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Application of the WEAP model to obtain an optimal delivery plan for a reservoir system

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Abstract: Reservoir operation is one of the most important issues in the management of water resources, due to the increasing demands for water compared to the increasingly limited water resources available. Efficient water resources management is achieved through the establishment of optimal operation policies and reservoir operation rules. The latter include decisions on the deliveries to be provided by the reservoir and the volumes to be impounded in each period of time. Based on the need for an efficient and rational use of water, mathematical modeling has been used as a tool to obtain solutions for the optimal operation of existing reservoirs. In the present work, a study is carried out to obtain an optimal operation policy for a water supply system of reservoirs with several interconnected users in the city of Santiago de Cuba. The study consisted of proposing a water delivery plan from the reservoirs to the users to obtain an optimal distribution of water in the reservoir-user system. In order to achieve this objective, the WEAP mathematical simulation model has been applied to the Northwest Water Supply System to the City of Santiago de Cuba, chosen as a case study. As a practical result of the application of the WEAP model, it is possible to obtain a water delivery plan that guarantees 90% of the water to the users. The results obtained with the WEAP model were compared with the results obtained with the HEC-PRM model for the same case study, showing that both models provide similar results.

Key words: reservoir; operation; optimization; users

1 Introduction

Water is a non-renewable natural resource and indispensable for life on the planet. One of the main problems facing the world today is the conservation and preservation of this resource, although three quarters of the planet is made up of water, only a small portion is fresh and suitable for human consumption. Water is found in nature in different forms such as snow, ice, clouds, on the earth's surface or in the subsoil. In this sense, it is essential to increase the saving and care of this resource to avoid its indiscriminate and irrational use. One measure to achieve this purpose is through the application of plans and measures that allow us to control and satisfy the needs of the population as best as possible, such measures must be based on adequate planning, operation, management and efficient handling of water resources, only in this way will the water resource be preserved for future generations. Waste, climate change and increasing water demands due to population and economic growth are conflicts that challenge man's capacity and intelligence to solve problems related to water resources if he wants to transcend as a species.

Climate change is a reality; many reports indicate that its effects may include an increase in the frequency, intensity and severity of extreme weather events, which may cause an alteration in the flow regimes of currents, water availability and the spatial and temporal patterns of precipitation, which are the main source of fresh water in our country.

Cuba is immersed in a complex scenario with respect to water resources and the government has been concerned about its use and protection. An example of this is the construction of hydraulic works such as dams, reservoirs, canals, water supply works, sanitary sewers, water purification and treatment plants. Our society is currently going through a period of prolonged drought that is causing serious economic and social damage. In this sense, the application of scientific and technological advances in the field of water resources is essential to achieve high economic and social development.

For Cuban society, it is necessary that hydraulic resources be properly managed and that tools and methodologies be incorporated in this task to improve their exploitation. This implies a challenge for hydraulic engineers in charge of the management, administration and exploitation of Cuban hydraulic resources.

2 Brief description of WEAP and HEC-ResPRM models

The following is an introduction to the WEAP and HEC-ResPRM models used in this contribution. The former is used as a state-of-the-art tool for planning the use of water resources, considering the use of scenarios to respond to changes caused by variations in demand and supply, impacts on future policy change and climate, compatibility with environmental objectives and costs. The second is used to determine the optimal monthly deliveries to be made by each reservoir to meet the planned demands of users.

2.1 Brief description of the WEAP model

The water evaluation and planning system (WEAP) is a computational tool for integrated water resources planning assessments intended to assist the expert planner. It provides a comprehensive, flexible and easy-to-use framework for planning and policy analysis. The program works using the basic principle of water balance, and can be applied to urban and agricultural water supply, in a single basin or in complex transboundary basin systems. It uses a database that maintains demand and supply information to drive the mass balance model in a node-linked architecture. It is a simulation-based program that calculates demand, supply, and can simulate a wide range of the natural components involved in these systems, including precipitation runoff, baseflow, and precipitation groundwater recharge; sectoral demands analysis; water conservation; water rights and allocation priorities; reservoir operations; hydropower generation; pollution and water quality monitoring; vulnerability assessments; and ecosystem requirements. It features a financial analysis module allowing the user to investigate cost-benefit comparisons for projects. WEAP presents water use policy scenarios in which it evaluates a wide range of water development and management options taking into account water resource uses. It uses a monthly time step.

Figure 1. General diagram showing the basic steps to perform a WEAP run

Santiago (2009)

2.2 Brief description of the HEC-ResPRM model

The hydrologic engineering center prescriptive reservoir model (HEC-ResPRM) (Carl 2003) [1] has implemented an optimization model for reservoir operation that minimizes the cost of a flow network formed by nodes and arcs, subject to flow and storage constraints (O'Connell and Harou 2011) [2]. This model uses linear programming (LP) to solve the flow network optimization problem. The algorithm implemented in HEC-ResPRM conceives the reservoir-user set as a system of arcs and nodes. Arcs are conveyance elements and represent conveyance works that transport flows (deliveries) from one node to another. Nodes connect the arcs at their beginning and end and represent reservoirs, connection points, confluences and bifurcations. At nodes the flow may enter or leave or both. Arcs and nodes support upper and lower contour restrictions, i.e. flow and storage, maxima and minima.

