Hydroeconomic Optimization of Citarum Cascade Reservoirs using Lexicographic Goal Programming

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Abstract

The past fifty years have seen rapid advances in hydroeconomic modelling to solve multi-objective problems in integrated river basin management. Hydroeconomic approaches, however, often face difficulties to transform management schemes and policies into an economic value of water. This study focuses on multi-purpose reservoir operation strategies to determine the most promising water allocation under similar attainment targets by constructing various hydroeconomic optimization models using a modelling package called RTC-Tools 2.0. It is shown that a hybrid combination of lexicographic goal programming (LGP) and the classical weighting method provides a transparent approach to build multi-objective hydroeconomic modelling free from arbitrary trade-off parameters. In this approach, LGP assists the optimization algorithm in satisfying the sequences of prioritized objectives while the weighting method subsequently searches for the highest total economic benefit. This approach is foreseen to be suitable for planning practices as stakeholders' perspectives on water priorities and rights can be explicitly set in the water allocation model.

Keywords: reservoir management, water allocation, multi-objective optimization, hydroeconomic model, lexicographic goal programming

1. Introduction

Development of better reservoir operation strategies is often preferred over costly construction of new supply to address the issues arising from the conflicting goals (e.g., downstream water users, hydropower and flood control) in many river basins. Constructing a hydroeconomic model is a well-established approach to analyse the trade-off for such multi-objective problems. With new modelling tools and innovative methods becoming available, seamless integration between prioritized target demands and conventional hydroeconomic modelling can be achieved in order to derive more transparent 'optimal' water allocation strategies. The present study compares different optimization methods to evaluate its suitability for decision-making on deriving promising multi-purpose reservoir operation strategies. A new set of software tools, called RTC-Tools 2.0 (Baayen, J., den Toom, M., Gijsbers, P., Vreeken, D. J., & Schwanenberg, D., "RTC-Tools 2.0: An open source toolbox for control and multi-objective convex optimization of environmental flow networks under predictive uncertainty," submitted, Deltares, Delft), were selected for its capacity to support the implementation of the optimization methods.

This paper begins with a brief literature review on the approach developed to bridge the gap between research and practice in hydroeconomic modelling, followed by an overview of the case study to validate the data collection of physical datasets and operational policies of Citarum cascade reservoirs. The following part of the paper

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outlines the application for finding reservoir operational rules with three distinctive multi-objectives optimization approaches. The remaining part of the paper compares and discusses the feasibility of each approach for planning practices, and also reviews the limitations of the resulting optimization problem on its practical implication for the study area.

2. Gap between Research and Practice

Various authors have discussed the hydroeconomic approach and its practical application (Braden, 2000) (Harou, et al., 2009). By combining the principles of economics and engineering, the hydroeconomic models transform the concept of fixed demand into the economic value of water defined through water priorities and rights. The concept of economic water demand is introduced to observe the maximum net benefit of the system by driving the water allocation and managing the existing supply-demand (Babel, Gupta, & Nayak, 2005). To identify 'the most promising' reservoir operation rules with this model, an optimization model is constructed based on a hydroeconomic objective and constraints that represent the system (Labadie, 2004).

Simplifications in time representation, such as constructing a deterministic and non-dynamic type of hydroeconomic model, are sometimes made considering that the quality of such model is mainly dependent on the formulation of objective function (Lund & Ferreira, 1996). Solving a problem from all model components in a simultaneous run, so-called holistic sub-model integration, is preferred in this study as exploring the inter-linkages between hydroeconomic parameters is more straightforward in this way.

Harou, *et al.* (2009) found that a major problem with this kind of hydroeconomic model is the discrepancy between the complex economic formulations of the model and the stakeholders' perspective which is generally expressed in priorities. Accordingly, the present study focuses on implementing those priorities (ordered by water resources policies or stakeholders) explicitly in a conventional hydroeconomic model.

Some studies have provided evidence that the lexicographic goal programming (LGP) approach could facilitate a comprehensive trade-off analysis in multi-objective optimization without the complete economic transformation proposed by the hydroeconomic approach. A study conducted by Eschenbach, *et al.* (2001) demonstrated that LGP is a useful technique to approach the problem of integrating the water-related policies explicitly into the water system.

