

UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION OF OPERATIONS OF RESERVOIR SYSTEMS FOR HYDROPOWER GENERATION IN TIGRIS RIVER BASIN, IRAQ

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FK 2016 20



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By

YOUSIF HASHIM ABDULLAH AL-AQEELI

Thesis Submitted to the School of Graduated Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the degree of Doctor of Philosophy

August 2016



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DEDICATION

To the dearest to my heart, my mother and father To my lovely wife To my son and daughters lovers to my heart To my dear brothers To my dear sister To my lovely wife's family



5

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

OPTIMIZATION OF OPERATIONS OF RESERVOIR SYSTEMS FOR HYDROPOWER GENERATION IN TIGRIS RIVER BASIN, IRAQ

By

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August 2016

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Samsuzana Abd Aziz, PhD Engineering

The aim of the study was to determine the optimal operation policies for the various combinations of up to four reservoirs (Mosul and Dokan reservoirs are currently in operation, Bekhma reservoir is under construction while Makhoul reservoir is under planning phase) along the Tigris river basin in Iraq for the purpose of optimally generating hydroelectric power, given the constraints pertinent to the area. A genetic algorithm optimization model (GAOM) was coded in the Matlab work environment to determine the optimal operating policy for a single reservoir to maximize the annual hydropower generation. Two algorithms were next formulated and used independently in the GAOM to improve the performance of the Mosul reservoir in Iraq, during 20 years of operation. The performances of these two algorithms were evaluated through comparing their optimal values. The GAOM achieved an increase in hydropower generation in 17 years of the 20 years with the second algorithm being the better. To determine the effect of precipitation and evaporation, their volumes were taken into consideration in the continuity equation, using the second algorithm. In this case, the obtained optimal values were decreased in all of the scenarios compared with ignoring the volumes of precipitation and evaporation. A simulation model (SM) for the Mosul reservoir was formulated by using the SIMULINK technique in the MATLAB environment. The r² and NSE are 0.92 and 0.87 respectively in comparison of elevations, and 0.81 and 0.77 respectively in comparisons of hydropower generated. Adopting the second algorithm and taking into consideration the evaporation and precipitation, the GAOM and SM of Mosul reservoir were combined. In this combination, the GAOM identified the optimal operation policy, while the SM adopted this optimal operation policy to evaluate the performance of GAOM calculations through comparing the three parameters; powers, elevations and storages in order to confirm the calculations of GAOM. In all of these comparisons, the coefficient of determination was 0.99.

Two operational strategies in the combination of GAOMs and SMs were used to determine the optimal operation policies for the multi-reservoir system located on the Tigris river basin in Iraq. In the first strategy, the target storage at the end of final

month is equal to, or above the minimum operational storage; and for the second strategy it is equal to, or above the initial storage. For each strategy, the performances of operation the reservoirs individually; as a dual-reservoir system; as a three-reservoir system and as a four-reservoir system were compared in terms of annual hydropower generation based on the three groups of annual inflows: minimum, average, and maximum during twenty years. Those operational situations where: firstly, running of Mosul and Dokan reservoirs, secondly, running of Mosul, Dokan and Bekhma reservoirs, and thirdly, running of Mosul, Dokan, Bekhma and Makhoul reservoirs. According to the values of T-test obtained, the results indicated that only using the first strategy and operating Mosul, Dokan, Bekhma and Makhoul reservoirs were significant in favor of running the reservoirs as one entity. The two strategies mentioned previously were also used in the combined GAOMs and SMs to determine the optimal operation policies for the multi-reservoir system in the case of using a new storage of Makhoul reservoir. For each strategy, the performance of the operation of the multi-reservoir system was assessed through comparing the annual hydropower production a prior to and after having used this new storage by relying on three modes of annual inflows, minimum, average, and maximum annual inflows. All of these comparisons were done in two cases: operating the reservoirs individually and as one system. Through using the first and second strategies, the hydropower production increased by good percentages through using those three modes of annual inflows. In addition, for each strategy, the performance of this multi-reservoir system was evaluated according to that new storage of Makhoul. In this evaluation, the annual hydropower production by operating the reservoirs individually and as one system were compared by using those three modes of inflows according to T-test. The results indicated that the differences between the hydropower generated were significant in favor of operating the reservoirs as one system through using the first strategy, while were non-significant by using the second strategy. The parameters of evaporation and precipitation must include in the continuity equation when using or creating a model simulates the dynamic processes of water storage system. Hybrid model, consists of GAOM and SM, was created. This model has high reliability and can be used in real applications with various storage systems.

Keywords: reservoir systems, optimization, simulation, optimal operation policy, genetic algorithms, Matlab, Simulink, hydropower generation, Tigris river basin, Iraq.

Abstrak tesis yang dikemukakan kepada Senat Universiti Puta Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGOPTIMUMAN OPERASI SISTEM RESERVOIR FOR HIDRO GENERASI DALAM TIGRIS LEMBANGAN SUNGAI, IRAQ

