Hydrothermal Coordination Model with Endogenous Irrigation Constraints Application to the Chilean Central Interconnected System

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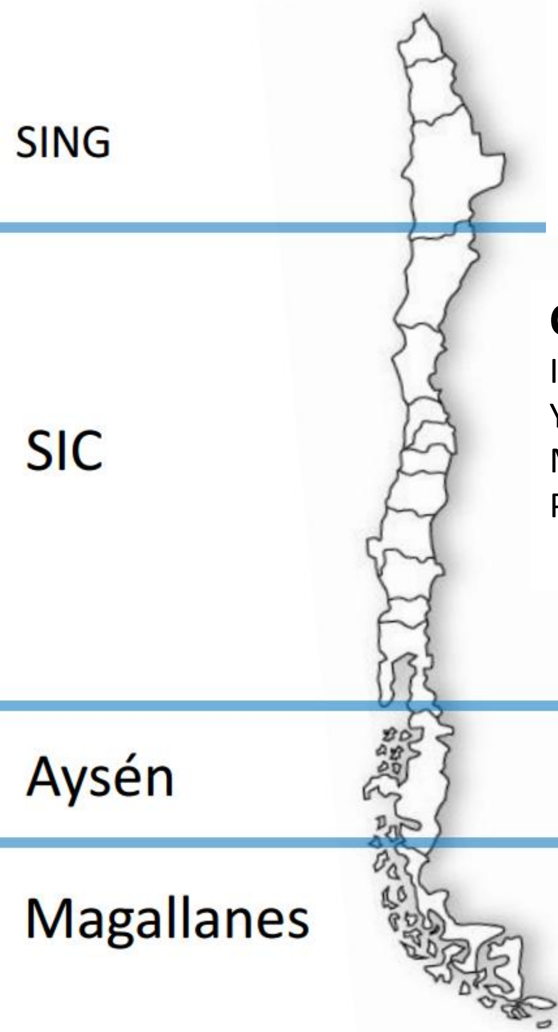
Chilean interconnected systems



Northern Interconnected System
Installed capacity: 4.607 MW
Yearly generation: 14.101 GWh
Maximum demand: 2226 MW
Population: 6.3%

Central Interconnected System
Installed capacity: 15.099 MW
Yearly generation: 50.939 GWh
Maximum demand: 7282 MW
Population: 92.2%

Aysen
Installed capacity: 44 MW
Yearly generation: 137 GWh
Maximum demand: 22MW
Population: 0.6%

Magallanes
Installed capacity: 118 MW
Yearly generation: 292 GWh
Maximum demand: 51 MW
Population: 0.96%

	Buses	Lines	Units
SIC	175	253	360
SING	67	119	97
Total	242	372	457

	Basins	Dams	Hydro units
SIC	4	9	98

Hydro system only in the SIC syst (until 2017)