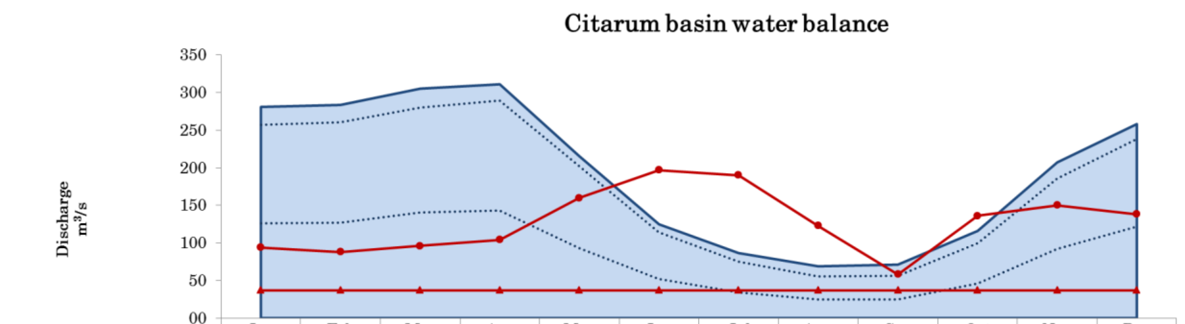
A study by McGregor & Dent (1993) applied inter-disciplinary variables as objective functions in single optimization model to derive an 'optimal' water allocation in a river basin. The objective functions were prioritized and the relative weighing were assigned to goals within the same priority level. The present study adopts s similar optimization approach but uses the hydroeconomic approach to derive the weights. The economic value of water provides a lesser degree of arbitrariness in the choice of weighting factors compared to the relative trade-off parameters in the study conducted by McGregor & Dent. This is desirable, as a degree of arbitrariness in the problem definition implies a degree of arbitrariness in the solution of the optimization problem.

3. Citarum Cascade Reservoirs System

A case-study approach of the Citarum cascade reservoirs was adopted to examine the integration between hydroeconomic models and the prioritized policies. Citarum is an intermountain basin that drains an area of 6,080 m^2 located on the main island of Java, Indonesia. The precipitation in this basin is ranging throughout the year but most annual rainfall of 2000-4000 mm happens during monsoon season between October and April. Water extractions are divided into 85% for irrigation and the rest is equally distributed between domestic uses of 15 million population, fisheries and industrial activities (MPW Indonesia, 2012). The evaporation rates are almost similar throughout the year (4.5 mm/day) due to the basin's high humidity and fairly constant tropical temperature.

A cascade of reservoirs was installed in the heart of the basin to satisfy these target water demands and to supply electricity for Java and Bali. Two upstream reservoirs, Saguling and Cirata were built mainly for hydropower generation while Jatiluhur reservoir was constructed as a multi-purpose reservoir.

The current water allocation model for Citarum basin is built within the rule-based simulation tool called RIBASIM (Meijer, van der Krogt, & van Beek, 2012). Fig. 1 summarises the relevant information from this model with an average monthly upstream inflow over a 90 years period and a fixed annual pattern of consumptive water demands. This figure indicates that a proper planning of operation strategies is necessary to reduce water shortage during the dry season.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Inflow in Jatiluhur	281	284	305	311	215	125	86	69	71	116	207	258
Inflow in Cirata	257	260	280	289	202	114	75	55	56	100	186	238
Inflow in Saguling	126	127	141	143	92	52	34	24	25	46	92	122
Agricultural demand	94	88	96	104	160	197	190	123	58	136	150	138
Drinking Demand & Environmental flow	36	36	36	36	36	36	36	36	36	36	36	36

Fig. 1. Overview of supplies and demands of Citarum basin (m^3/s)

The current RIBASIM model implements explicit priorities of water use in a lumped model schematization run on a monthly time step (Dijkman, van der Krogt, Hendarti, & Brinkman, 2012). Most priorities directly refer to the water resources policy No.7/2004 (MPW Indonesia, 2012) and the associated 'consultation meeting' of stakeholders which mainly discusses the operational concepts and strategies for the basin. Accordingly, the hydroeconomic model built in the present study should also be able to explicitly comprise those priorities in the water allocation model.

4. Data Collection

Datasets needed to construct a new optimization model are extracted from the existing RIBASIM model of the Citarum basin. Physical, hydrological and management (rules and priorities) datasets were collected. The physical datasets include infrastructure characteristics, such as reservoir volume-area-level relations, reservoir dead storage level, dam height and turbine capacities. The hydrological figures include upstream inflow into three reservoirs, evaporation rate and target demands, such as agricultural water demand and firm energy demand. The management datasets reflect the priorities assigned to different types of target demands. Most economic valuations to transform these target demands are taken from the RIBASIM-PS study from Van der Vat (2016) which applied a Particle Swarm optimization of hydroeconomic objective function in combination with the RIBASIM model for Citarum basin.

