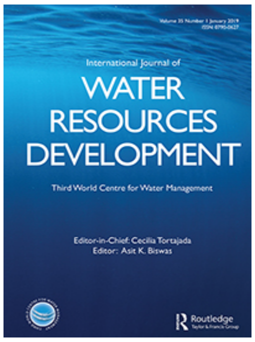

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The Tigris hydropower system operations: the need for an integrated approach

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ABSTRACT
The Tigris hydropower system is analyzed through an integrated operational policy. The operation algorithm is formulated in terms of non-linear programming to maximize energy production while satisfying water demands in the basin. The system is optimized for different cases, and the effects of system modifications in terms of the reservoir volume of Ilisu Dam and the demand constraints are examined. In addition, the state of the Garzan subsystem is analyzed to explore plant utilization when optimizing the entire system operations. The results show the necessity of such an integrated operation plan to supply water demands in the basin.

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Reservoir operation; hydropower; non-linear programming; Tigris Basin; Ilisu Dam; Turkey

Introduction

The Southeastern Anatolia Project (GAP) was initiated as a set of water and land sources development projects in the less developed south-eastern region of Turkey in the 1970s. In the early 1980s, the project was turned into a multi-sectoral and socio-economic-integrated development programme, including 22 dams, 19 hydropower plants and the irrigation of approximately 1.7 million ha of land, in the Tigris–Euphrates River Basin. The expectation was that this comprehensive development project would improve the living standards of approximately 7.5 million people living on the borders of the GAP region in terms of income, health, education and other factors (DSI (General Directorate of State Hydraulic Works), 2009; Unver, 1997).

To date, although approximately 80% of the energy projects have been completed, fewer than 20% of the irrigation schemes have yet been put into operation (Kaplan, 2012). In spite of spending over US$20 billion, the GAP has basically remained a group of separate hydropower schemes, including Ilisu Dam, that has been under debate for more than half a century due to its possible adverse effects on the environment (Guven, 2014; Yalcin & Tigrek, 2015). Thus, the region has only experienced the benefits of separate projects instead of exploiting the benefits of integration.

Unfortunately, the commissioning of the irrigation systems will not solely solve the problem because of the private-sector-owned reservoirs. The influence and control of the

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administration over the basin have loosened as a result of the increasing number of stakeholders involved. Today, through the rapid development of the Tigris and Euphrates watershed with the projects developed by private-sector companies, a new problem arises on how to operate a cascade reservoir system composed of state- and private-sector-owned reservoirs in terms of the volume and timing of water releases to meet downstream irrigation demands.

In most of the cascade hydropower systems in the basin, single-reservoir operational policies are employed with limited knowledge of the short- and long-term operation strategies of the upstream schemes. The existing policies fail to consider water demands in an integrated operation plan, but rather emphasize the maximization of energy production for individual projects. Thus, these operational policies run the risk of not being able to supply water demands in the basin. Moreover, downstream hydropower projects cannot supply their foreseen energy production provided in the planning stages due to the unpredictable outflow rates of upstream reservoirs. Therefore, the conflicts between stakeholders related to the operation of reservoirs have become increasingly complex with the commissioning of new power plants and irrigation schemes. The situation has resulted in a growing need for an integrated approach that considers the integrated operation of cascade reservoirs instead of operating them as separate independent projects.

In the present study, the Tigris hydropower system, one of the two main constituents of the GAP, is analyzed through an integrated operational policy. The hydropower system consists of 15 energy, nine irrigation and four multipurpose reservoirs, and to benefit fully from this complex system, an integrated reservoir system optimization model is developed. The optimization algorithm is formulated in terms of non-linear programming to maximize total energy production while satisfying water demands in the basin.