Data 2014

Laja Lake basin

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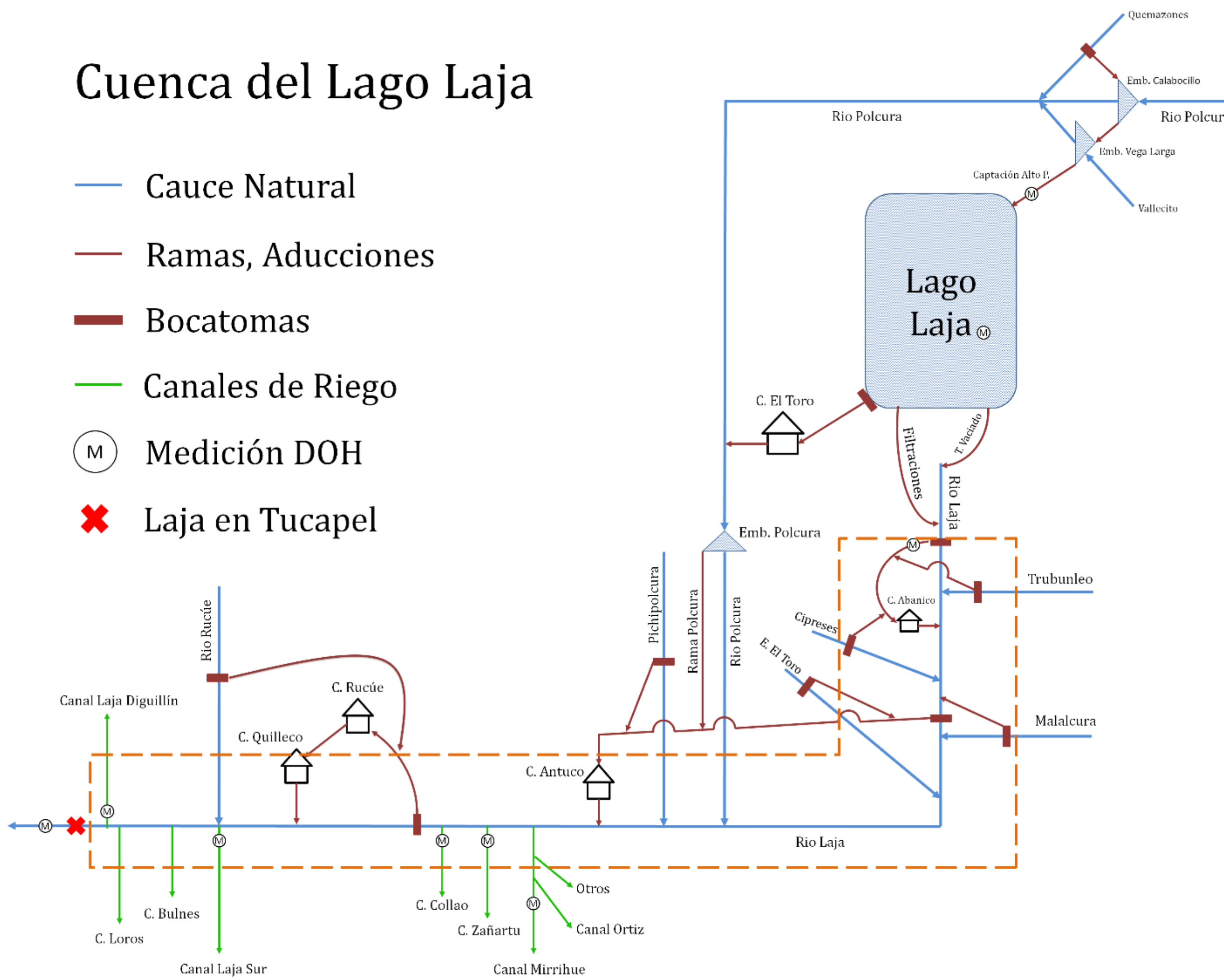
- Laja is a natural and the largest lake (5.5e9 m3) with important filtrations (47 m3/sec).
- Irrigation agreement signed in 1958, 27 years before the electric market existed.
- The purpose was to "ensure the same level of irrigation resources before the power plant was built."