2.3 Application of WEAP and HEC-ResPRM models to the northwest water supply system for the city of Santiago De Cuba

The Northwest System of water supply to the city of Santiago de Cuba, hereinafter referred to as the Northwest System, is made up of five reservoirs with a combined useful volume of 351.55 hm^3, whose main objective is to guarantee the water demand of the city of Santiago de Cuba. The most important reservoirs are Céspedes, Gota Blanca and Gilbert, which together have a useful volume of 346.7 hm3, 98.62% of the useful volume of the Northwest System. This system has four main users associated with it: the Céspedes HPP, the Quintero and El Cobre water treatment plants and Entregas Ruta, the last three of which are users in the city of Santiago de Cuba. Figure 2 shows a linear scheme with the topology of the Northwest System.

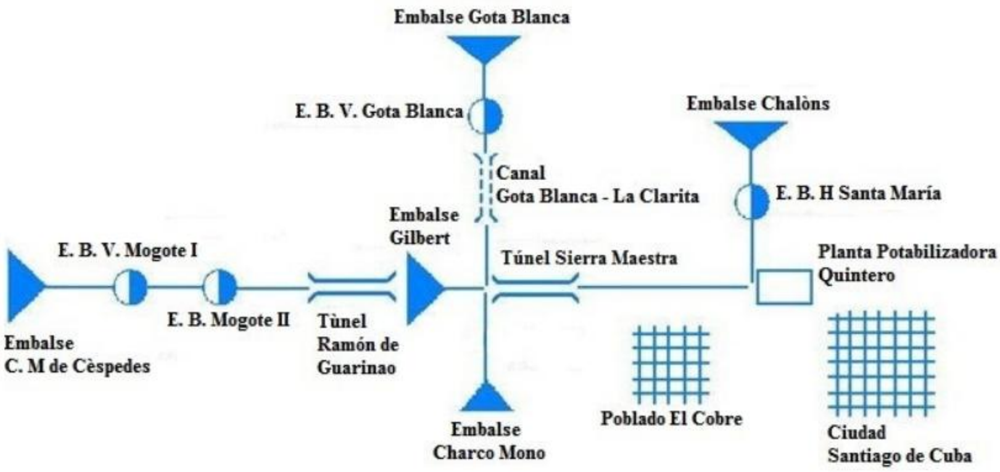

Figure 2. Linear diagram showing the topology of the reservoir-user system

Recio et al (2016)

Table 1 shows the main physical and hydrological parameters of all the reservoirs. In the physical data we see the parameter β, which is the ratio between the reservoir water mirror area for a given fill level and its corresponding volume and is obtained by performing a linear fit between the elevation-area and elevation-volume curves of each reservoir. The parameter β is needed to determine water losses due to evaporation. The WEAP model considers seepage losses, although several reservoir operation models that use linear programming as an optimization technique do not consider these losses. The remaining physical and hydrological parameters are widely known.

Table 1. Main physical and hydrological parameters of the reservoirs

Embalse	Parámetros físicos					Datos hidrológicos		
	Vol. NAM	Vol. NAN	Vol. NVM	Vu	β	Wm	Cv	Año Hidrológico
	hm^3	hm^3	hm^3	hm^3	km^2/hm^3	hm^3/año		
Gota Blanca	115,8	83,6	5,0	78,60	0,09	21,54	0,65	Mayo - Abril
Gilbert	76,4	59,67	5,0	54,67	0,09	50,40	0,57	
Charco Mono	5,85	4,55	0,42	4,13	0,11	17,70	0,61	
Céspedes	310,0	243,0	30,0	213,0	0,05	285,00	0,57	
Chalóns	1,40	0,95	0,00	0,95	0,11	2,47	0,69	

Own elaboration

In order to carry out a reservoir operation study with the WEAP model, it is necessary to know the runoff and the evaporation sheet that arrive and occur in the reservoirs, respectively. The Provincial Delegation of Hydraulic Resources of Santiago de Cuba carried out one of the main studies under the name: "Design of the Northwest Exploitation System. Optimal Operation of the System's Reservoirs. Hydrological Study" by Eng. Rafael Bauta Rubalcaba in 2014, Bauta (2014) [3]. In this study, an update of the runoff and evaporation of the reservoirs is shown, considering different probabilities of occurrence of the same. Table 2 shows the runoff for 75% probability and Table 3 shows the reduced monthly evaporation for 50% probability of the reservoir system. Table 2 shows the runoff for probabilities of 25%, 50%, 75% and 95% and Table 3 shows the evaporation of all the reservoirs of the Northwest Water Supply System for the City of Santiago de Cuba.

Table 2. Runoff (hm3/month) for 75% probability

Embalses	Escurrimiento de los embalses para probabilidad de 75 %, en hm³												Total
	May.	Jun.	Jul.	Agos.	Sep.	Oct.	Nov.	Dic.	Ene.	Feb.	Mar.	Abr.	
Gota Blanca	3,95	1,14	0,82	1,64	2,69	3,52	3,92	1,13	0,86	0,72	0,68	0,47	21,54
Gilbert	4,35	4,24	0,85	2,02	5,32	3,60	3,28	0,84	0,69	1,28	2,55	1,96	30,98
Charco Mono	1,72	1,45	0,37	0,32	1,19	1,40	0,97	0,32	0,41	0,20	0,40	0,47	9,22
Céspedes	26,26	17,45	15,58	17,45	23,38	21,51	13,9	7,11	6,61	7,11	6,1	6,95	169,40
Chalóns	0,21	0,09	0,06	0,08	0,14	0,23	0,23	0,05	0,05	0,04	0,02	0,20	1,22

Own elaboration.