The system is optimized for different cases during the 12-month operation period, and the effects of the system modifications in terms of the reservoir volume of Ilisu Dam and the demand constraints on energy production are examined. In addition, the state of the Garzan subsystem in the integrated Tigris operation plan is analyzed to explore the plant utilization of this subsystem when optimizing the operations of the entire hydropower system. In this context, to investigate the maximum energy that can be produced, the operation optimization of the Garzan subsystem is repeated on a monthly basis for one- and 30-year operation periods.

The Tigris hydropower system

The Tigris River Basin is analyzed up to the drainage area of the Ilisu Dam and Hydroelectric Power Plant (HEPP) Project in the present study. In this area of 36,408 km^2, the main tributaries of the Tigris River are Garzan, Bitlis, Botan and Batman Creeks, and the full upstream development comprises 30 dams and eight pond projects, as presented in Figure 1. It is planned that approximately 0.5 million hectares of land will be irrigated, and over 14.5 million m^3 of water will be abstracted annually to supply domestic water for Diyarbakir, Van and Siirt provinces. To date, all the pond projects and seven dams have been put into operation, and a gross area of 34,756 ha has been irrigated through these schemes, as detailed in Table 1 (DSI (General Directorate of State Hydraulic Works), 2014).

The Garzan subsystem consists of Aysehatun Dam and HEPP Project with the Mutki Derivation, Kor Dam and HEPP Project, Garzan Dam and HEPP Project and the Garzan

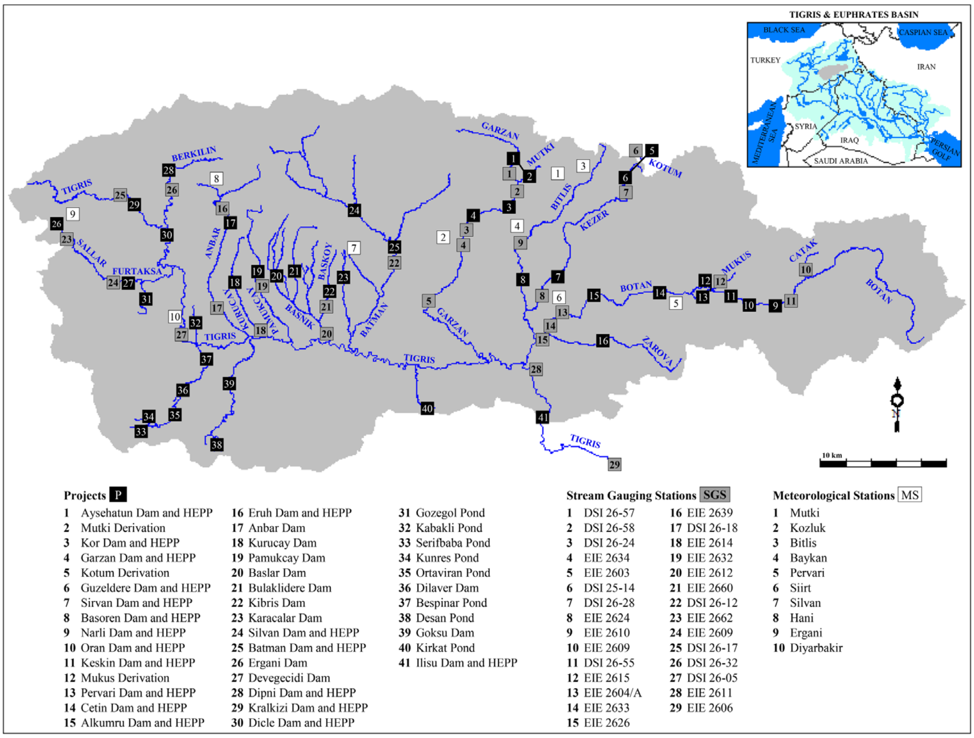

Figure 1. Location map of the study area.

irrigation scheme, which covers an area of 60,000 ha (Aksa (Aksa Energy Generation Incorporated Company), 2004; DSI (XVIIth Regional Directorate of State Hydraulic Works), 1987; Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company), 2008; Jemas-Su (Jemas-Su Groundwater Survey and Engineering Limited Company), 2001). The flows of Mutki Creek are diverted into Aysehatun Dam by a transmission canal with a capacity of 25.74 m^3/s (DSI (XVIIth Regional Directorate of State Hydraulic Works), 1987).