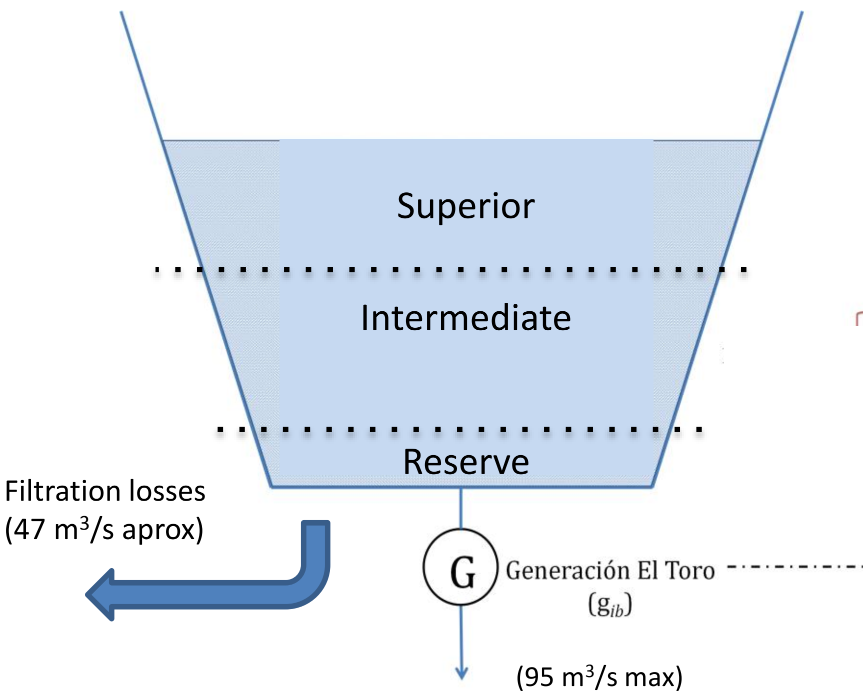


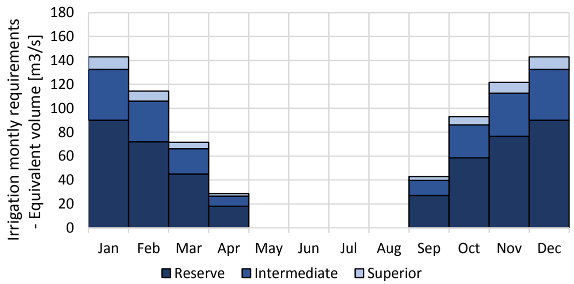
Laja Irrigation Agreement

The agreement defines an amount of irrigation/generation rights that may be expended to at least complete the historical filtrations for irrigation, and also to generate electricity.

The water for irrigation is needed mainly during the summer season, and the rights are modulated accordingly. Rights that are not used can be saved for the next year.

The agreement explicitly it reduces the water rights as the lake reaches lower portions, to avoid the depletion of the lake.





The irrigation season goes from September to April

Generation rights
Savings (in intermediate portion)
Savings (in reserve portion)

Mutually exclusive

Maule and Invernada basin

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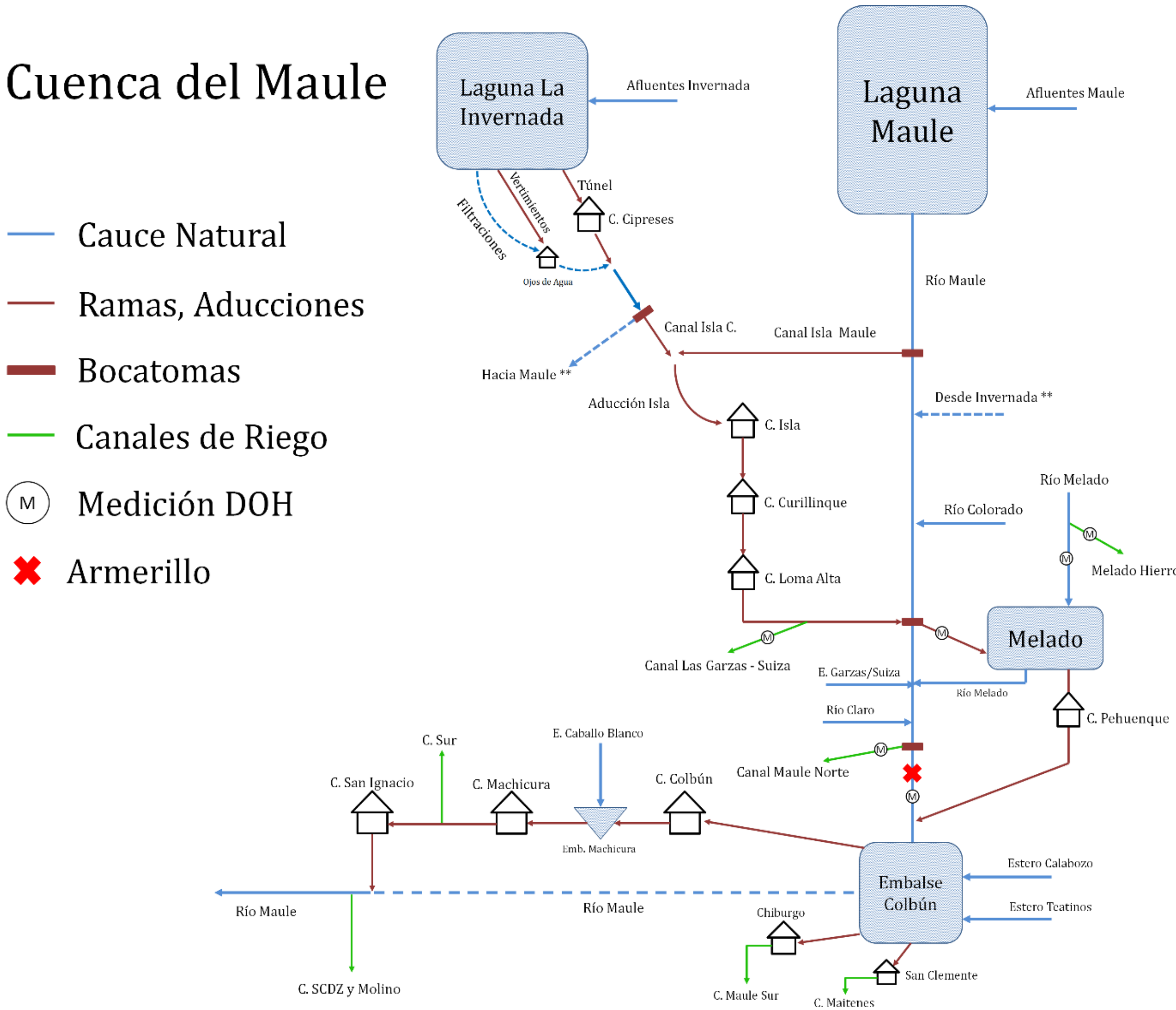
- Maule is the largest artificial lake in a 4 reservoirs basin.
- Irrigation agreement signed in 1947, 38 years before the electric market, and complemented in 1983 with Colbún additional rules.
- The purpose was to "improve the water availability for irrigation and power uses."
- It separates the generation and irrigation rights in different accounts.