5. Optimization Methods and Applications

The coming part of the paper is divided into three sections; each section presents technical knowledge of a multi-objective optimization approach and the practical application of constructing a model. In order to obtain comparable results, each approach aims to optimize similar attainment goals of the constructed water allocation models over a 90 years optimization horizon. It is important to note that the optimization horizon chosen has an important influence over the optimization results; a longer optimization horizon is likely to result in more uniform achievement of objectives (Chandrasekaran, Vasudevan, & Vincent, 2007). The terms goal and objective are used interchangeably throughout this paper.

The target demands of each optimization approach are identical, but formulated differently. Saguling and Cirata are single purpose reservoirs intended to generate the firm energy demand of 100 GWh/month and 60 GWh/month. As part of a fully integrated cascading reservoirs operation system, those upstream reservoirs could release extra discharge in case of water shortage in the downstream reservoir. The Jatiluhur multi-purpose reservoir is responsible for satisfying the downstream agricultural water demands, generating firm energy demand of 69.7 GWh/month and reducing the occurrence of flooding events. The downstream flooding is expected to start when the average monthly released discharge from the Jatiluhur reservoir passes 320 m^3/s (Dijkman, van der Krogt, Hendarti, & Brinkman, 2012) (van der Vat, 2016). Drinking water demand and environmental flow are neglected due to the substantial differences in the mathematical formulation of the highest priority water demands in the different optimization approaches taken.

5.1. Weighting Method

When using the weighting method to solve multi-objective problems, a real-valued weight ($\boldsymbol{\lambda}_i$) is assigned to each goal function ($f_i(x)$). The optimization solver searches for a minimum value of the total weighted goal functions subject to the constraints ($g(x)$). The optimization problem becomes

$$\min_{x} \sum_{i} \boldsymbol{\lambda}_i f_i(x) \text{ subject to}$$
$$g(x) \leq 0 \tag{4}$$

In the hydroeconomic modelling, the assigned weights represent the economic value of goal functions. The reservoir target demands, such as agricultural water demand, firm and extra hydropower generation and flood damage reduction, are transformed into a combined economic function. The maximum total benefit from satisfying those demands presents single objective function for the weighting method applied to the system model.

The separation between objective function and constraints in this method are always clear-cut. The physical constraints are always inviolable whereas other aspects should be formulated in a hydroeconomic objective function. Energy shortage as undesired behaviour, for instance, is a non-physical constraint and therefore could be prevented by assigning a penalty function to the hydroeconomic objective. This way, the model provides some degree of flexibility in the possible violations of non-physical constraints (Pulido-Velazquez, Andreu, Sahuquillo, & Pulido-velazquez, 2008).

In the case study of Citarum cascade reservoirs, a penalty for energy shortage should be applied to represent the operational cost of alternative sources for meeting firm energy demand. Unsatisfied agricultural water demand, on the other hand, is penalized by a lower economic benefit due to the reduction in crop yield. The total economic benefit, expressed in 2010 US Dollars, is formulated as

$$B_{total} = \sum_{1}^{i=T} B^{i}_{agr} + B^{i}_{firmE} + B^{i}_{extraE} - P^{i}_{firmE} - P^{i}_{flood} \tag{4}$$

where B_{total} = total economic benefit over period i; T = length of the operational time horizon; B^{i}_{agr} = benefit from delivered agricultural demand; $B^{i}_{firmE,}$ B^{i}_{extraE} = benefit from firm and extra hydropower generation; P^{i}_{firmE} = penalty for the shortage of firm energy demand; P^{i}_{flood} = binary penalty for flooding event. Table 1 summarises the economic valuations of target demands applied to the functions formulated in the hydroeconomic model.

Table 1. Summary of benefit and penalty functions

Economic valuation	Unit	Value
Benefit		
Agricultural delivered demand	US$/m3	0.02
Hydropower generation		
Firm	US$/GWh	0.066
Extra	US$/GWh	0.033
Penalty		
Firm energy shortage	US$/GWh	0.132
Flood event (Qr>320 m3/s)	million/month	14

Note: Qr=Jatiluhur released discharge

At the same time, the weighting method employed in RIBASIM-PS model by Van der Vat (2016) generates promising results although the penalty for energy shortage is entirely neglected. These results are likely to be related to the role of rule-based simulation tools in providing the explicit value of firm target demands for the hydroeconomic optimization algorithm.