Table 3. Evaporation sheet in (mm) of the reservoirs for an average year

Embalses	Lámina de evaporación en (mm) de los embalses para un año medio.												Total
	May.	Jun.	Jul.	Agos.	Sep.	Oct.	Nov.	Dic.	Ene.	Feb.	Mar.	Abr.	
Gota Blanca	73,4	71,8	76,4	72,7	60,3	59,4	48,4	47,9	53,7	56,5	63,1	73,0	756,6
Gilbert	68,2	67,4	73,0	68,7	58,2	55,1	46,9	45,2	49,4	53,0	66,0	72,0	723,1
Charco Mono	52,0	51,2	55,4	52,3	45,0	42,0	36,0	35,0	37,4	40,2	50,0	54,5	551,0
Céspedes	151,6	140,7	157,9	153,2	125,0	117,3	98,5	87,7	100,9	106,7	140,3	143,2	1523,0
Chalóns	52,6	51,2	55,4	52,3	45,0	42,0	36,0	35,0	37,4	40,2	50,0	54,5	551,0

Own elaboration.

2.4 General user data

In the northwest system of the city of Santiago de Cuba there are three main users: "El Cobre" drinking water treatment plant, "Quintero" drinking water treatment plant and the demand site "Consumos o Entregas en ruta". The demands of these users have been estimated by the Provincial Delegation of Hydraulic Resources of Santiago de Cuba, as shown in Table 4.

Table 4. User demand

Principales usuarios	Potabilizador a el Cobre	Potabilizadora Quintero	Entregas en Ruta	PCHE Céspedes
Demandas (hm^3/año)	1,56	75,60	6,24	152,40
Demandas (hm^3/mes)	0,13	6,3	0,52	12,7
Demanda (L/s)	50,15	2430,56	200,00	4899,69

Own elaboration.

The demand of the user "Deliveries on Route" represents towns that are connected along the pipelines to the "Quintero" water treatment plant, as shown in Table 5.

Table 5. On-road consumption of the Northwest System

Poblados	Dotación (lppd)	Caudal (l/s)
Cobre	235	50
La Caoba	125	2,0
El Castillito	125	2,5
Espartillo	125	1,5
El Paujil	125	0,5
Refugio	125	0,9
La Caridad	125	0,3
Consumidores locales	-	142
Total	-	200

Own elaboration.

Table 6 shows the boundary restrictions that the reservoirs must comply with and that are introduced in the WEAP model; these are referred to deliveries and storage from the reservoirs. In the case of volumes, the minimum values refer to the dead volume level (DVL) of each reservoir and the maximum values correspond to the normal water level (NWL). Compliance with this restriction guarantees that no spills will occur.

Table 6. Restrictions on deliveries and volumes in reservoirs.

Embalses	Volúmen (hm^3)		Entregas (hm^3/mes)
	Mínimo	Máximo	Máximo
Gilbert	5	59,67	5,25
Céspedes	74,57	243	25
Gota Blanca	5	83,6	5,25
Charco Mono	0,42	4,55	2,63
Chalóns	0	0,95	0,16

Own elaboration.

Table 7 shows the initial volumes of the reservoirs, which arise from the condition of the reservoirs of the Northwest Water Supply System to the City of Santiago de Cuba at the beginning of May 2016.

Table 7. Relationship of the initial volumes of the reservoirs

Embalses	Volúmen inicial (hm³)
Gilbert	10,70
Céspedes	83,68
Gota Blanca	21,51
Charco Mono	0,42
Chalóns	0,20

Own elaboration.

2.5 Premises of the reservoir operating policy

This contribution is an initial approach to propose an optimal operation policy for the Northwest System. In order to achieve this objective, two fundamental premises have been established:

(1) Use the Mogote Diversion system only during the dry period (November - April).

(2) To guarantee 90% of the annual water delivery to each user.

3 WEAP model application results

Below, the results of the application of the WEAP model are shown and analyzed, through which the monthly (Rei) and annual net delivery plan of the reservoirs and the Mogote Transfer, the deliveries to the users, the evaporation losses were obtained.

(Pe), gross deliveries (Ue), volumetric guarantee (g), monthly (Defi) and annual (Def) deficit at users and reservoir levels and volumes. The above results are summarized in tables 8, 9 and 10 below. Table 8 shows reservoir deliveries and losses and their monthly magnitudes.

In qualitative terms, the proposed delivery plan complies with the two operating premises of the reservoirs, with the Gilbert and Charco Mono reservoirs delivering all year round and the Mogote Diversion system during the dry period.

Table 8. Summary of evaporation losses (mm), net and gross deliveries (hm³) of the reservoirs and the Mogote Diversion.

