eléctrico. En los meses de no riego estos costos en promedio aumentan 7.3% debido a que la decisión del operador hidro es almacenar agua para elevar el precio de la energía. El agua retenida por el operador es luego utilizada en los periodos de riego lo cual genera una disminución del costo de 5.9% respecto a la operación del sistema eléctrico sin la incorporación del comportamiento estratégico del operador hidro. Este movimiento de energía —agua— del operador hidro entre temporadas —riego y no riego—, genera una operación estable del embalse beneficiando implícitamente al sector agrícola. Independientemente de los costos del sistema eléctrico, este trabajo buscó destacar el impacto en los sistemas de recursos hídricos, la incorporación al análisis del conflicto temporal de los usos agrícola e hidroeléctrico, la particularidad de que el operador hidro pueda ejercer poder de mercado en el sistema eléctrico. Lo cual puede dar luces en la toma de decisiones en la gestión de los recursos hídricos.

Como trabajo futuro, es importante contar con una metodología que vincule los resultados de mediano y largo plazo de este estudio, con la operación de corto plazo de los sistemas de embalse multipropósito. Esta metodología debe permitir la evaluación en tiempo real de la planificación conjunta del recurso hídrico, en comparación con la planificación mediante reglas de operación fijas, para incluir los objetivos de los usos del agua en el sistema. Por otro lado, es necesario incorporar en esta planificación, además de criterios económicos, criterios medioambientales que permitan abordar integralmente el problema actual de gestión y planificación de los sistemas de recursos hídricos.

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