Oleh

YOUSIF HASHIM ABDULLAH AL-AQEELI

Ogos 2016

Pengerusi Fakulti Samsuzana Abd Aziz, PhD Kejuruteraan

Tujuan kajian adalah untuk menentukan dasar operasi yang optimum untuk pelbagai kombinasi sehingga empat buah takungan (Mosul dan Dokan sedang beroperasi pada masa kini, Bekhma sedang dibina manakala Makhoul di peringkat perancangan) sepanjang Sungai Tigris di Iraq untuk tujuan menjana kuasa hidroelektrik secara optimum, memandangkan kekangan berkaitan kawasan itu. Sebuah model pengoptimuman algoritma genetic (GAOM) dikodkan dengan persekitaran-kerja Matlab demi untuk menentukan dasar beroperasi optimum untuk satu takungan bagi memaksimumkan penjanaan tenaga hidro tahunan. Dua algoritma berikutan kemudian diformulasikan dan diguna secara bebas di dalam GAOM untuk meningkatkan prestasi takungan Mosul di Iraq, menggunakannya dalam 20 buah scenario (tahun) pengendalian masa nyata. Persembahan dua algoritma tersebut telah dinilaikan melalui membandingkan nilai optimum dihasilkan, pada mulanya dengan nilai cerapan, dan kemudian dengan satu sama lain semasa semua scenario digunakan. GAOM telah mencapai satu peningkatan penjanaan tenaga hidro dalam 17 tahun daripada 20 tahun berkenaan, menggunakan dua algoritma itu, yang mana tertunjuk bahawa algoritma kedua yang lebih baik. Demi untuk menentukan kesan pemendakan dan penyejatan, isipadu masing masing diambil kira di dalam persamaan keselanjaran, menggunakan algoritma kedua. Dalam kes ini, nilai optimum yang diperolehi berkurangan dalam semua senario berbanding dengan mengabaikan isipadu pemendakan dan penyejatan. Satu model simulasi (SM) untuk takungan Mosul telah dirumuskan menggunakan teknik SIMULINK dengan persekitaran MATLAB. r² and NSE ialah 0.92 dan 0.87 masing masing dalam perbandingan ketinggian paras air, dan juga bernilai 0.81 dan 0.77 masing masing dalam perbandingan penjanaan kuasa hidro. Dengan algoritma kedua serta mengambil kira penyejatan dan pemendakan, GAOM dan SM takungan Mosul telah digabungkan. Dalam gabungan ini, GAOM mengenal pasti dasar operasi yang optimum, manakala SM mengamalkan dasar operasi optimum ini untuk menilai prestasi GAOM melalui membandingkan tiga parameter iaitu; kuasa yang dihasilkan, paras ketinggian dan storan untuk mengesahkan pengiraan GAOM. Dalam kesemua perbandingan, pekali penentuan adalah 0.99.

Dua strategi dalam gabungan GAOMs and SMs digunakan untuk menentukan dasar operasi yang optimum untuk pelbagai system takungan terletak di dalam lembangan Sungai Tigris di Iraq. Dalam strategi pertama, sasaran storan pada hujung bulan lepas di ambil sebagai sama dengan, atau melebihi storan operasi minimum; dan untuk strategi kedua ia sama dengan, atau melebihi simpanan pada mulanya. Untuk setiap strategi, persembahan takungan air, operasi secara individu; sebagai sistem takungan berdua; sebagai sistem takungan bertiga atau sebagai sistem takungan berempat telah dipertandingkan dalam soal penjanaan tenaga hidro tahunan berdasarkan tiga kumpulan aliran masuk tahunan: minimum, sederhana, dan maksimum sepanjang jangkamasa dua puluh tahun. Situasi operasi merangkumi: pertama sekali, operasi Mosul bersama Dokan, keduanya, operasi bersama Mosul, Dokan and Bekhma, dan ketiganya, operasi bersama Mosul, Dokan, Bekhma and Makhoul, Menurut nilai hasil ujian T yang diperolehi, keputusan menunjukkan bahawa hanya dengan menggunakan strategi pertama berserta dengan beroperasi Mosul, Dokan, Bekhma and Makhoul berasingan secara individu, dan juga sebagai satu sistem takungan berempat penting menyokong mengoperasikan takungan air sebabagi satu entiti. Dua strategi tersebut terlebih dahulu juga digunakan dalam gabungan GAOMs and SMs untuk menentukan dasar operasi optimum bagi system multi takungan didalam hal menggunakan satu storan baru takungan Makhoul. Untuk setiap strategi, prestasi operasi system pelbagai combinasi takungan ditaksir melalui membandingkan pengeluaran kuasa hidro tahunan sebelum dan setelah menggunakan storan baru ini dengan bergantung pada tiga corak aliran masuk tahunan iaitu: minimum, purata, dan maksimum. Kesemua perbandingan ini dibuat dalam dua kes: beroperasi takungan air secara individu dan kemudia sebagai satu sistem multi takungan. Melalui menggunakan strategi pertama dan kedua, pengeluaran kuasa hidro bertambah sebanyak peratusan yang baik melalui menggunakan ketiga-tiga mod daripada aliran masuk tahunan. Tambahan pula, untuk setiap strategi, prestasi system multi takungan ini dinilaikan berdasarkan storan baru di Makhoul. Dalam penilaian ini pengeluaran kuasa hidro tahunan, melalui operasi takungan berasingan secara individu dan melalui operasi sebgaia gabungan system takungan telah dipertandingkan dengan menggunakan tiga mod aliran masuk mengikut Ujian T. Keputusan menunjukkan bahawa perbezaan kuasa hidro dijana adalah penting dan sedia menyokong cadangan mengoperasikan takungan takungan air sebagai satu sistem gabungan menggunakan strategi pertama; manakala ialah tidak bererti sekirn menggunakan strategi kedua. Parameter penyejatan dan Kerpasan mesti termasuk dalam persamaan keselanjaran apabila menggunakan atau mewujudkan model yang menyerupai proses dinamik sistem penyimpanan air. model hibrid, terdiri daripada GAOM dan SM, telah dicipta. Model ini mempunyai kebolehpercayaan yang tinggi dan boleh digunakan dalam aplikasi sebenar dengan pelbagai sistem penyimpanan.

Kata Kunci: sistem takungan, simulasi, pengoptimuman, dasar operasi optimum, algoritma genetik, Matlab, Simulink, penjanaan kuasa hidro, lembangan sungai Tigris, Iraq.

ACKNOWLEDGEMENTS

My deepest graduate goes to the Most Merciful Allah S.W.T. Who granted me a knowledge help me to pursue my PhD degree in Malaysia.