Meses	Céspedes			Chalóns			Charco Mono		Gota Blanca			Gilbert			Trasvase Mogote
	Rei	*Pei*	*Ue*	*Rei*	*Pei*	*Ue*	*Rei*	*Pei*	*Rei*	*Pei*	*Ue*	*Rei*	*Pei*	*Ue*	*Rei*
May.	10,80	1,56	12,36	0,19	0,0000	0,19	1,66	0,00	2,04	0,04	2,08	3,07	0,00	3,07	0,000
Jun.	7,40	1,45	8,85	0,14	0,0005	0,14	0,78	0,00	4,86	0,17	5,03	1,09	0,07	1,16	0,000
Jul.	8,13	1,63	9,76	0,09	0,0005	0,09	0,51	0,02	3,59	0,14	3,73	2,77	0,11	2,88	0,000
Agos.	9,00	1,58	10,58	0,10	0,0005	0,10	0,41	0,01	3,26	0,12	3,38	3,19	0,08	3,27	0,000
Sep.	10,41	1,29	11,70	0,12	0,0004	0,12	1,11	0,01	1,28	0,10	1,38	4,35	0,06	4,41	0,000
Oct.	11,53	1,21	12,74	0,23	0,0004	0,23	1,40	0,01	2,44	0,10	2,54	2,90	0,06	2,96	0,004
Nov.	11,66	1,01	12,67	0,22	0,0003	0,22	0,92	0,01	3,08	0,09	3,17	2,66	0,05	2,71	0,006
Dic.	11,09	0,90	11,99	0,08	0,0003	0,08	0,46	0,01	3,74	0,09	3,83	2,67	0,05	2,72	0,004
Ene.	10,52	1,04	11,56	0,09	0,0003	0,09	0,57	0,01	3,65	0,09	3,74	2,65	0,05	2,70	0,003
Feb.	10,01	1,10	11,11	0,06	0,0004	0,06	0,30	0,01	3,13	0,09	3,22	2,92	0,06	2,98	0,005
Mar.	9,46	1,45	10,91	0,05	0,0004	0,05	0,52	0,01	2,49	0,09	2,58	3,90	0,04	3,94	0,002
Abr.	9,05	1,48	10,53	0,22	0,0005	0,22	0,53	0,01	1,64	0,08	1,72	2,79	0,04	2,83	0,000
Total	119,06	15,72	134,78	1,59	0,0005	1,59	9,15	0,10	35,21	1,20	36,41	34,95	0,69	35,64	0,024

Own elaboration.

In quantitative terms, the reservoirs as a whole have a net and gross delivery of 199.98 hm^3/year and 217.67 hm^3/year respectively, with losses amounting to 16.53 hm^3/year, representing 8.27% of the net deliveries made by the system. The great use made of the Céspedes reservoir is observed, being the one with the highest net and gross deliveries, with values of 119.06 hm^3/year and 134.78 hm^3/year, respectively. This reservoir is responsible for supplementing the water supply to the consumer nodes in the dry period (November - April) and for supplying water to the PCHE. The table also shows how no reservoir fails to deliver water throughout the year.

Table 9. Summary of net deliveries by periods of the reservoirs of the Northwest System

Embalses	Húmedo (hm^3)	Seco (hm^3)	Total (hm^3)	Húmedo (%)	Seco (%)	Total (%)
Gilbert	17,37	17,59	34,96	17,57	17,39	17,48
Trasv. Mogote	0,004	0,02	0,024	0,004	0,02	0,01
Gota Blanca	17,48	17,74	35,22	17,68	17,54	17,6
Charco Mono	5,86	3,29	9,15	5,93	3,25	4,57
Chalóns	0,88	0,72	1,60	0,89	0,71	0,8
Céspedes	57,27	61,79	119,06	57,93	61,09	59,53
Total	98,86	101,15	200,01	49,43	50,57	100

Own elaboration.

Table 9 shows a summary of the magnitude and percentage of net deliveries by period of the reservoirs of the Northwest System. Regarding the annual net delivery in the wet period (May - October) 98.86 hm^3 are delivered, 49.43%, while in the dry period (November - April) 101.15 hm^3 are delivered, 50.57%. In terms of magnitude the reservoirs with the largest deliveries in the dry period in descending order are: Céspedes with 61.79 hm^3 representing 61.09%, Gota Blanca with 17.74 hm^3 representing 17.54 %, Gilbert with 17.59 hm^3 representing 17.39 %, Charco Mono with 3.29 hm^3 representing 3.25%, Chalóns with 0.72 hm^3 representing 0.71% and Trasvase Mogote with 0.02 hm^3 representing 0.02%. In the wet period the reservoirs that deliver the most in descending order are: Céspedes with 57.27 hm^3 representing 57.93%, Gota Blanca 17.48 hm^3 representing 17.68%, Gilbert is 17.37 hm^3 representing 17.57%, Charco Mono 5.86 hm^3 representing 5.93%, Chalóns 0.88 hm^3 representing 0.89% and Trasvase Mogote with 0.004 hm^3 representing 0.004%.