Cuenca del Maule



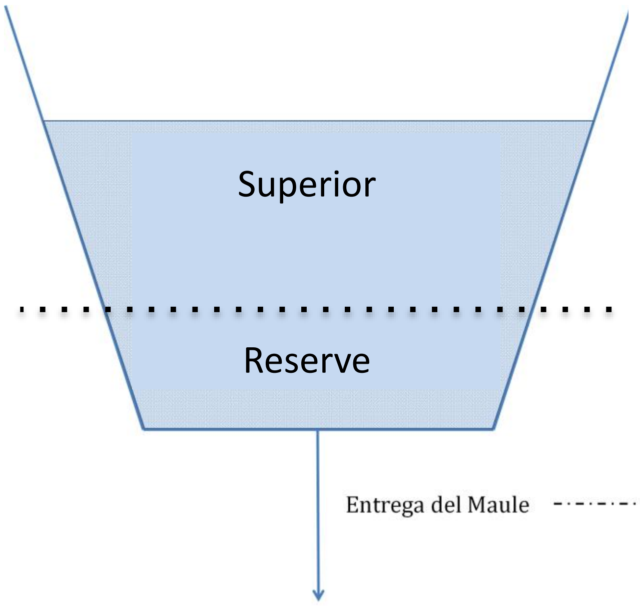
Maule Irrigation Agreement

In the same fashion, two portions were established for the Maule lake, and different variables are defined to represent irrigation and power rights, as well as savings.

There are irrigations rights for the whole year and they are provided by the Maule, Invernada and Colbún lakes (and sometimes melado).

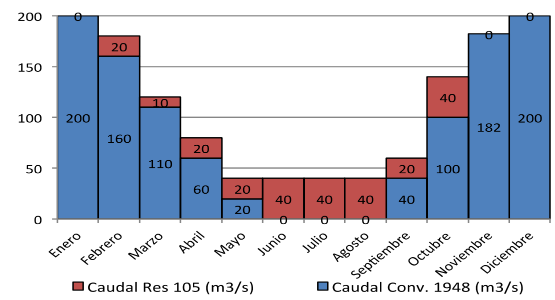
The is also a multi-year savings account for generation rights, but it has a limit.

The irrigation associations built their own power plants units, totalizing 11 in the basin.