The full version of this thesis would not have been possible without supporting of many people. I am very grateful to all those who supported me in the completion of this work and stand with me in all circumstances. I would like to extend my thanks to my supervisor, Dr. Samsuzana Abd Aziz, who provided me valuable advice, encouragements and support in order to continue and complete my work. I would like to thank my former supervisor, Dr. Professor Lee Teang Shui, who support and advise me during the first three semesters, before he retired. Gratitude and appreciation to the other members of my committee, Dr. Badronnisa bt. Yusuf and Dr. Aimrun Wayayok, for the suggestions and insights which contributed to strengthen of the thesis.

I want to thank my parents, my father, who spent his life in our care and my mother for her prayers and supplication to Allah S.W.T. to help me in my studies. I wish to thank my dear wife for the kind words and support. To my brothers, my friends, thank you for your kind words and support.

I certify that a Thesis Examination Committee has met on 11 August 2016 to conduct the final examination of Yousif Hashim Abdullah Al-Aqeeli on his thesis entitled "Optimization of Operations of Reservoir Systems for Hydropower Generation in Tigris River Basin, Iraq" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	XV
LIST OF FIGURES	xviii
LIST OF ABBREVIATIONS	xxiv

CHAPTER

1	INT	DODUC	TION			1
I		Intro du	TION			1
	1.1	Statem	ont of the	Droblom		1
	1.2	Ohiset	ives of the	Study		2
	1.5	Object	ives of the	Study		3
	1.4	Scope o	n the Stud	y		3
	1.5	Tools a	nd Data			4
2	LITER	ATURE	REVIEW	7		5
	2.1	Introdu	iction			5
	2.2	Literat	ure <mark>Reviev</mark>	v Pertaining to	the Optimal Operations of Water	5
		Storage	e Sy <mark>stems</mark>	Ũ		
		2.2.1	Literatu	re Review Per	taining to the Using of Genetic	5
			Algorith	ms in the Ope	eration of Water Storage Systems	
		2.2.2	Literatu	re Review Per	taining to the Using of Other	10
			Optimiz	ation Techniq	ues in the Operation of Water	
			Storage	Systems	1	
		2.2.3	Literatur	re Review Per	taining to the Simulation Models in	19
			the Oper	ation of Wate	r Storage Systems	
	2.3	Compu	itational In	telligence	5 ,	22
	2.4	Evoluti	ionarv Cor	nputation		23
		2.4.1	Brief his	story of Evolu	tionary Computation	24
	2.5	Genetic	c Algorithi	ns	J I I I I I I I I I I I I I I I I I I I	24
		2.5.1	Historic	al Overview o	f Genetic Algorithms	25
		2.5.2	Descript	ion the Genet	ic Algorithms function	26
		2.5.3	Genetic	Algorithms T	erminology	26
		2.5.4	Encodin	g the Solution	s in Genetic Algorithms	27
		2.5.5	Genetic	Algorithms E	lements	27
		2.0.0	2551	Representat	ion	27
			2.0.0.1	25511	Dynamic Real Representation	27
				25512	Real Representation of Integer	28
				2.2.2.1.2	Variables	20
			2.5.5.2	Fitness Eval	uation	29
			2.5.5.3	Selection		29

2.5.5.3.1Selection for Reproduction292.529

				2.5.5.3.2	Selection of Replacement	32
			2.5.5.4	Crossover		33
				2.5.5.4.1	N-Point Crossover	34
				2.5.5.4.2	Uniform Crossover	34
				2.5.5.4.3	Arithmetical Crossover	35
				2.5.5.4.4	Blend Crossover	35
			2.5.5.5	Mutation		36
				2.5.5.5.1	Uniform Mutation	36
				25552	Non-Uniform Mutation	36
				25553	Breeder Mutation	37
			2556	Termination	Criteria	37
	26	Consid	2.5.5.0 oration tha	Evaporation	and Procinitation into Continuity	39
	2.0	Equation	eration the	Pasarnoir Su	and Precipitation into Continuity	30
	27	-Decomp	ni unougn	Concentions	stems Operations	20
	2.7	Reservo	oir System	s Operations		39
	2.8	Summa	iry			40
3	METH		GV			41
5	3.1	Introdu	ction			
	3.1	Storage	System u	ndor Study		45
	5.2	3 2 1	Mogul P	aservoir		45
		3.2.1	Dokon D	eservoir		40
		3.2.2	Dokali K		dan Construction	47
		5.2.5 2.2.4	Malahani	Reservoir, ui	the Distruction	47
		3.2.4	Maknou	r Reservoir; ii	the Planning Stages	47
		3.2.5	Data			47
	2.2	3.2.6	Chosen (Operating Per	Tod for the Multi-Reservoir System	57
	3.3	Reserve	ig of Op oir	timization a	nd Simulation Models for Mosul	57
		3.3.1	Building Reservoi	a Mathemat	ical Optimization Model for a Single ervoir)	58
			3.3.1.1	Objective F	unction	58
			3.3.1.2	Constraints		60
			3.3.1.3	The Two A	lgorithms Formulated	62
			3.3.1.4	Effect of Ev	aporation and Precipitation	66
			3.3.1.5	Determinati Algorithm	on of Elements in the Genetic	66
			3.3.1.6	Applying Model	and Evaluating the Optimization	69
				3.3.1.6.1	Using the Two Algorithms	69
					without Taking into)
					Consideration the Effect of	Ĩ
					Evaporation and Precipitation	
				3.3.1.6.2	Using the Best Algorithm	69
					(Second Algorithm) with Taking	ŗ
					into Consideration the Effect of	Ĩ
					Evaporation and Precipitation	
		3.3.2	Building	of Simulatio	n Model for Mosul Reservoir	70
		0.0.2	3.3.2.1	Building a	Simulation Mathematical Model for	· 71
			5.5.2.1	Single Rese	rvoir (Mosul Reservoir)	/1
			3322	Simulation	Model Description and its Working	71
			5.5.2.2	Mechanism	inouer Description and its working	/1