There are Guzeldere Dam and HEPP Project and Sirvan Dam and HEPP Project on Kezer Creek (DSI (Department of Investigation and Planning of State Hydraulic Works), 1986; Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company), 2009). Moreover, there is a trans-basin diversion from Kotum Creek to Guzeldere Dam with a transmission canal with a capacity of 12.00 m^3/s. A discharge of 0.35 m^3/s will be pumped from Guzeldere Reservoir to supply the domestic water demand of Van province (DSI (Department of Investigation and Planning of State Hydraulic Works), 1986). Basoren Dam and HEPP Project is the single reservoir on Bitlis Creek (Yolsu (Yolsu Engineering Services Limited Company), 2009). Downstream of the junction of Kezer and Bitlis creeks, a discharge of 0.60 m^3/s will be abstracted from the riverbed to supply the domestic water demand of Siirt province (EIE (General Directorate of Electrical Power Resources Survey and Development Administration), 1990).

There are Narli Dam and HEPP Project, Oran Dam and HEPP Project, Keskin Dam and HEPP Project, Pervari Dam and HEPP Project, Cetin Dam and HEPP Project, and Alkumru Dam and

Table 1. Irrigation projects.

		In operation		In planning	
		Irrigation area		Irrigation area	
Project	Commissioning year	Gross (ha)	Net (ha)	Gross (ha)	Net (ha)
Ortaviran	1963	550	516	550	516
Kahlara	1965	380	380	–	–
Serifbaba	1971	130	120	130	120
Devegecidi	1972	10,600	5800	10,600	5800
Silvan	1972	8790	7590	202,306	176,613
Gozegol	1974	650	550	650	550
Kunres	1979	19	19	19	19
Kabakli	1980	182	87	182	87
Bespinar	1980	140	121	140	121
Kirkat (Gercus)	1985	350	348	350	348
Goksu	1996	4234	3582	4234	3582
Kozluk	1996	3973	3362	–	–
Kralkizi–Dicle	2002	4758	4758	130,159	110,115
Garzan	–	–	–	60,000	60,000
Silvan Plain Dams					
Anbar	–	–	–	13,498	11,784
Kurucay	–	–	–	6013	5249
Pamukcay	–	–	–	5134	4482
Baslar	–	–	–	4309	3762
Bulaklidere	–	–	–	5890	5142
Kibris	–	–	–	3124	2727
Karacalar	–	–	–	5099	4451
Batman	–	–	–	37,744	32,951
Ergani	–	–	–	1861	1861
Total		34,756	27,233	491,992	430,280

Source: DSI (General Directorate of State Hydraulic Works) (2014).

HEPP Project on Botan Creek (EIE (General Directorate of Electrical Power Resources Survey and Development Administration), 1986; Hidrokon (Hidrokon Engineering Consultancy Incorporated Company), 2009; Limak (Limak Hydropower Plant Investments Incorporated Company), 2006; Su Yapi (Su Yapi Engineering and Consultancy Incorporated Company), 2007). In addition, the flows of Mukus Creek are diverted to Pervari Reservoir by a transmission canal with a capacity of 30 m^3/s (Su Yapi (Su Yapi Engineering and Consultancy Incorporated Company), 2007). Upstream of the junction of Botan Creek with the Tigris River, the outflows of Eruh Dam and HEPP Project enter Botan Creek. Eruh Dam is the single reservoir on Zarova Creek (Met (Met Project Engineering Consultancy Construction Industry and Trade Limited Company), 2006).