Generation rights
Irrigation rights
Savings (in upper portion)
Savings (in lower portion)

Mutually exclusive



Irrigation Agreement Modelling

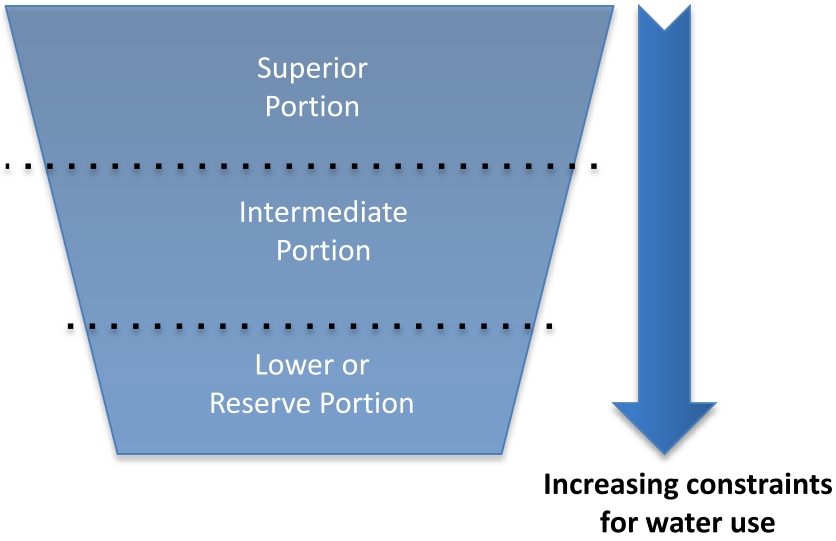
- Feasibility cuts were implemented in the SDDP program PLP (forward/backward), needed for the filtration and irrigation agreements (Laja)

- Additional state/stage variables and constraints for irrigation codes
  - Laja Lake irrigation agreement: 7 state / 20 stage variables
  - Maule/Invernada irrigation agreement: 9 state / 26 stage variables

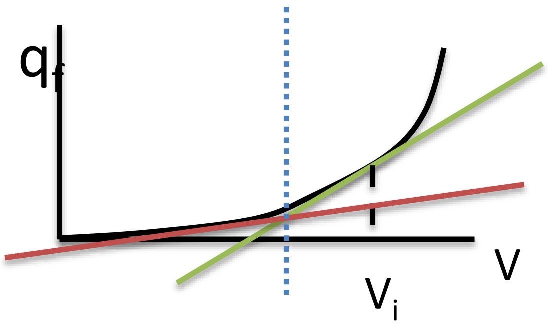
- The lake "portion" for each lake is set at each stage depending of the initial volume of the reservoir.

- Explicit filtration models were also needed

Lake Portion defined by V_i



Explicit filtration model



$$qf_i - M_i \cdot vf_{it} = B_i$$

Convexity Caveats

- Besides the natural concerns about the convexity of an hydro-thermal coordination problem, the concept of “lake portions” in both irrigation agreements (Laja and Maule) introduces “if” conditions or binary states.
- The binary states required to fully represent the irrigation agreements introduce discontinuities that will affect (or break) the convexity, specially in the stages where there is a portion transition.
- We have developed a formalism to better understand these kind of constraints and the implication in the irrigation agreement modeling in Chile.
- The formalism may be extended to other hydro system with similar binary constraints, and the current approach can be understood as a near-optimal/feasible solution.

Optimizing hydrothermal scheduling with non-convex irrigation constraints: Case on the Chilean electricity system

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Multipurpose reservoirs and portions

▶ Near optimal approach / Small scale system example

- In order to maintain the convexity, we use a near-optimal approach; portion-dependant constraints are updated dynamically before solving the particular stage problem.