A sensitivity analysis is conducted to assess the robustness of this particular hydroeconomic model. By running the same model with different values of the parameters, the changes in the water allocation in the system could be analysed under various economic valuations. The sensitivity analysis is conducted by dividing the economic valuation of penalty for firm energy shortage by the factor of 5 and dividing the economic valuation of benefit from hydropower generation by the factor of 2.

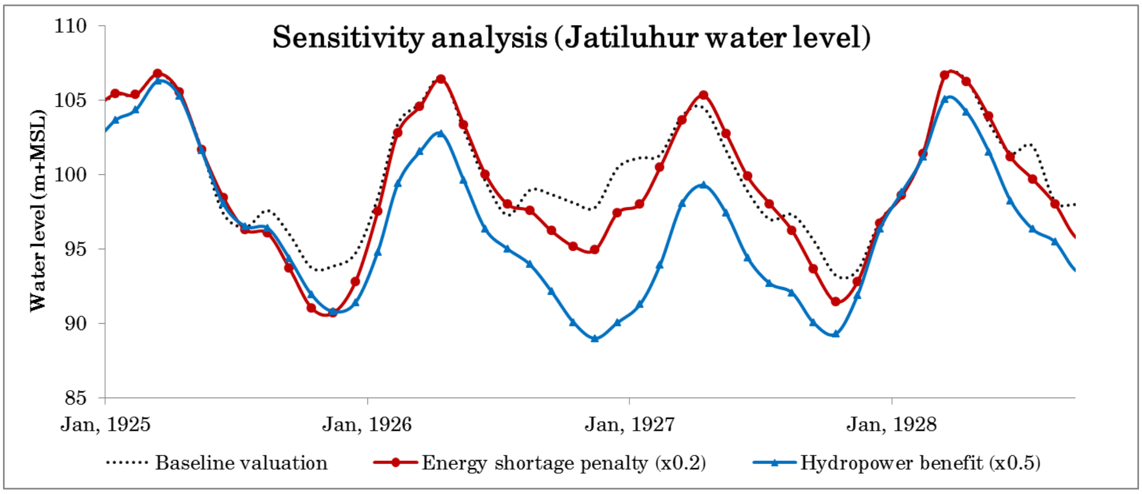


Fig. 2. Sensitivity analysis

As presented in Fig. 2, lower economic valuation of benefit from hydropower generation tends to result in a lower reservoir water level and increased shortage of firm energy demand. Another hydroeconomic model run with a lower economic valuation of penalty for energy shortage presents rather similar trends, but the model seems to be less sensitive to such change. This analysis strengthens the presumption that economic valuation is a sensitive parameter in the optimization model using the weighting method, especially when the necessary trade-off between reservoir conflicting objectives is substantial. The changes in economic valuations could considerably alter the operation rules in the system while pricing them accurately is difficult.

5.2. Lexicographic Goal programming

In the LGP approach, the prioritized goals are optimized in order. Let $f_i(x)$ denote the goal function at priority level i^{th}. The optimization problem of solving for priority k^{th} becomes:

$$\min_x f_k(x) \ \text{subject to} \quad \begin{cases} g(x) \leq 0 \\ f_i(x) = \mathrm{G}_i \qquad \forall i < k, \qquad \mathrm{G}_i := f_i(x_{opt,i}) \end{cases} \tag{3}$$

The optimization algorithm first satisfies the higher priority goals for the specified optimization time horizon before solving the lower priority goals. All solutions ($x_{opt,i}$) must always satisfy the constraints ($g(x)$). An optimum solution of k^{th} optimization problem is attained when every goal ($f_k(x)$) converges to its minimum value whilst the goal attainment levels (G_i) of the previous goals (i^{th}) must remain constant (Eschenbach, Magee, & Zagona, 2001).

In LGP approach, it is possible to define goal functions that penalize state trajectories when they lie outside the provided upper and/or lower bounds (Baayen, J., den Toom, M., Gijsbers, P., Vreeken, D. J., & Schwanenberg, D., "RTC-Tools 2.0: An open source toolbox for control and multi-objective convex optimization of environmental flow networks under predictive uncertainty," submitted, Deltares, Delft). These bounding state goals, henceforth referred as *soft constraints*, progressively shrink the optimization search space with every subsequent goal. Unlike the conventional (hard) constraints, a soft constraint can be violated if no trajectory fully satisfying the bounds is found.