			3.3.2.3	Applying and Evaluating the Simulation Model	74
	3.4	Combir	ning the O	Optimization and Simulation Models for Mosul	74
		Reservo	oir and its .	Application	
	3.5	Buildin	g of Opti	mization and Simulation Models for the Multi-	75
		Reservo	oir System	under Study	
		3.5.1	Building	a Mathematical Optimization Model for the	75
			Multi-Re	eservoir System under Study	
	3.6	Evaluat	ion of Flor	ws at the Fatha Station	77
	3.7	Buildin	g the Co	mbination of the Optimization and Simulation	77
		Models	for the M	ulti-Reservoir System under Study	
		3.7.1	Operatin	g the Combined of Optimization and Simulation	82
			Models of	of the Various Multi-Reservoir Systems	
		3.7.2	Compari	ng the Performance of the Various Multi-	87
			Reservoi	r Systems	
	3.8	Storage	Volume o	of the Makhoul Reservoir	87
		3.8.1	Operatin	g the Combination of Optimization and Simulation	87
			Models v	with New Volume of Makhoul	
4	RESUL	TS AND	DISCUS	SION	90
	4.1	Introdu	ction		90
	4.2	Determ	ination of	the Population Size and Number of Generations in	90
		the GA	OM		
	4.3	Applica	ition a <mark>nd</mark> E	Evaluation of the GAOM of Mosul Reservoir	92
		4.3.1	Using 1	the Two Algorithms without Taking into	92
			Consider	ation the Effect of Evaporation and Precipitation	
		4.3.2	Using th	e Best Algorithm (Second Algorithm) with taking	97
			into Co	onsideration the Effect of Evaporation and	
			Precipita	tion	
	4.4	Applica	ition and	Evaluation the Simulation Model of Mosul	99
		Reserve	oir		
	4.5	Applica	tion the C	ombined GAOM and SM of Mosul Reservoir	101
	4.6	Evaluat	ion of the	Observed Flows at Fatha Station	102
	4.7	Operati	ng the Co	ombined GAOM and SM for the Various Multi-	104
		Reservo	or System	S	104
		4.7.1	Using the	e First Strategy	104
			4.7.1.1	Operating the Combined GAOM and SM for	104
				Each Reservoir Individually, Using the First	
			4710	Strategy	100
			4.7.1.2	Operating the Combined GAOM and SM for the	109
				Dual Reservoir System of Mosul and Dokan,	
			4712	Operating the Combined CAOM and SM for the	112
			4.7.1.5	Three December Sectors of Macul Dalars and	112
				Relation Reservoir System of Mosul, Dokan and	
			1711	Operating the Combined CAOM and SM for the	116
			4./.1.4	Four Deservoir System of Meaul Delter	110
				Rokhma and Makhaul Using the Einst Strategy	
			1715	Comparing the Results of CAOM with the	121
			+./.1.J	Results of SM Using the First Stratagy	121
			1716	Comparing the Performance of the Various	121
			····	comparing the renormance of the valious	141

G

Multi-Reservoir Systems in Terms of Hydropower Generation, Using the First Strategy Second Strategy

	4.7.2	Using th	e Second Strategy	123
		4.7.2.1	Operating the Combined GAOM and SM for	124
			Each Reservoir Individually, Using the Second	
			Strategy	
		4.7.2.2	Operating the Combined GAOM and SM for the	129
			Dual Reservoir System of Mosul and Dokan,	
			Using the Second Strategy	
		4.7.2.3	Operating the Combined GAOM and SM for the	132
			Three Reservoir System of Mosul, Dokan and	
			Bekhma, Using the Second Strategy	
		4.7.2.4	Operating the Combined GAOM and SM for the	136
			Four Reservoir System of Mosul, Dokan,	
			Bekhma and Makhoul, Using the Second	
			Strategy	
		4.7.2.5	Comparing the Results of GAOM with the	141
			Results of SM, Using the Second Strategy	
		4.7.2.6	Comparing the Performance of the Various	141
			Multi-Reservoir Systems in Terms of	
			Hydropower Generation, Using the Second	
1.0	The Me		Strategy	144
4.8	The Ne	w Design	of Makhoul Reservoir	144
4.9	Combin	the New	storage of Makhour Reservoir in Operating the	145
		Operation	and SM for the Multi-Reservoir	145
	4.9.1	Deservoi	r Individually Using the New storage of Makhoul	143
		Reservoi	r Using the First Strategy	
	492	Operatin	g the Combined GAOM and SM for Mosul	147
	7.7.2	Dokan	Bekhma and Makhoul Reservoirs as One System	147
		Using th	e New storage of Makhoul Reservoir Using the	
		First Stra	ategy	
	4.9.3	Operatin	g the Combined GAOM and SM for Each	151
		Reservoi	r Individually Using the New storage of Makhoul	
		Reservoi	r, Using the Second Strategy	
	4.9.4	Operatin	g the Combined GAOM and SM for Mosul,	153
		Dokan, 1	Bekhma and Makhoul Reservoirs as One System	
		Using th	e New storage of Makhoul Reservoir, Using the	
		Second S	Strategy	
	4.9.5	Compari	ng the Results of GAOM with the Results of SM	158
		Using th	e New storage of Makhoul Reservoir, Using the	
		First and	Second Strategies	
	4.9.6	Compari	ng the Performance of the Linkage Forms of	158
		System	Reservoirs Using the New Storage of Makhoul	
		Reservoi	r, Using the First and Second Strategies	
	4.9.7	Evaluate	the Performance of Makhoul Reservoir Using the	160
		First and	Second Strategies with its New Storage	

G

5	CON	ICLUSIONS	163
	5.1	Summary	163
	5.2	Conclusions	164
	5.3	Major Contribution	166
	5.4	Recommendations for Future Research	167
RE	FERI	ENCES	168
AP	PENI	DICES	177
BIC)DAT	TA OF STUDENT	198
LIS	ST OF	FPUBLICATIONS	199