- Example: 1 reservoir divided in 2 portions

Portions rules

- $Q_t^i \leq Q_{MAX}^i \quad if\ v_{t-1}^{final} \geq \frac{v^{max}}{2}$
- $Q_t^i \leq \frac{Q_{MAX}^i}{2} \quad if\ v_{t-1}^{final} < \frac{v^{max}}{2}$

Equivalent MILP

- $Q_t^i - (1 + u_t) \cdot \frac{Q_{MAX}^i}{2} \leq 0$
- $u_t \cdot \frac{v^{max}}{2} - v_{t-1}^{final} \leq 0$
- $(1 + u_t) \cdot \frac{v^{max}}{2} - v_{t-1}^{final} > 0$

- Although this clearly corresponds to an approximation, it permits optimization of very large problems associated with country-size systems in an SDDP fashion, which cannot be undertaken through direct solution of MILP problem

- The above approach also allows us to find a feasible solution that cannot be found through relaxations (i.e. the solution obtained through near-optimal approach is a feasible –but not optimal– solution of MILP problem)

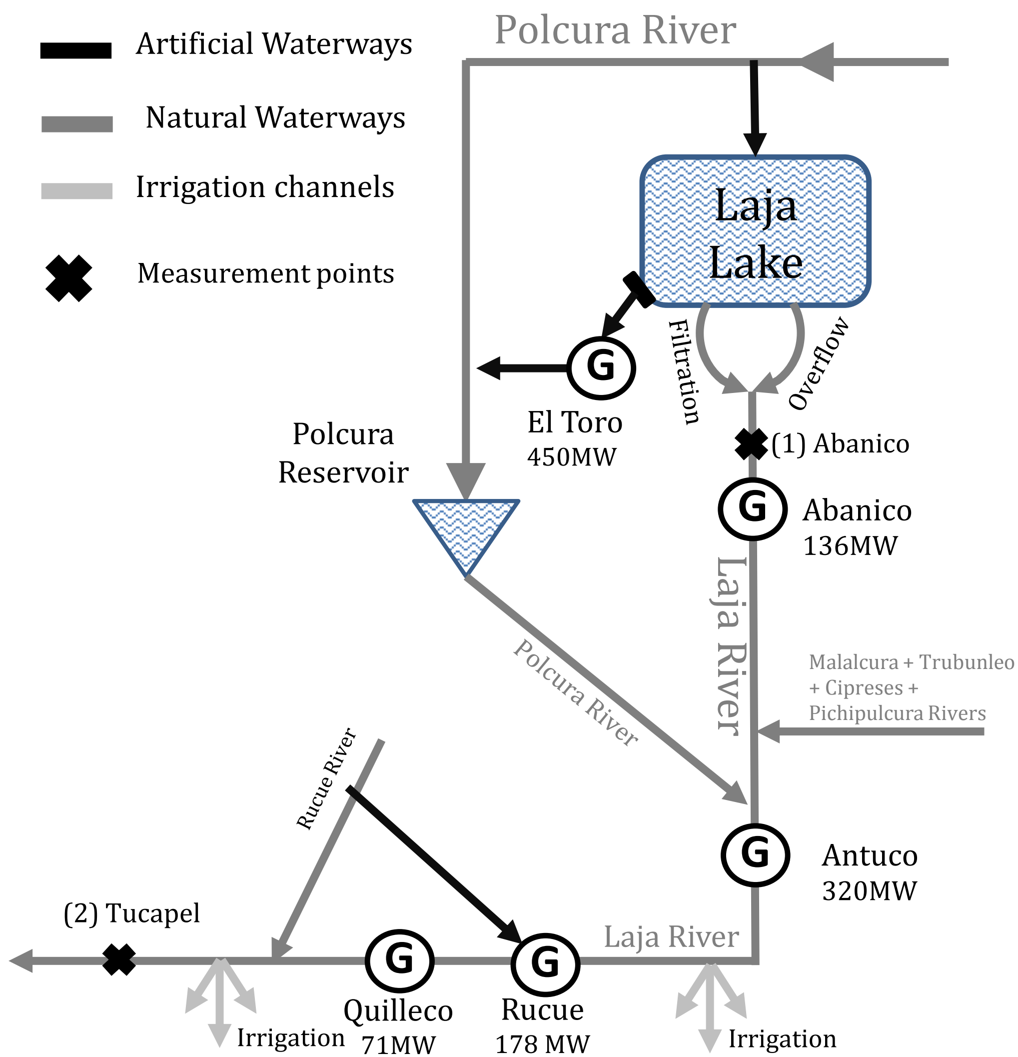
Laja Lake in Chile case study

- Example of the concept of operating policy based in portions

- An example of such policy is the code that rules the withdrawals from Laja Lake in Chile, suscribed in 1958

- Regulates the release of water for electricity generation of El Toro power plant (450 MW) with the purpose of ensuring supply for downstream water user associations (WUA), which are mainly agricultural.