The Batman–Silvan Project is the major irrigation scheme in the study area, covering a gross area of 283,117 ha, as detailed in Table 1. The project consists of Silvan Dam and HEPP Project, Batman Dam and HEPP Project, and the Silvan Plain Dam Projects, namely Anbar, Kurucay, Pamukcay, Baslar, Bulaklidere, Kibris and Karacalar dams. Gross areas of 202,306 and 37,744 ha will be irrigated by the Silvan and Batman dam projects respectively. In addition, a gross area of 43,067 ha will be irrigated by the Silvan Plain Dam Projects, with the understanding that when the demand is greater than the available storage in the plain dam reservoirs, this deficiency will be compensated by water transfer from Silvan Reservoir through canals (Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture), 2001).

In the upstream region of the Tigris River, there are Ergani Dam and HEPP Project, Devegecidi Dam Project, Dipni Dam and HEPP Project, Kralkizi Dam and HEPP Project, and Dicle Dam and HEPP Project (DSI (Xth Regional Directorate of State Hydraulic Works), 1999; En-Su (En-Su Engineering Consultancy Limited Company), 2008; FPGA (Euphrates Planning Group Authority), 1968; Ilisu Environment Group, 2005). Gross areas of 1861, 10,600 and 130,159 ha will be irrigated by the Ergani, Devegecidi and Dicle reservoirs respectively. In addition, a discharge of 4.53 m^3/s will be pumped from Dicle Reservoir to supply the domestic water demand of Diyarbakir province. Whenever Dicle Reservoir is not sufficient to supply this demand, Kralkizi Reservoir will be used as a backup (FPGA (Euphrates Planning Group Authority), 1968; Ilisu Environment Group, 2005).

Finally, there are several irrigation schemes in the basin, namely Gozegol Pond, Kabakli Pond, Kunres Pond, Serifbaba Pond, Ortaviran Pond, Dilaver Dam, Bespinar Pond, Desan Pond, Goksu Dam and Kirkat (Gercus) Pond, as listed in Table 1. These projects are not included in the integrated system due to lack of data, and it is assumed that there is no spillway release from these reservoirs.

Optimization model

A non-linear optimization model is developed to improve the operational effectiveness of this complex reservoir system for maximizing total energy production while satisfying water demands in the basin. Monthly time steps are used for an operation period of 12 months. Energy production is formulated as a function of net head, power release and system efficiency, as detailed in Table A1 in the supplemental data online. The constraint set includes flow continuity, turbine capacity, spillway capacity, minimum release, minimum energy production, minimum storage and reservoir capacity, as listed in Table A2, also online. The distinct feature of the proposed model is the calculation of the energy production of a cascade hydropower system considering the realistic turbine efficiency and net head values in each time step of the operation period. The MINOS solver, which employs a projected Lagrangian algorithm on a sequence of linearly constrained sub-problems, is used to solve this operation optimization problem with the non-linear constraints and objective function within the General Algebraic Modeling System package (Murtagh, Saunders, Murray, and Gill, 2014).

In the non-linear programming model, the flow continuity constraint described in equation (8) in Table A2 in the supplemental data online is modified if water transfer is allowed from reservoirs. For example, water can be transferred from Kralkizi and Silvan reservoirs to the Dicle Dam and Silvan Plain Dam Projects respectively. In the flow continuity equations for the Dicle and Silvan Plain Dam reservoirs, a term $T_{i,t}$ is added to the incoming flows to represent the water transfer from the upstream reservoir. This modification in the model algorithm provides the needed water transfer from the upstream reservoir when the demand cannot be supplied by the storage of the downstream reservoir. Conversely, in the flow continuity equations for the upstream reservoirs that are used to satisfy the deficiency, a term $T_{i+1,t}$ is added to the outflows as a non-power release. Moreover, an additional constraint is integrated into the algorithm to ensure that the outflows of the Basoren and Sirvan reservoirs are sufficient to supply the domestic water demand of Siirt province.