 \mathbf{G}

LIST OF TABLES

Tabl	e	Page
2.1	Taking into consideration the quantities of evaporation and precipitation into continuity equation, or not, , as found in the literature review	38
2.2	The forms of water storage systems, as found in the literature review	39
3.1	Design values for the elevations of the reservoirs (m.a.s.l), (WMWRI), (Fadhil, 1990) and (DCSD, 1996)	48
3.2	The storage volumes of the reservoirs (MCM), (WMWRI), (Fadhil, 1990) and (DCSD, 1996)	48
3.3	The capacity of different outlets of the reservoirs, and maximum permissible flows (m ³ /sec) (WMWRI) and (DCSD, 1996)	48
3.4	The monthly water requirements at downstream of the reservoirs (MCM) (Ishaq, 1998) and (Fadhil, 1990)	50
3.5	The average monthly rainfall depth onto the reservoirs (mm) (Fadhil, 1990) and (DCSD, 1996)	51
3.6	The average monthly evaporation depth from the reservoirs (mm) (Fadhil, 1990) and (DCSD, 1996)	51
3.7	Minimum releases from the reservoirs using the first strategy	85
3.8	Minimum releases from the reservoirs using the second strategy	86
3.9	Minimum releases from the reservoirs using the first strategy with a new volume of Makhoul	88
3.10	Minimum releases from the reservoirs using the second strategy with a new volume of Makhoul	89
4.1	Determination of the statistical parameters for the values of the objective function obtained by setting the number of generations and changing the population size, using the first algorithm	91
4.2	Determination of the statistical parameters for the values of the objective function obtained by setting the population size and changing the number of generations, using the first algorithm	91
4.3	Determination of the statistical parameters for the values of objective function obtained by setting the number of generations and changing the population size, using the second algorithm	92

- 4.4 Determination of the statistical parameters for the values of objective function obtained by setting the population size and changing the number of generations, using the second algorithm
 4.5 The increase and decrease of hydropower as a percentage using the 93 GAOM with the two algorithms compared with the observed hydropower generated for Mosul reservoir
- 4.6 The values of T-test in different forms of comparison for Mosul reservoir

95

- 4.7 Optimal energy generation from two reservoirs (Mosul and 121 Dokan), when they were operated individually and as one system, using the first strategy (GWhr)
- 4.8 The performance comparison of two reservoirs (Mosul and Dokan) 122 in terms of hydropower generation, when they were operated individually and as one system, using the first strategy (GWhr)
- 4.9 Optimal energy generation from three reservoirs (Mosul, Dokan, 122 and Bekhma), when they were operated individually and as one system, using the first strategy (GWhr)
- 4.10 The performance comparison of three reservoirs (Mosul, Dokan and Bekhma) in terms of hydropower generation, when they were operated individually and as one system, using the first strategy (GWhr)
- 4.11 Optimal energy generation from four reservoirs (Mosul, Dokan, 123 Bekhma and Makhoul), when they were operated individually and as one system, using the first strategy (GWhr)
- 4.12 The performance comparison of four reservoirs (Mosul, Dokan, Bekhma and Makhoul) in terms of hydropower generation, when they were operated individually and as one system, using the first strategy (GWhr)
- 4.13 Optimal energy generation from two reservoirs (Mosul and 141 Dokan), when they were operated individually and as one system, using the second strategy (GWhr)
- 4.14 The performance comparison of two reservoirs (Mosul and Dokan) 142 in terms of hydropower generation, when they were operated individually and as one system, using the second strategy (GWhr)
- 4.15 Optimal energy generation from three reservoirs (Mosul, Dokan, 142 and Bekhma), when they were operated individually and as one system, using the second strategy (GWhr)

- 4.16 The performance comparison of three reservoirs (Mosul, Dokan 143 and Bekhma) in terms of hydropower generation, when they were operated individually and as one system, using the second strategy (GWhr)
- 4.17 Optimal energy generation from four reservoirs (Mosul, Dokan, Bekhma, and Makhoul), when they were operated individually and as a system, using the second strategy (GWhr)
- 4.18 The performance comparison of four reservoirs (Mosul, Dokan, Bekhma and Makhoul) in terms of hydropower generation, when they were operated individually and as one system, using the second strategy (GWhr)
- 4.19 The operational storages with corresponding elevations and areas 144 for new volume of Makhoul reservoir
- 4.20 Optimal energy generation from four reservoirs (Mosul, Dokan, 159 Bekhma, and Makhoul), when they were operated individually and as a system with new storage of Makhoul, using the first strategy (GWhr)
- 4.21 The performance comparison of four reservoirs (Mosul, Dokan, 159 Bekhma and Makhoul) in terms of hydropower generation, when they were operated individually and as one system with new storage of Makhoul, using the first strategy (GWhr)
- 4.22 Optimal energy generation from four reservoirs (Mosul, Dokan, 160 Bekhma, and Makhoul), when they were operated individually and as a system with new storage of Makhoul, using the second strategy (GWhr)
- 4.23 The performance comparison of four reservoirs (Mosul, Dokan, 160 Bekhma and Makhoul) in terms of hydropower generation, when they were operated individually and as one system with new storage of Makhoul, using the second strategy (GWhr)
- 4.24 The increments of hydropower generation as a percentage, from all 161 the four reservoirs of the system, when they were operated individually and as one system with new storage of Makhoul, using the first strategy
- 4.25 The increments of hydropower generation as a percentage, from all 161 the four reservoirs of the system, when they were operated individually and as one system with new storage of Makhoul, using the second strategy
- 4.26 The values of T-test for the various forms of linkage for the system 162 reservoirs