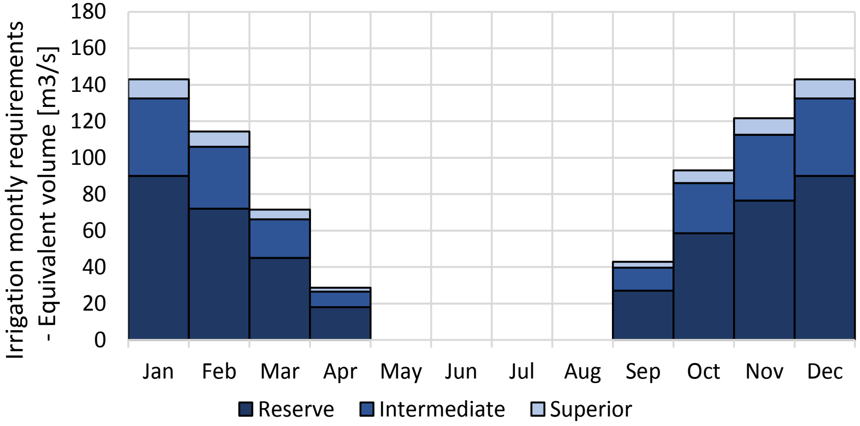
- Many rules in different time scales apply. In this work we describe those related to the use of portions.



Laja Lake in Chile case study

- Example of the concept of operating policy based in portions

- Three portions are established (superior, intermediate and reserve)
- *El Toro* power plant is required to complete irrigation requirements, depending on portion and month of the year (lower bound)
- Electricity generation has an upper bound on each portion
  - 57 m^3/s in the intermediate and superior portions
  - 47 m^3/s in the reserve portion



$$Q_{total\_Laja_t} = Q_{FILT_t} + Q_{T\_ElToro_t}$$

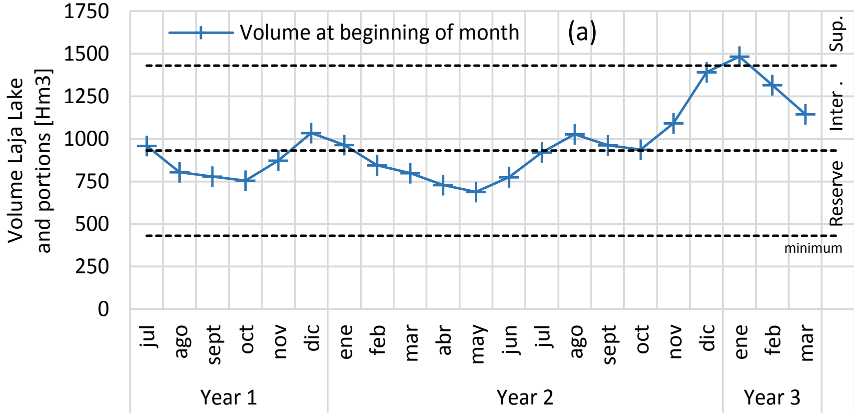
$$Q_{total\_Laja_t} \leq \overline{Q_{W\_RIGHTS_t}}\left(v_{t-1}^{final}\right)$$

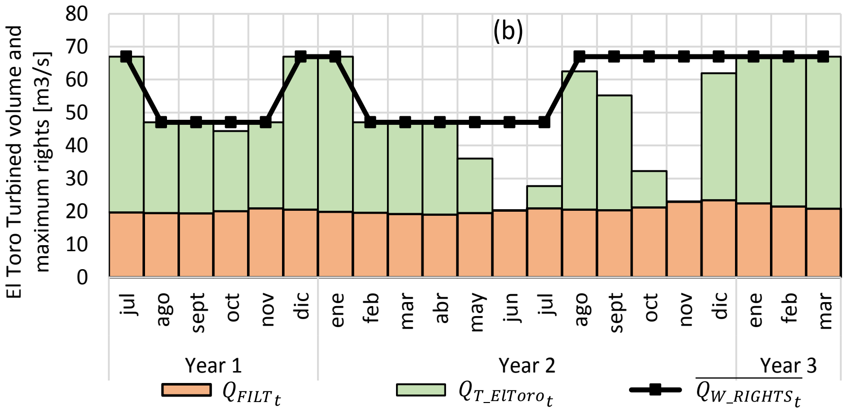
$$Q_{total\_Laja_t} \geq Q_{IRR\_REQ_t}\left(v_{t-1}^{final}\right) - Q_{inflows_t}$$