Turbine efficiency curves, net evaporation rates, monthly mean flows and water demands are the inputs for the proposed model, together with the topographical and technical features of the projects, as listed in Table 2. Reservoir area and water level functions are expressed as high-order polynomials of storage in the model (Yalcin, 2015). The efficiency curves for Francis-type turbines, which are utilized in all the catchment power plants, are also defined as high-order polynomials of the ratio of the power releases to the designed discharges (Pro-sem (Pro-sem Engineering Architecture Consultancy Limited Company), 2008). The net evaporation rates of the reservoirs are determined using monthly mean temperature, monthly total evaporation and monthly total precipitation records of the appropriate stations operated by the General Directorate of State Meteorological Works (DMI (General Directorate of State Meteorological Works), 2009; Yalcin, 2015). These stations are listed in Table A3 in the supplemental data online and shown in Figure 1.

The investigations of the water potential commence with the analysis of the monthly mean flow records obtained from a large number of stream-gauging stations operated by the General Directorate of State Hydraulic Works and the General Directorate of Electrical Power Resources Survey and Development Administration (DSI (General Directorate of State Hydraulic Works), 2007; EIE (General Directorate of Electrical Power Resources Survey and Development Administration), 2003). These stations are detailed in Table A4 in the supplemental data online and shown in Figure 1.

First, the raw flow data are corrected for the existing irrigation abstractions, as listed in Table A5 in the supplemental data online. The monthly water demands of crops in the irrigated areas are taken from the irrigation modules included in the feasibility, pre-feasibility and reconnaissance study reports. In accordance with the commissioning dates of the operating projects, 80% of the demand for the net irrigation areas is added to the observations under the assumption that 20% of the abstraction will return to the riverbed (Ilisu Hydropower Consultants, 1983). For the Kozluk irrigation scheme, the monthly irrigation water demands are taken from the Garzan–Kozluk irrigation module (Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company), 2008). For the Devegecidi, Gozegol, Ortaviran, Serifbaba, Kunres, Bespinar, Kirkat (Gercus) and Goksu irrigation schemes, the Tigris irrigation module is used (FPGA (Euphrates Planning Group Authority), 1968). The Batman–Silvan irrigation module is utilized for the Silvan and Kabakli irrigation schemes (Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture), 2001). In addition, the raw flow data from Yolkopru station are corrected for the Kahlara irrigation scheme, which covers an area of 380 ha and has been in operation since 1965, by adding net abstraction amounts of 0.35, 0.33, 0.32 and 0.27 hm^3 to the records from June, July, August and September respectively (DSI (Xth Regional Directorate of State Hydraulic Works), 1999). As in the case of Yolkopru station, the raw flow data of Koprubasi station are corrected for the local upstream irrigations by adding net abstraction amounts of 3.86, 2.61 and 0.99 hm^3 to the records from July, August and September respectively (Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture), 2001).

The Kralkizi and Dicle projects have been in operation since the end of 1997. The construction of Batman Dam and HEPP Project was completed in 1999 (DSI (General Directorate of State Hydraulic Works), 2014). Because of the effects of these reservoirs on the flow regime, the records from the stream-gauging stations located downstream of these schemes are not used for the months following the commissioning dates of these projects.

Table 2. Characteristics of the Tigris projects.