LIST OF FIGURES

Figure		Page
2.1	Analysis of literature review pertaining to the optimization and simulation models for operation of water storage systems	21
2.2	Computational Intelligence Paradigms (Sumathi and Paneerselvam, 2010)	23
2.3	Principle of roulette-wheel selection (Shopova and Vaklieva-Bancheva, 2006)	30
2.4	Principle of Tournament selection (Shopova and Vaklieva- Bancheva, 2006)	32
2.5	Principle of Selection for replacement (Shopova and Vaklieva- Bancheva, 2006)	33
2.6	Principle of N-point crossover	34
2.7	Principle of uniform crossover	35
3.1	Flowchart of the applied methodology	43
3.1	Flowchart continuation	44
3.2	Diagram sketch for the storage system under study	45
3.3	Location of the system reservoirs in the Tigris river basin (UN-ESCWA and BGR, 2013)	46
3.4	The observed monthly inflow to Mosul reservoir	52
3.5	The observed monthly outflow from Mosul reservoir	53
3.6	The observed monthly inflow to Dokan reservoir	53
3.7	The observed monthly flow at Aski Kalak station	54
3.8	The observed monthly outflow from Dokan reservoir	54
3.9	The observed monthly flow at Fatha station	55
3.10	The observed monthly power generated from Mosul reservoir	56
3.11	The observed monthly elevation of storage in Mosul reservoir	56
3.12	The observed volume of storage on the first day for every water year in Mosul reservoir	57

3.13	Site of the Mosul Dam	58
3.14	Flowchart of the first algorithm	64
3.15	Flowchart of the second algorithm	65
3.16	Simulation model scheme for Mosul reservoir using SIMULINK technique	70
3.17	Legend to the SIMULINK model of the Mosul reservoir	73
3.18	Combined of GAOM and SM for the reservoirs of system, when the reservoirs work individually	78
3.19	Combined GAOM and SM for the dual Reservoir System of Mosul and Dokan	79
3.20	Combined GAOM and SM for the Three Reservoir System of Mosul, Dokan and Bekhma	80
3.21	Combined GAOM and SM for the Four Reservoir System of Mosul, Dokan, Bekhma and Makhoul	81
3.22	The three groups of annual inflows to Mosul reservoir	82
3.23	The three groups of annual inflows to Dokan reservoir	83
3.24	The three groups of annual inflows to Bekhma reservoir	83
4.1	The annual energy using the GAOM by the two algorithms during twenty scenarios for Mosul reservoir	94
4.2	The execution time using the GAOM by the two algorithms during twenty scenarios for Mosul reservoir	96
4.3	The observed and optimal elevations using the second algorithm taking into consideration the volume of evaporation and precipitation for different years	98
4.4	Elevation from the SM with observed elevation (m.a.s.l)	100
4.5	Power from the SM with observed power (MW)	100
4.6	Elevation from the SM and observed elevation with time	101
4.7	Power from the SM and observed power with time	101
4.8	Observed flows at Fatha station with a sum of the observed flows at three stations (at downstream of Mosul and Dokan reservoirs and at Aski Kalak)	102

4.9	Sum of observed flows in three stations (downstream of Mosul and Dokan reservoirs and in Aski Kalak) and the observed flows in Fatha station	103
4.10	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated individually, using the first strategy	105
4.11	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated individually, using the first strategy	106
4.12	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated individually, using the first strategy	107
4.13	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir, when it was operated individually, using the first strategy	108
4.14	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with Dokan reservoir as one system, using the first strategy	110
4.15	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with Mosul reservoir as one system, using the first strategy	111
4.16	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with Dokan and Bekhma reservoirs as one system, using the first strategy	113
4.17	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with Mosul and Bekhma reservoirs as one system, using the first strategy	114
4.18	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated with Mosul and Dokan reservoirs as one system, using the first strategy	115
4.19	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with other three reservoirs as one system, using the first strategy	117
4.20	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with other three reservoirs as one system, using the first strategy	118

4.21	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated with other three reservoirs as one system, using the first strategy	119
4.22	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir, when it was operated with other three reservoirs as one system, using the first strategy	120
4.23	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated individually, using the second strategy	125
4.24	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated individually, using the second strategy	126
4.25	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated individually, using the second strategy	127
4.26	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir, when it was operated individually, using the second strategy	128
4.27	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with Dokan reservoir as one system, using the second strategy	130
4.28	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with Mosul reservoir as one system, using the second strategy	131
4.29	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with Dokan and Bekhma reservoirs as one system, using the second strategy	133
4.30	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with Mosul and Bekhma reservoirs as one system, using the second strategy	134
4.31	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated with Mosul and Dokan reservoirs as one system, using the second strategy	135
4.32	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir, when it was operated with other three reservoirs as one system, using the second strategy	137

xxi

4.33	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir, when it was operated with other three reservoirs as one system, using the second strategy	138
4.34	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir, when it was operated with other three reservoirs as one system, using the second strategy	139
4.35	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir, when it was operated with other three reservoirs as one system, using the second strategy	140
4.36	The higher contour line without overflow and the elevation of the new operational storage for Makhoul reservoir	145
4.37	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir with its new volume, when it was operated individually, using the first strategy	146
4.38	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the first strategy	148
4.39	The optimal operation policies in terms of outflow, elevation and power for Dokan reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the first strategy	149
4.40	The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the first strategy	150
4.41	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir with its new volume, when it was operated with other three reservoirs as one system, using the first strategy	151
4.42	The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir with its new volume, when it was operated individually, using the second strategy	152
4.43	The optimal operation policies in terms of outflow, elevation and power for Mosul reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the second strategy	154

- 4.44 The optimal operation policies in terms of outflow, elevation and 155 power for Dokan reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the second strategy
- 4.45 The optimal operation policies in terms of outflow, elevation and power for Bekhma reservoir using the new volume of Makhoul reservoir, when it was operated with other three reservoirs as one system, using the second strategy
- 4.46 The optimal operation policies in terms of outflow, elevation and power for Makhoul reservoir with its new volume, when it was operated with other three reservoirs as one system, using the second strategy