Table 10. Summary of delivery, deficit and user demand

Meses	Entregas en Ruta (hm^3)			PCHE Céspedes (hm^3)			Potabilizadora El Cobre (hm^3)			Potabilizadora Quintero (hm^3)		
	D	*R*	*Def.*	*D*	*R*	*Def.*	*D*	*R*	*Def.*	*D*	*R*	*Def.*
May.	0,53	0,53	0,00	25,20	10,80	14,40	0,13	0,13	0,00	6,30	6,30	0,00
Jun.	0,53	0,52	0,01	25,20	7,40	17,81	0,13	0,13	0,00	6,30	6,22	0,08
Jul.	0,53	0,53	0,00	25,20	8,13	17,07	0,13	0,13	0,00	6,30	6,30	0,00
Agos	0,53	0,53	0,00	25,20	9,00	16,20	0,13	0,13	0,00	6,30	6,30	0,00
Sep.	0,53	0,52	0,01	25,20	10,41	14,79	0,13	0,13	0,00	6,30	6,22	0,08
Oct.	0,53	0,53	0,00	25,20	11,53	13,67	0,13	0,13	0,00	6,30	6,30	0,00
Nov.	0,53	0,52	0,01	25,20	11,66	13,54	0,13	0,13	0,00	6,30	6,22	0,08
Dic.	0,53	0,53	0,00	25,20	11,09	14,11	0,13	0,10	0,00	6,30	6,30	0,00
Ene.	0,53	0,53	0,00	25,20	10,52	14,68	0,13	0,13	0,00	6,30	6,13	0,00
Feb.	0,53	0,48	0,05	25,20	10,01	15,19	0,13	0,12	0,01	6,30	5,81	0,50
Mar.	0,53	0,53	0,00	25,20	9,46	15,74	0,13	0,13	0,00	6,30	6,30	0,00
Abr.	0,53	0,40	0,14	25,20	9,06	16,14	0,13	0,10	0,03	6,30	4,68	1,62
Total	6,36	6,14	0,22	302,40	119,07	183,34	1,56	1,49	0,04	75,60	73,26	2,36
SD (%)	---	---	97	---	---	39	---	---	97	---	---	97

Own elaboration.

Table 10 shows the deliveries, demands, deficits, and demand satisfaction index for the users that make up the Northwest System and the PCHE-Céspedes. This table shows how the demand of these users is fully met: the "El Cobre" Water Treatment Plant in the months of May through January and March; the "En Route Deliveries" in the months of May, July, August, October, December, January, and March; and the "Quintero" Water Treatment Plant in the months of May, July, August, October, December, January, and March. It should be noted that the users with the greatest deficits are the PCHE-Céspedes and the Quintero Water Treatment Plant with 183.34 hm³/year and 2.36 hm³/year, respectively. The demand satisfaction index obtained for users is 97%, and for the PCHE-Céspedes, 39%. The second requirement, which establishes that a minimum delivery value of 90% must be met, is met for all three users. In the case of the PCHE-Céspedes, demand is not met in any month, and the demand satisfaction rate is 39%, because the WEAP model's priority is meeting user demand, not energy generation.

Table 11 shows the volumes (storage) of each reservoir corresponding to the results obtained by the WEAP model.

Table 11. Summary of reservoir storage volume (Vol.), in hm³, and water elevation (Elev.), in m

Meses	Céspedes		Chalóns		Charco Mono		Gota Blanca		Gilbert	
	Vol.	Elev.	Vol.	Elev.	Vol.	Elev.	Vol.	Elev.	Vol.	Elev.
May.	120,80	109,16	0,03	3,09	0,54	189,50	7,00	163,91	6,42	172,37
Jun.	92,25	106,39	0,16	1,32	1,09	192,11	17,62	143,43	13,78	180,03
Jul.	98,55	107,00	0,12	13,70	0,95	191,56	14,73	141,84	11,77	178,43
Agos.	105,96	107,72	0,10	11,43	0,87	191,19	13,04	140,82	10,59	177,36
Sep.	117,59	108,84	0,12	13,17	0,93	191,47	14,35	141,61	11,50	178,18
Oct.	127,02	109,76	0,13	14,16	0,97	191,64	15,45	142,24	12,27	178,88
Nov.	128,21	109,88	0,14	15,31	1,02	191,82	16,20	142,66	12,79	179,36
Dic.	123,55	109,42	0,11	11,91	0,88	191,25	13,54	141,12	10,94	177,67
Ene.	118,80	108,96	0,07	7,76	0,72	190,51	10,68	139,41	8,95	175,87
Feb.	114,31	108,53	0,04	4,79	0,60	189,90	8,13	137,71	7,18	173,63
Mar.	109,67	108,08	0,03	1,79	0,49	189,21	6,25	136,21	5,87	171,45
Abr.	106,09	107,73	0,02	1,20	0,42	188,80	5,00	135,04	5,00	170,00

Own elaboration.

In November, the Céspedes reservoir reaches its maximum storage volume and water elevation, with values of 128.21 hm^3 and 109.88 m, respectively, and Chalóns a volume of 0.14 hm^3 and 15.31 m. In June, Charco Mono reaches a volume of 1.09 hm^3 and 192.11 m; Gota Blanca reaches a volume of 17.62 hm^3 and 143.43 m; and Gilbert reaches a volume of 13.78 hm^3 and 180.03 m. The Céspedes and Chalóns reservoirs reach their highest volume and water elevation in November, the month of the beginning of the dry period. The Charco Mono, Gota Blanca, and Gilbert reservoirs reach their highest volume and water elevation in June, the second month of the wet period.

In April, the reservoirs reached their lowest storage volume and water elevation with values of: 0.03 hm^3 and 0.00 m in Chalóns; 0.42 hm^3 and 188.80 m in Charco Mono; 5.00 hm^3 and 135.04 m in Gota Blanca; and 5.00 hm^3 and 170 m in Gilbert. This behavior is logical, since this month is the last month of the dry period. During the dry period the levels of the reservoirs decrease considerably until the rainy season begins and they begin to fill. The Céspedes reservoir reaches its minimum volume in June with a value of 92.25 hm^3.

The Charco Mono reservoir has the highest water storage elevation at 192.11 m and Chalóns has the lowest elevation when empty.

Power generation from the Céspedes reservoir PCHE.