By setting the sequences of objectives, the determination of a reservoir release crucially depends on the purpose of a reservoir and the order of priority between specified target demands and reservoir storage. Table 2 shows the sequences of objectives set that correspond to the priorities of target demands in the Citarum basin. This table presents rather straightforward priority settings; for example, the translation of row 2 to 4 would be 'the hedging zone 4 water level of three reservoirs begins to fill after Saguling and Cirata generated 10% of firm energy demand.

The hedging storages determine what percentage of firm target demands is released if the reservoir water level drops into a hedging zone. The firm storage reflects the minimum level required to fully supply the firm target demands (energy and consumptive), while extra energy generation remains possible until the water level reaches the target storage. Extra water must be released if the water level is higher than the flood control storage to accommodate storage of flood waves when needed. It becomes apparent that the concept of solving water allocation problems with those sequences of objectives is similar to rule-based simulation tools such RIBASIM. Both concepts tend to maintain a certain reservoir water level by reducing released discharge during drought events and releasing extra discharge in case of full storage conditions.

Table 2. Sequences of objectives

Priority	Model component	Objective function	Lower soft constraint	Upper soft constraint
1	Cascade reservoirs	Water level	Reservoir Hdead	Reservoir H full
2	Saguling reservoir	Energy generation	S: 10% FirmP	S: MaxP
3	Cirata reservoir	Energy generation	C: 10% FirmP	C: MaxP
4	Cascade reservoirs	Water level	Hhedging4	Hflood
5	Saguling reservoir	Energy generation	S: 30% FirmP	S: MaxP
6	Cirata reservoir	Energy generation	C: 30% FirmP	C: MaxP
7	Jatiluhur reservoir	Energy generation	J: 50% FirmP	J: MaxP
7	Agricultural terminal	Target released	J: 50% Qagr	Qagr
8	Cascade reservoirs	Water level	Hhedging2	Hflood
9	Saguling reservoir	Energy generation	S: 70% FirmP	S: MaxP
10	Cirata reservoir	Energy generation	C: 70% FirmP	C: MaxP
11	Jatiluhur reservoir	Energy generation	J: 90% FirmP	J: MaxP
11	Agricultural terminal	Target released	J: 90% Qagr	Qagr
12	Cascade reservoirs	Water level	Hfirm	Hflood
13	Jatiluhur reservoir	Energy generation	J: FirmP	J: MaxP
14	Agricultural terminal	Target released	J: Qagr	Qagr
15	Saguling reservoir	Energy generation	S: FirmP	S: MaxP
15	Cirata reservoir	Energy generation	C: FirmP	C: MaxP
16	Cascade reservoirs	Water level	Htarget	Hflood
17	Jatiluhur reservoir	Released discharge	0	Flooding threshold

Note : S=Saguling ; C=Cirata ; J=Jatiluhur
H=Reservoir water level ; P=Hydroelectricity demand ; Qagr=Agicultural water demand

LGP maps directly onto the systems where policy dictates a priority order for the different water management objectives. However, when the order of priority is subject to a degree of arbitrariness, caution must be applied, as the solution greatly depends on the priority setting.

5.3. Hybrid Method

Considering the issue of model sensitivity, this paper proposes a hybrid method to develop a robust hydroeconomic model with a reduced dependency on accurate economic valuations and order of priority. The method consists of a LGP approach in combination with the weighting method. This approach is taken since valuing some goals economically is difficult due to a lack of information, particularly on the cost of flood damage and the operational cost of alternative sources for meeting firm energy demand. LGP assists in satisfying water management priorities directly while the weighting method subsequently searches for the highest total economic benefit.

Inspired by the RIBASIM-PS study, the hydroeconomic objective formulated for this approach eliminates the penalty functions as the satisfaction of some target demands are explicitly incorporated in the first priority. As presented in Table 3, both target demands and hydroeconomic functions are formulated as an integrated problem.