157

LIST OF ABBREVIATIONS

GAOM	Genetic Algorithm Optimization Model
SM	Simulation Model
GAOMs	Genetic Algorithm Optimization Models
SMs	Simulation Models
GA	Genetic Algorithm
GAs	Genetic Algorithms
CI	Computational Intelligence
EC	Evolutionary Computation
EP	Evolutionary Programming
ES	Evolution Strategies
<i>x</i> _{<i>n</i>}	Real variable in the dynamic real representation
ge_n	Genes
in_n^*	Integer variable in the real representation of integer variables
fitness	Fitness function
f_{min}	Minimum observed value of the objective function up to generation (t)
f _{max}	Maximum observed value of the objective function up to generation (t)
$Pr(\vec{v_i})$	Selection probabilities in Roulette-wheel selection
$Pr_{lr}(i)$	Selection probabilities in Rank-based selection (Linear ranking)
$gene_m^{nm}$	Gene mutated by Non-Uniform Mutation
$gene_m^{bm}$	Gene mutated by Breeder Mutation
m.a.s.l	Meter above sea level
МСМ	Million cubic meter
m ³ /sec	Cubic meter per second

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mm	Millimeter
Ε	Energy in Gigawatt hour (GWhr)
Dt	Number of hours in the time period
P _t	Power in megawatts (MW) in time period (t)
k	Constant (0.003)
RP _t	Release from the tunnels connected to the hydroelectric station (MCM)
H _t	Average head in the time period (meter)
t	Time period (month)
S_{t+1}	Storage at beginning of time period $(t + 1)$
S _t	Storage at beginning of time period (t)
I _t	Inflow during time period (t)
R _t	Outflow during time period (t)
S _{min}	Minimum operational storage
S _{max}	Maximum operational storage
PC	Capacity of tunnels connected to the hydroelectric station
D _t	Monthly water requirements
НС	Hydraulic capacity downstream the reservoir
<i>S</i> _{<i>e</i>12}	Storage at the end of the last month
S _T	Target storage at the end of the last month
Ev_t	Evaporation in time period (t)
Pr _t	Precipitation in time period (t)
Sp_t	Seepage from reservoir in time period (t)
r^2	Coefficient of determination
<i>o_i</i>	Observed values in duration i

e_i \bar{o}	Calculated values in duration i Average of observed values
ē	Average of observed values
n	Number of values
NSE	Nash-Sutcliffe efficiency
Ι	Number of reservoirs
Т	Total time period (12 months)
P _{i,t}	Power (megawatts) in time period (t) for each reservoir (i) of the multi-reservoir system
ST 1	First strategy
ST 2	Second strategy

CHAPTER I

INTRODUCTION

1.1 Introduction

An operation research model generally consists of three basic components: (1) identification of specific decision variables, (2) the objective for optimization and (3) the constraints that the solution must satisfy (Taha, 2011). Thus, the main function of optimization models is to search through a large number of possible solutions. The intention is to derive numerical values of decision variables. Such a procedure will maximize or minimize the objective function value under all considered restrictions.

In water resource systems, integrated strategies are determined for storage system operations. This is the current scientific research trend regarding the satisfaction of requirements. In the operation and management of storage systems, it is essential to combine models of optimization and simulation through software related to the field. Several of these software were explained by Wurbs (2012). Optimization and simulation models are effective tools for reservoir systems analysis. Optimization models formulate a mathematical algorithm to determine decision variable values that maximize or minimize an objective function. Combining both models (Rani and Moreira, 2010) produces the best results. Optimization models seek to find solutions to satisfy the decision maker's pre-specified criteria. Simulation models work as a filter in specifying the ideal solution among a large number of possible solutions, and simulation models evaluate the performance of the adopted solution (Nandalal and Bogardi, 2007).

Reservoir operation requires operators to manage the frequency and quantity of the water releases. The reservoir is designed to address different requirements at downstream, such as water supply, hydropower production, recreation, and flood control. Thus, operations must meet the demands efficiently and reliably. Because the inflows and volumes of the storage are unconfirmed in the future, it is important to determine the best reservoir releases for a group of possible inflows and storage conditions (Loucks et al., 2005). An evolution tool is used to solve an unusual problem as stated above. Holland (1975) was the first to propose the genetic algorithm, which is a computational model that simulates natural evolution to solve various types of problems (Ribeiro Filho et al., 1994). The genetic algorithm is one of the optimization methods frequently used in frameworks of management and water storage systems operation. Wurbs (2005) stated that the greatest benefits from reservoir storage are the following: (1) maximization of hydropower generation, (2) maximization of the advantages from irrigation projects, and (3) reduction of flood damage, etc. These benefits are represented by objective functions with values that change as decision variables change.

The present study combines the optimization and simulation models to derive an optimal operating policies for the multi-reservoir system located at the Tigris river basin in northern Iraq, which comprises four reservoirs. The objective function will maximize annual hydropower generation through identifying ideal values of releases and noting the corresponding levels from the reservoir. A genetic algorithm optimization model (GAOM) was coded and a simulation model (SM) was built for the storage system using the SIMULINK technique. The GAOM was used to determine the optimal operating policies for this storage system, while the SM was used to predict the system behavior and validate the operating policies provided by the optimization model. These procedures were conducted in the Matlab work environment.

1.2 Statement of the Problem

Water storage systems have been established to achieve many goals. Conducting periodical assessments of these systems is necessary to improve their performance, as a result of population growth and the expansion of the water supply projects that belong to the municipality as well the development or creation of irrigation projects that derive their water from the storage systems (Jothiprakash and Shanthi, 2006), (Sattari et al, 2009), (Khan et al, 2012), in addition to adapt to the effects of climate change (Fayaed et al, 2013). The performance of water storage systems should be re-assessed to discover new rules of improvement and to consider the possible addition of new storage units. These improvements can be achieved through the identification of new optimal operation policies. New software and techniques can be used to calculate the highest benefit while considering all the restrictions imposed by the new system structure. These new developments were applied to the Mosul and Dokan reservoirs. Identifying new operational policies for storage system performance of the Bekhma and Makhoul reservoirs under different scenarios is necessary because they will be added to the storage system consists of Mosul and Dukan reservoirs.