The small hydroelectric plant called PCHE-Céspedes is located in the Céspedes reservoir. From the technical report presented by Faure (2012) [4], the characteristic data were obtained and can be seen in Table 12. These data were implemented in the WEAP model to obtain the hydroelectric generation of the PCHE-Cespedes, the results are shown in Table 12. The required monthly and annual energy production target imposed on the PCHE-Cespedes is 428 MW-h and 5136 MW-h respectively.

Table 12. Hydroelectric generation and demand not covered by the Céspedes hydroelectric power plant

Meses	Energía Generada (MW-h)	Energía Generada (%)	Demanda no cubierta (MW-h)	Demanda no cubierta (%)
May.	235,31	4,58	192,69	3,75
Jun.	161,18	3,14	266,82	5,20
Jul.	177,11	3,45	250,89	4,88
Agos.	196,11	3,82	231,89	4,51
Sept.	226,88	4,42	201,12	3,92
Oct.	251,28	4,89	176,73	3,44
Nov.	254,08	4,95	173,93	3,39
Dic.	241,61	4,70	186,39	3,63
Ene.	229,31	4,46	198,69	3,87
Feb.	218,05	4,25	209,95	4,09
Mar.	206,14	4,01	221,86	4,32
Abr.	197,31	3,84	230,69	4,49
Total	2 594,37	50,51	2 541,63	49,49

Own elaboration.

Table 12 shows the energy generated and the demand not covered by the Céspedes CHP with their representative monthly percentages. The total energy generated amounts to 2,594.37 MW/h and 2,541.63 MW/h not generated. It should be noted that energy generation does not remain constant throughout the year and that it is not a priority for the Northwest System. The average monthly behavior of energy generation reached 216.20 MW/h, representing 8.33%.

By way of conclusions, the WEAP model has a satisfactory policy for the operation of the reservoirs, meeting 97% of the demands of the three users and 39% of the demands of the Céspedes PCHE in all months of 2016. In the case of PCHE-Céspedes, the satisfaction of the demand is 37% because the fundamental objective of the reservoirs is to satisfy the demand in the users and not the generation of electric energy. As a final result, there is a monthly deficit in the users of: 0.22 hm^3 in the Deliveries on Route; 0.04 hm^3 in the El Cobre Water Treatment Plant; 2.36 hm^3 in the Quintero Water Treatment Plant and 183.34 hm^3 in the PCHE-Céspedes.

In the reservoirs, volumes vary, increasing in the wet period (May-October) and decreasing in the dry period (November-April). The Charco Mono reservoir has the highest water storage elevation with 192.11 m and Chalóns the lowest elevation when empty, while Céspedes is the reservoir with the highest water storage capacity.

With respect to the generation of electric power, good results are obtained by managing to generate 2,594.37 MW-h, representing 50.51% of the proposed plan, which was 5,136 MW-h in 2016. The results obtained with the WEAP model can be proposed to carry out the optimal operation of the northwest system supplying the city of Santiago de Cuba.

Results of the application of the HEC- ResPRM model

To evaluate whether the three premises of the reservoir operation policy are met, it is necessary to determine for users: monthly net deliveries (Rui), annual demand satisfaction index (SD), monthly deficit (Defi) and annual deficit (DefA). In reservoirs: monthly net delivery (Rei), annual net delivery (R), monthly losses (Pei), annual losses (P), monthly gross delivery (Uei) and annual gross delivery (U). The equations are used for this purpose.

$$SDu = \frac{\sum Ru_i}{\sum Du_i} \cdot 100$$

Equation 1

$$Def_i = Du_i - Ru_i$$

Equation 2

$$Ue_i = Re_i - Pe_i$$ Equation 3

$$Ue = Re - Pe$$ Equation 4

where: i: identifies the month; u: identifies the user; e: identifies the reservoir.

SDu: annual demand satisfaction index of user u,

Ru.: monthly delivery to user u; *Du*.: *dd*user's monthly demand,

Def.: monthly deficit of each user ; *Ue*.: monthly gross delivery from reservoir,

Re_i: monthly net delivery from reservoir; Pe_i: monthly reservoir loss, Ue: annual gross delivery from reservoir, Re: annual net delivery from reservoir, *Pe*: annual reservoir loss.

Table 13 shows the costs of flows and storage in the reservoirs, users and conveyance works of the Northwest System, which resulted from the model run. The HEC-ResPRM model proposes a solution, in which there are no costs in reservoir storage, meaning that all monthly reservoir volumes are between the NVM and NAN and there are no releases. As for deliveries from the reservoirs, only the Gota Blanca reservoir is penalized, while in the arches there is only the cost of the flow due to the Mogote Transfer system. These costs are a consequence of the penalty functions created for the reservoir and the Mogote Diversion system. Finally, the value of the objective function is obtained, which is the total cost of the flow network, resulting from the sum of the costs of the volumes, flows and arcs of the Northwest System.

Tables 14, 15, and 16 summarize the delivery plan proposed by the HEC-ResPRM model for the 2015-2016 hydrological year (75%). Table 15 shows the deliveries and losses from the reservoirs and their monthly magnitudes. In qualitative terms, the proposed delivery plan meets the second and third operating premises of the reservoirs by assuming that the Gilbert and Charco Mono reservoirs deliver year-round and the Mogote Transfer System delivers during the dry season. Table 15 shows that the Chalóns and Gota Blanca reservoirs deliver for eight months, and Céspedes, through the Mogote Transfer System, delivers during four months of the dry season. In quantitative terms, the reservoirs as a whole deliver a gross annual volume of 243.13 hm^3/year, a net annual volume of 232.47 hm^3/year, and total annual losses amount to 10.66 hm^3/year.