Table 3. Priority setting of objectives

Priority	Hybrid optimization	Unit	Valuation	Saguling	Cirata	Jatiluhur
1	Sequences of explicit objectives					
	Firm energy demand	GWh/month		100	60	69.7
	Flooding threshold	m^3/s				320
2	Hydroeconomic objectives					
	Agricultural	US$/$m^3$	0.02			
	Hydropower					
	Firm	US$/GWh	0.066			
	Extra	US$/GWh	0.033			

6. Software Implementation in RTC-Tools 2.0

RTC-Tools (https://www.deltares.nl/en/software/rtc-tools/) is an open-source toolbox for control and optimization of environmental systems developed by Deltares. RTC-Tools 1.0, which was published in 2005, uses the Model Predictive Control (MPC) technique to compute operational strategies for hydraulic structures using single objective function. This study uses the new generation of RTC-Tools (version 2.0). RTC-Tools 2.0 is a modular software framework set up for multi-objective MPC, with or without taking predictive uncertainty into account (Baayen, J., den Toom, M., Gijsbers, P., Vreeken, D. J., & Schwanenberg, D., "RTC-Tools 2.0: An open source toolbox for control and multi-objective convex optimization of environmental flow networks under predictive uncertainty," submitted, Deltares, Delft). RTC-Tools 2.0 supports the lexicographic goal programming, the weighting method, as well as the hybrid method.

When using RTC-Tools 2.0, it is possible to develop physical models in the Modelica system modelling language (Elmqvist, Mattsson, & Otter, 1998). Modelica is an object-oriented modelling language, allowing the construction of reusable model components, such as reservoirs and channel reaches. Furthermore, a declarative equation based modelling language such as Modelica leads to a shorter, more understandable code which directly corresponds to the mathematical formulation of water allocation problems. Both features provide the flexibility in developing user-specified model components that extend the existing Modelica library.

The introduction of Modelica also separates of the definition of system model from the definition of the optimization problem. As presented in Fig. 3, the water allocation network of the Citarum cascade reservoirs is schematized in Modelica by connecting model components from the Deltares Modelica model library.

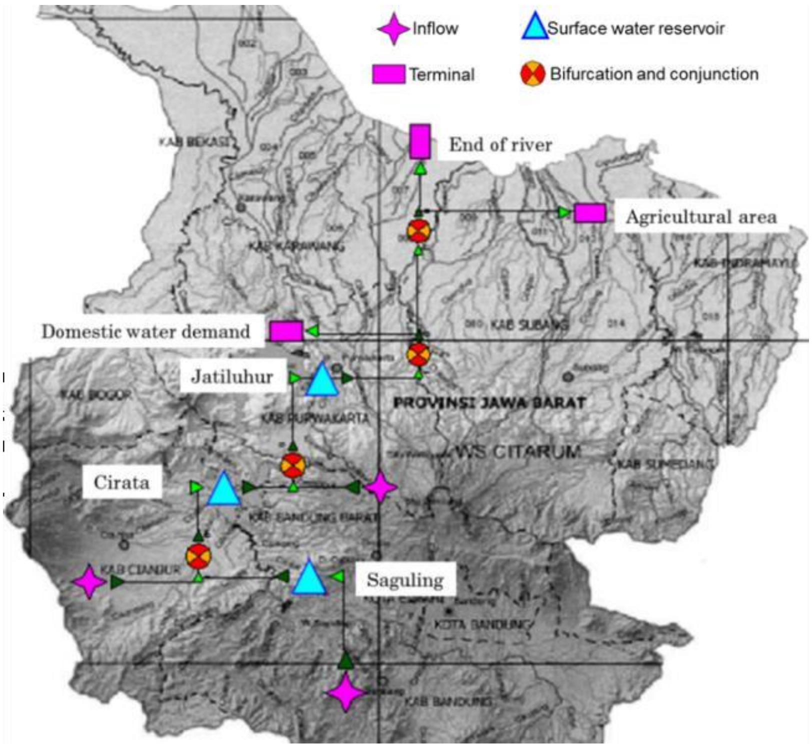


Fig. 3. Model schematization of the Citarum cascade reservoirs in Modelica (Background map is adapted from BBWS Citarum **(2014)**)

7. Results Comparison and Discussion

In the section that follows, the results and findings from the three optimization approaches are discussed. The current study found that different optimization approaches generate distinctive reservoir operation rules where certain results could be more suitable for the study area compared to the others. Fig. 4 presents the time series results of delivered target demands of the Citarum cascade reservoirs from 1925 to 1935. At the end of this section, Table 4 compares the annual average of the total economic benefit and the satisfaction of target demands when those reservoir operation rules applied.