Iraq suffers from a severe electricity processing shortage (IAU-UNDP, 2012), (Rashid, 2012), (Kazem and Chaichan, 2012) and (Al-Khatteeb and Istepanian, 2015). The Ministry of Electricity reports that Iraq only generates 8×10^3 of the 13 to 15×10^3 MW of currently required power (IAU-UNDP, 2012). The objective function of these new operating policies is to maximize the hydropower generation from storage systems by combining the optimization and simulation models. Based on its wide application in solving such these issues, the genetic algorithm (GA) was used to formulate an optimization model (Wardlaw and Sharif, 1999), (Karamouz et al., 2004), (Lin et al., 2005), (Cheng et al., 2008), (Hinçal et al., 2011), (Sreekanth et al., 2012), and (Li and Qiu, 2015). Assessing hydropower generation through this method will provide insight regarding the potential of the storage system to generate hydropower.

1.3 Objectives of the Study

This study aims to identify the optimal operation policies for the multi-reservoir systems located at the Tigris river basin in Iraq by combining the optimization and simulation models.

Specific Objectives

- 1. To investigate strategies of reservoir systems operations.
- 2. To create combined optimization and simulation models for the multi-reservoir systems located in the Tigris river basin, Iraq in different forms of operation:
 - a. Combining the optimization and simulation models to represent each reservoir in the system individually (Mosul, Dokan, Bekhma, and Makhoul reservoirs).
 - b. Combining the optimization and simulation models to improve the efficiency of the current storage system particularly the Mosul and Dokan reservoirs
 - c. Combining the optimization and simulation models for the storage system for the Mosul, Dokan, and Bekhma reservoirs to gauge their combined performance in one system.
 - d. Combining the optimization and simulation models for the storage system of all four reservoirs (Mosul, Dokan, Bekhma, and Makhoul) to find the optimal operating policy when they work as one system.
 - 3. To test the optimal individual and simultaneous operating performance of the reservoirs of that multi-reservoir systems (dual reservoirs, three reservoirs and four reservoirs).
 - 4. To determine and assess a new storage volume for the Makhoul reservoir.

1.4 Scope of the Study

This study uses GAOM and SM combinations to identify optimal operation policies for the multi-reservoir systems located in the Tigris river basin. These multi-reservoir systems include a dual-reservoir system, a three-reservoir system, and a four-reservoir system. The following describe the detailed scope of this study:

- 1. Collecting the data of the Mosul reservoir that represents the monthly inflow, outflow, elevation, and hydropower generation.
- 2. Collecting the monthly inflow for Dokan reservoir, as well the observed flow at the Fatha and Aski Kalak stations.
- 3. Collecting the hydraulic properties for the reservoirs of Mosul, Dokan, Bekhma, and Makhoul.
- 4. Formulating a GAOM for a single reservoir (Mosul reservoir) in the workspace of the Matlab environment through two algorithms.
- 5. Evaluating the performance of these two algorithms independently of operating the GAOM prior to adding the evaporation and precipitation to the continuity equation.
- 6. Adding the evaporation and precipitation to the continuity equation and reassessing the performance of the GAOM by using the most appropriate algorithm.

- 7. Formulating and evaluating a SM for a single reservoir (Mosul reservoir).
- 8. Combining a GAOM and SM for a single reservoir (Mosul reservoir) to evaluate the calculation of the GAOM.
- 9. Building the combination of GAOMs and SMs for each reservoir individually and for multi-reservoir systems (dual-reservoir, three-reservoir, and fourreservoir) to identify the optimal operation policies.
- 10. Maximizing the storage volume of Makhoul reservoir and re-assessing the performance of this reservoir by combining its GAOMs and SMs individually and with three other reservoirs as one entity.

1.5 Tools and Data

- 1. Matlab program (2013b).
- 2. Computer with sufficiently high specifications to program the GAOM and SM using Matlab.
- 3. The hydraulic properties of the system reservoirs that include the following:
 - a. Designing elevations related to the storages in the reservoirs.
 - b. Designing volumes of the storage in the reservoirs.
 - c. The capacity of different outlets of the system reservoirs.
 - d. The elevation-storage-area curves that belong to those four reservoirs.
 - e. The maximum capacity of hydropower generating stations.
- 4. Data representing the monthly flows during a period of 240 months from October 1989 to December 2009 in the first four stations (a, b, c and d), as well this data including the flows for a period of 120 months from October 1989 to December 1999 (see points e and f):
 - a. The monthly inflows of Mosul reservoir.
 - b. The monthly outflows from Mosul reservoir.
 - c. The monthly inflows of Dokan reservoir.
 - d. The monthly flows at Aski Kalak station, located on the Greater Zab near Bekhma reservoir.
 - e. The monthly outflows from Dokan reservoir.
 - f. The monthly flows at the Fatha station, located along the Tigris river near the site of the Makhoul reservoir.
- 5. The following data from the Mosul reservoir exclusive to the 240 months of October 1989 to December 2009:
 - a. Monthly hydropower generated.
 - b. Monthly storage elevations.
 - c. The volumes of storage at the first day for every water year (each 1 October for every year) from 1 October 1989 to 1 October 2009.
- 6. Other data related to the system reservoirs:
 - a. Monthly rainfall rate as a depth on the system reservoirs.
 - b. Monthly evaporation rate as a depth from the system reservoirs.
 - c. Monthly water requirements downstream the system reservoirs that comprise demands of irrigation, fishery development, forestry, the population, industrial development, thermal energy, and the environment.

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