In terms of magnitude, the Céspedes reservoir makes the largest net annual delivery with 156.75 hm^3/year, of which 15.44 hm^3 are delivered through the Mogote Transfer system to the city of Santiago de Cuba, the rest, 141.31 hm^3/year, are turbined in the PCHE for the generation of electric power and irrigation of agricultural areas. Recio (2016) [5].

Table 13. Summary of costs for the Northwest System flow network

Elemento	Volumen	Flujos en embalses	Flujos en Arcos	Total
	($)	($)	($)	($)
Gilbert	0,00	0,00	------	0,00
Céspedes	0,00	0,00	------	0,00
Gota Blanca	0,00	2805,84	------	2805,84
Charco Mono	0,00	0,00	------	0,00
Chalóns	0,00	0,00	------	0,00
TrasvaseMogote	0,00	0,00	19416,29	19416,29
PCHE	0,00	0,00	------	0,00
Potabilizadora El Cobre	0,00	0,00	------	0,00
Potabilizadora Quintero	0,00	0,00	------	0,00
Entregas Ruta	0,00	0,00	------	0,00
Total	0,00	2805,84	19416,29	22222,13

Own elaboration.

Users in the city of Santiago de Cuba (remember Quintero, El Cobre and Entregas Ruta Water Treatment Plants) are guaranteed a net annual delivery of 75.16 hm^3, of which Gilbert contributes 46.10 hm^3, 61.33%, Gota Blanca 18.76 hm^3, 24.96%, Céspedes through the Mogote Transfer 15.44 hm^3, 20.54%, Charco Mono 9.14 hm^3, 12.16% and Chalóns 1.16 hm^3, 1.54%. Comparing the deliveries between tables 2, 5 and 6, it is observed that the maximum and minimum flow restrictions are met in all reservoirs and users.

Table 14. Summary of monthly and annual deliveries and losses from reservoirs

Relación de Entregas y Pérdidas desde los Embalses y el Trasvase Mogote, en (hm^3/mes)															
Meses	Gota Blanca			Charco Mono			Gilbert			Céspedes			Chalóns			Trasv. Mogote
	Re_i	Pe_i	Ue_i	Re_i	Pe_i	Ue_i	Re_i	Pe_i	Ue_i	Re_i	Pe_i	Ue_i	Re_i	Pe_i	Ue_i	Re_i
May.	0,00	0,16	0,16	1,01	0,004	1,02	5,25	0,07	5,32	12,70	0,71	14,96	0,00	0,002	0,002	0,00
Jun.	0,00	0,17	0,17	1,08	0,007	1,09	5,18	0,06	5,24	12,52	0,72	14,29	0,00	0,003	0,003	0,00
Jul.	0,44	0,18	0,62	1,24	0,006	1,25	4,58	0,05	4,63	12,70	0,83	12,22	0,00	0,003	0,003	0,00
Ago.	3,74	0,17	3,91	0,50	0,003	0,50	2,02	0,03	2,05	11,41	0,83	12,23	0,00	0,003	0,003	0,00
Sep.	0,00	0,14	0,14	1,02	0,002	1,02	5,18	0,03	5,21	11,41	0,73	12,13	0,06	0,003	0,067	0,00
Oct.	3,80	0,14	3,94	0,50	0,005	0,50	1,81	0,03	1,84	11,41	0,74	12,15	0,16	0,003	0,163	0,00
Nov.	0,41	0,12	0,54	0,51	0,007	0,52	5,18	0,03	5,21	11,41	0,65	12,05	0,16	0,003	0,159	0,00
Dic.	3,51	0,12	3,63	0,50	0,007	0,51	2,09	0,02	2,12	12,66	0,57	13,23	0,16	0,003	0,163	1,25
Ene.	3,78	0,12	3,90	0,50	0,007	0,51	1,83	0,03	1,86	16,85	0,61	16,74	0,16	0,003	0,163	4,73
Feb.	0,00	0,12	0,12	1,28	0,005	1,29	4,84	0,03	4,87	11,41	0,60	12,00	0,15	0,002	0,147	0,00
Mar.	2,65	0,13	2,78	0,50	0,003	0,50	2,95	0,04	3,00	16,14	0,73	16,86	0,16	0,002	0,162	4,73
Abr.	0,42	0,14	0,57	0,50	0,003	0,50	5,18	0,07	5,25	16,14	0,66	16,80	0,16	0,002	0,157	4,73
Total	**18,76**	**1,72**	**20,48**	**9,14**	**0,058**	**9,20**	**46,10**	**0,49**	**46,59**	**156,75**	**8,36**	**165,67**	**1,16**	**0,032**	**1,192**	**15,44**

Own elaboration.