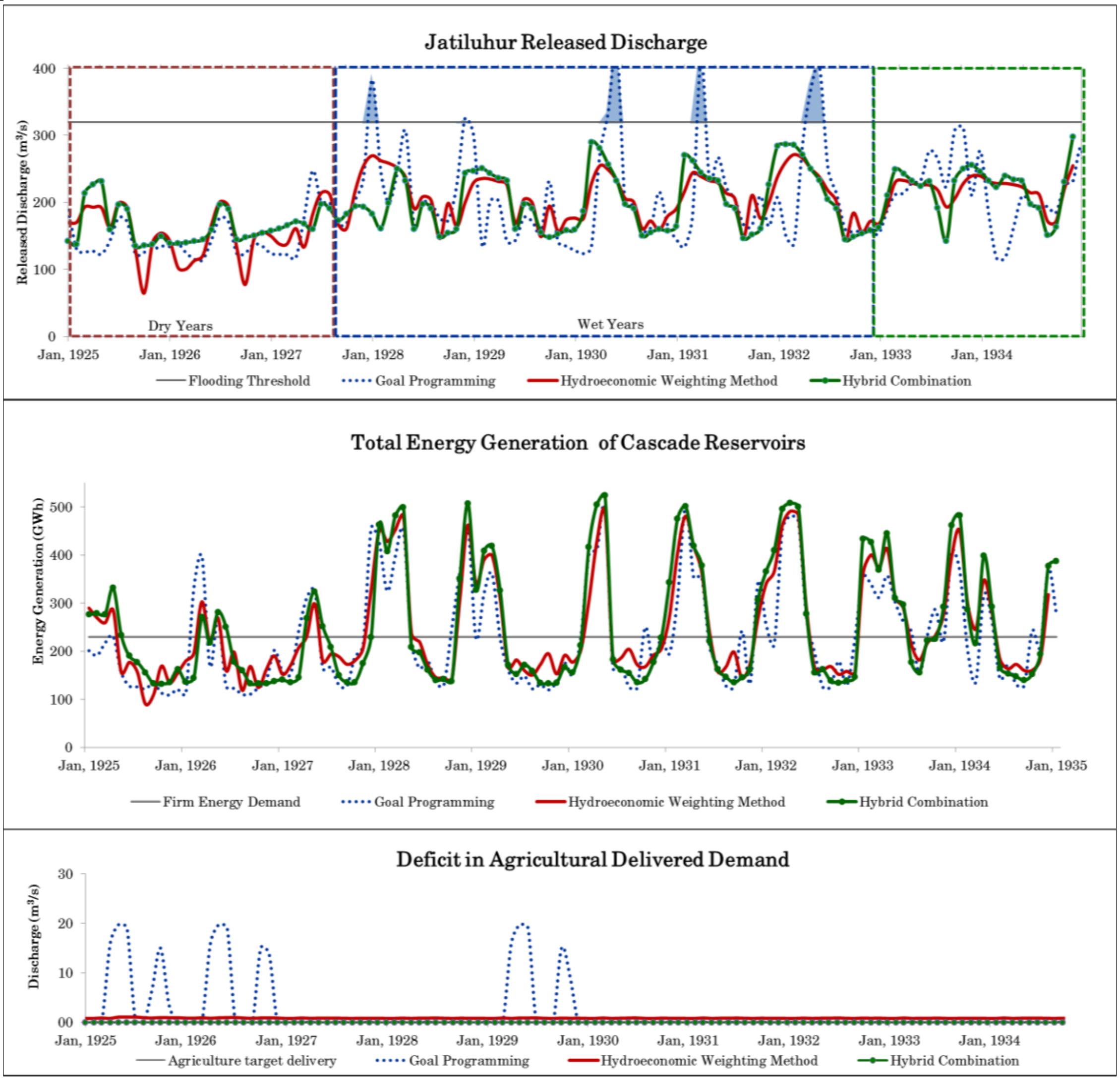


Fig. 4. Delivered target demands

Three optimization models present rather similar results but the pure LGP approach generates more flooding events and the lowest annual economic benefit (349 US$ million). These results provide important insights into the competency of LGP approach in trade-off management without any target demands transformation into an economic value of water. The flooding events during the wet years could have been prevented by setting the objective of limiting reservoir releases at higher order than the current priority listed in Table 3. A relatively low total economic benefit may be explained by the fact that this model excludes the information about economic valuations. Economic valuation is an expensive and time-consuming process but completely eliminating it comes at a cost.