Laja Lake in Chile case study

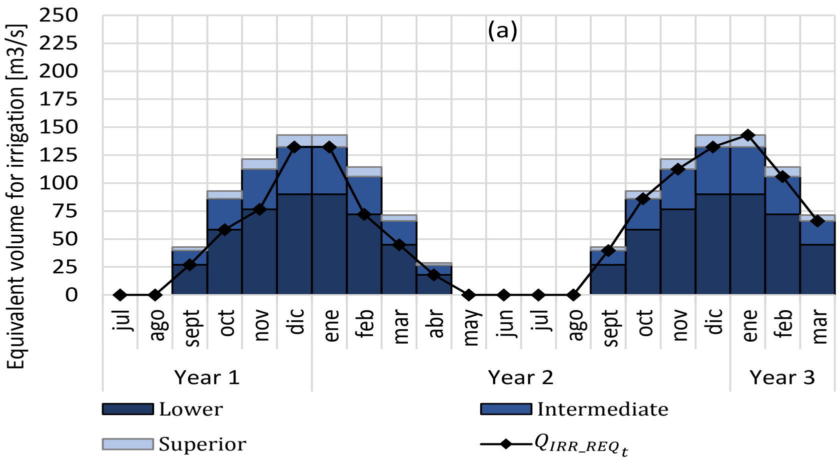
- Results for Chilean interconnected system case study

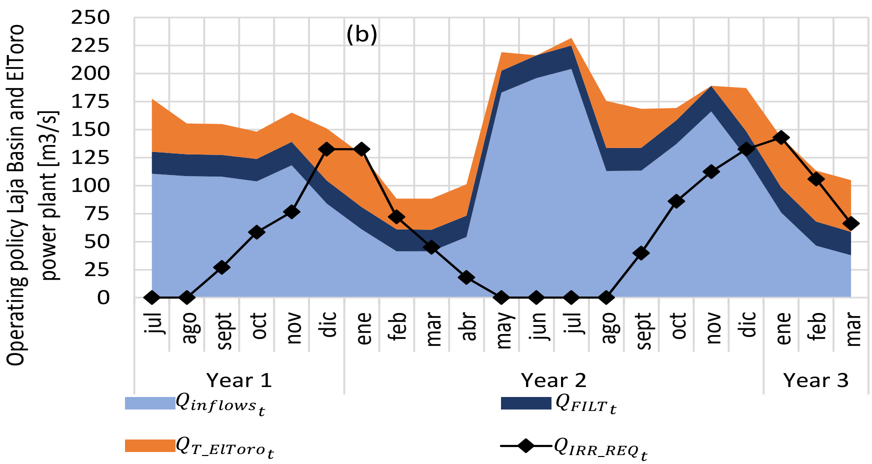
- Operating policy of reservoir and water withdrawals for electricity generation





- Irrigation requirements fulfillment





Conclusions and further work

The near-optimal approach maintains the linear structure of each subproblem, allowing us to apply SDDP method to include irrigation constraints with mutually exclusive rules

Although this is proved to be suboptimal, optimization problem can be successfully solved for very large-scale power systems, finding a feasible solution (i.e. the solution obtained through near-optimal approach is a feasible –but not optimal– solution of MILP problem).

The application is illustrated on a real representation of the Chilean power system to model nation wide irrigation agreements. In this context, we demonstrated that the near-optimal approach provides feasible solutions that meet code requirements, while minimizing operating costs.

We are currently working on alternative SDDP formulations, especially in terms of how to determine Benders cuts, to improve quality of the presented near-optimal approach.

Issues associated with the security of supply levels obtained by this approach are under further analysis

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