Table 15 shows a summary of the net deliveries and percentages by period for the city of Santiago de Cuba through the reservoirs of the Noroeste System. Regarding the annual net delivery, in the wet period (May-October), 37.58 hm^3 are delivered, 41.48%, and in the dry period (November-April), 53.02 hm^3 are delivered, 58.52%. Essentially, the operating rule proposed by the HEC-ResPRM model conceives the constant use of the Gilbert and Charco Mono reservoirs throughout the year. In the wet period, the net delivery from the reservoir Gilbert is 24.03 hm^3, 63.94%, followed by Gota Blanca with 7.98 hm^3, 21.23%, Charco Mono 5.35 hm^3, 14.23%, and Chalóns 0.22 hm^3, 0.58%. The Gota Blanca, Gilbert, and CharcoMono reservoirs together deliver 37.36 hm^3, or 99.41% of the total volume. In the dry period, the net delivery from the Gilbert reservoir is 22.08 hm^3, or 41.64%, Gota Blanca 10.78 hm^3, or 20.33%, Charco Mono 3.79 hm^3, or 7.15%, and Chalóns 0.94 hm^3, or 1.77%. The Mogote Transfer is used to transfer 15.44 hm^3, or 29.12% of the total volume, from the Céspedes reservoir to the Gilbert reservoir. The Gota Blanca, Gilbert, and Charco Mono reservoirs together deliver 36.65 hm^3, representing 69.12% of the net annual output. In terms of annual net output, Gilbert is the Noroeste System's largest reservoir, delivering 46.10 hm^3, or 50.88%, followed by Gota Blanca with 18.76 hm^3, or 20.70%; Céspedes with 15.44 hm^3, or 17.04%; and Charco Mono with 9.14 hm^3, or 10.08%.

Table 15. Summary of net deliveries by period from the Northwest System reservoirs

Embalse	Húmedo (hm^3)	Seco (hm^3)	Total (hm^3)	Húmedo %	Seco %	Total %
Gilbert	24,03	22,08	46,10	52,11	47,89	100
Trasvase Mogote	0,00	15,44	15,44	0,00	100,00	
Gota Blanca	7,98	10,78	18,76	42,54	57,46	
Charco Mono	5,35	3,79	9,14	58,55	41,45	
Chalóns	0,22	0,94	1,16	19,31	80,69	
Total	37,58	53,02	90,61	41,48	58,52	

Own elaboration.

Table 16 shows the deliveries, demands, deficits, and demand satisfaction index for the four users of the Northwest System. Although the demand of the PCHE user is only fully satisfied in the months of May and July, and for the remaining users, the HEC-ResPRM model proposes distributing the annual user deficit into small monthly deficits, the delivery plan proposed by this model is considered adequate since, with the monthly net deliveries designed for users, it is possible to obtain a user demand satisfaction index equal to or greater than 90%. These results demonstrate that the delivery plan proposed by the HEC-ResPRM model meets the first operating premise established for the Northwest System.

Table 16. Summary of user deliveries, demands and deficits

Meses	Potabilizadora El Cobre			Potabilizadora Quintero			Entregas Ruta			PCHE Céspedes.		
	D (hm^3)	R (hm^3)	Def. (hm^3)	D (hm^3)	R (hm^3)	Def. (hm^3)	D (hm^3)	R (hm^3)	Def. (hm^3)	D (hm^3)	R (hm^3)	Def. (hm^3)
May.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	12,70	0,00
Jun.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	12,52	0,18
Jul.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	12,70	0,00
Ago.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Sep.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Oct.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Nov.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Dic.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Ene.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	12,12	0,58
Feb.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Mar.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Abr.	0,13	0,12	0,01	6,30	5,67	0,63	0,53	0,48	0,05	12,70	11,41	1,29
Total	**1,56**	**1,40**	**0,16**	**75,60**	**68,04**	**7,56**	**6,36**	**5,72**	**0,64**	**152,40**	**141,31**	**11,10**
SD (%)	----	----	90,0	----	----	90,0	----	----	90,0	----	----	93,0

Own elaboration.

The reservoirs guarantee a net annual delivery of 216.47 hm^3/year to all users. At the El Cobre and Quintero water treatment plants, 1.40 hm^3/year and 68.04 hm^3/year are delivered, respectively; to Entregas Ruta 5.72 hm^3/year, and to the Céspedes Water Treatment Plant (PCHE Céspedes), 141.31 hm^3/year. The total annual deficit for users associated with the city of Santiago de Cuba is 8.36 hm^3/year, and for the Noroeste System, 19.46 hm^3/year.

4 Conclusion

(1) The bibliographical research conducted in this paper provides insight into global trends related to the use of mathematical modeling for reservoir operation. Currently, mathematical modeling is a very powerful tool for proposing optimal operating policies for reservoir systems, and its best use is through simulation and optimization techniques.

(2) Through the application of the WEAP program, a conceptual model was developed that led to the proposal of an optimal operating policy for the Northwest Water Supply System serving the city of Santiago de Cuba. This guarantees that 97% of user water demand and 39% of the Céspedes PCHE's demand will be met. The Céspedes PCHE will generate 2,594,373 MWh of annual energy.

(3) The water delivery plan proposed by the WEAP model envisions that the reservoirs of the Northwest System will deliver a net annual supply of 199.99 hm^3/year to users in the city of Santiago de Cuba, with 98,848 hm^3 (49.43%) being delivered during the wet season and 101.15 hm^3 (the remaining 50.57%) during the dry season. It defines Céspedes as the main reservoir, providing 119.06 hm^3/year, 59.53% of the net annual supply.

(4) The WEAP and HEC-PRM models propose similar results for obtaining an optimal operating policy for the reservoirs of the Northwest System, and therefore it cannot be stated that one model is superior to the other.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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