The hydroeconomic model with the pure weighting method generates the highest annual economic benefit (US$ 409 million). Despite these promising results, it is important to notice that such optimization model is highly sensitive to the economic valuations chosen. This finding suggests that building a robust water allocation model based on this approach could be demanding since valuating priorities of target demands economically is very challenging. Economic representation of priorities, however, is likely to avoid conflict of interest issues that often arise during the process of justifying a relative weighted value.

The hybrid method generates a slightly lower annual economic benefit (408 US$ million) in comparison to the weighting method but effectively reduces the drought and flood events occurring in the study area. This result is roughly comparable to the results of the RIBASIM-PS study by Van der Vat (2016). Both the hybrid model and the RIBASIM-PS study present that a low satisfaction level of firm energy demand, especially in the most downstream reservoir, is due to the naturally limited water availability.

The distributed minor drought events in Table 4 are likely due to the long (90 years) optimization horizon which should be shortened to reduce the influence of knowledge on future inflows. The same models run in a short (a year) optimization horizon generates severe but sparse shortage events which become difficult to manage. These findings are in agreement with the conclusion from another study by Chandrasekaran, *et al.* (2007). The presented results, therefore, need to be interpreted with caution.

Table 4. Summary of the optimization results

Annual benefit of Citarum cascade reservoirs	Unit	LGP	Hydroeconomic Weighting	Hybrid Combination
Economic benefit				
Total Benefit	million US$ (2010 value)	349.2 (L)	409.3 (H)	408.2 (M)
Irrigation		79.2	79.3	80
Hydropower		279.8	331	328
Flood damage		9.8	0.98	0
Undesired events				
Agricultural drought				
Occurances	months/year	2.8	12	12
Severities	m^3/s /month	6.9	2	1
Shortage	%	1.3 (L)	1.6 (M)	0.07 (H)
Energy shortage (S, C, J)				
Occurances	months/year	6.0 6.1 11.9	6.6 5.6 11.7	6.6 5.9 10.4
Severities	GWh/month	36 19 27	23 17 18	32 20 19
Shortage	%	24 (L)	17 (H)	19 (M)
Flood events				
Occurances	months/year	0.7 (L)	0.07 (M)	0 (H)

Note:
Relative satisfaction level: L=Low ; M= Moderate ; H=High
Reservoir: S=Saguling ; C=Cirata; J=Jatiluhur

8. Limitations Due to Model Simplifications

The hydroeconomic model simplifies the cost of damage caused by flooding by applying a binary penalty when the Jatiluhur monthly average released discharge exceeds a threshold value. A flooding event should be properly assessed with a hydrologic routing model run preferably based on hourly values. The analysis of flooding events is limited due to the data availability.

The highest priority water demands, such as drinking water and environmental flow, often have a substantial impact on the overall mass balance and should not be neglected in the optimization model. These water demands can be directly implemented as the highest priority soft constraints in LGP. In the weighting method, estimating these demands economically is difficult while setting them as constraints might be impractical during years of severe drought.

The present hydroeconomic study does not incorporate monetary discounting. Discounting may be incorporated by including the relevant terms in the objective function.

The results of the constructed deterministic models presume perfect knowledge on future events. Despite these promising results, questions remain as inflow uncertainty is very high, especially on a longer time horizon. Optimization under predictive uncertainty, which is supported by RTC-Tools 2.0, will be addressed in future research.

9. Conclusions

The present study highlights the advantages of lexicographic goal programming in combination with the hydroeconomic weighting method. The hybrid method yields a transparent water allocation since the priorities and rights are explicitly represented as sequences of objectives. This hybrid method furthermore is robust in the sense that the objectives which cannot be valued economically are not subject to arbitrary weights. This approach is foreseen to be suitable for planning practices particularly when formulating single hydroeconomic objective function is difficult.

The objective functions of the hybrid method applied to the case study of Citarum cascade reservoirs consist of i) the satisfaction of explicitly prioritized target demands and ii) the highest total economic benefit generated from the relevant target demands weighted with the economic values of water use. The hybrid method generates a visible reduction in both drought and flood events while maintaining a promising total economic benefit. The open source modelling package RTC-Tools 2.0 has shown to be a valuable tool for the task of finding ‘the most promising’ reservoir operation rules derived from different optimization approaches for the case study.

10. Recommendation on Future Research

Further research should focus on using forecast ensembles to generate operational strategies that are robust in face of predictive uncertainty.

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