Characteristics	Units	Aysehatun	Kor	Garzan	Guzeldere	Sirvan	Basoren	Narli	Oran
Purpose	–	Energy	Energy	Energy	Energy/Water supply	Energy	Energy	Energy	Energy
Drainage area	km^2	405.0	942.2	1266.0	170.0	1010.0	737.3	3176.2	3275.0
Thalwag elevation	m	1180.0	895.0	675.5	1690.0	600.0	540.0	1280.0	1180.0
Maximum water level	m	1250.0	956.0	788.3	1720.0	688.0	561.0	1370.0	1280.0
Minimum water level	m	1230.0	930.0	757.7	1704.5	662.0	553.0	1345.0	1250.0
Tailwater level	m	950.0	830.0	676.0	1270.0	577.0	530.0	1280.0	1180.0
Design discharge	m^3/s	13.36	26.54	43.60	8.00	33.80	34.92	55.20	55.97
Penstock: number/diameter/length	–/m/m	1/2.3/250	1/2.5/210	1/3.2/210	2/1.1/1100	1/2.6/210.54	1/3.3/61	1/3.75/200	1/3.75/200
Energy tunnel: number/diameter/length	–/m/m	1/3.5/8410	1/3.3/6370	1/4.0/382	1/4.0/10,000	1/3.5/2497	1/3.8/2360	–	–
Number of units	–	2	2	2	2	2	2	2	2
Gross head/net head	m/m	300.0/282.0	126.0/109.9	112.3/108.6	435.0/430.2	111.0/101.6	31.0/25.7	90.0/89.1	100.0/99.2
Turbine type	–	Francis	Francis	Francis	Francis	Francis	Francis	Francis	Francis

Keskin	Pervari	Cetin	Alkumru	Eruh	Anbar	Kurucay	Pamukcay	Baslar	Bulaklidere	Kibris	Karacalar
Energy	Energy	Energy	Energy	Energy	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation	Irrigation
4241.8	4288.1	7066.2	7562.5	600.0	480.0	122.0	312.5	136.0	88.0	150.0	32.5
980.0	820.0	677.0	542.0	682.0	673.0	650.0	650.0	658.0	678.0	618.0	677.0
1180.0	980.0	822.0	647.0	772.0	708.7	678.0	677.0	680.0	705.0	647.0	685.0
1137.5	930.0	760.0	611.8	725.0	688.0	665.0	670.0	670.0	685.0	638.0	707.0
980.0	820.0	647.0	541.8	545.0	–	–	–	–	–	–	–
108.25	160.00	315.49	277.00	26.00	–	–	–	–	–	–	–
1/5.2/200	1/6.4/125	1/9.4~4.0/313[a]	3/4.7/124	1/2.5/1375	–	–	–	–	–	–	–
–	1/7.15/600	1/9.4/5302	1/8.4/443	1/3.65/10,875	–	–	–	–	–	–	–
3	4	5	3	2	–	–	–	–	–	–	–
200.0/199.4	160.0/158.8	175.0/162.6	105.2/103.9	227.0/200.3	–	–	–	–	–	–	–
Francis	Francis	Francis	Francis	Francis	–	–	–	–	–	–	–

Table 2. (*Continued*).

Silvan	Batman	Ergani	Devegecidi	Dipni	Kralkizi	Dicle	Ilisu
Energy/Irrigation	Energy/Irrigation	Irrigation	Irrigation	Energy	Energy	Energy/Water supply/Irrigation	Energy
2305.0	4105.0	44.5	1576.0	1275.0	1300.0	3216.0	36,408.0
658.0	596.0	873.5	724.0	746.0	707.0	640.0	400.0
820.0	666.0	916.32	757.0	850.0	815.75	710.0	525.0
790.0	645.0	889.5	740.0	820.0	762.0	702.5	485.0
659.85	595.5	–	–	715.0	708.0	641.0	400.0
137.00	362.00	–	–	25.00	144.00	155.00	1266.0
–	1/9.5~5.0/332[b]	–	–	1/2.6/150	2/5.5/395	1/7.5/455	3/11.0/407.0
2/5/740 + 765	–	–	–	1/4.0/4600	1/6.8/500	1/6.6/500	–
4	3	–	–	2	2	2	6
160.15/148.42	70.50/70.02	–	–	135.00/129.5	107.75/106.5	69.00/67.83	125.0/118.4
Francis	Francis	–	–	Francis	Francis	Francis	Francis

Notes: [a]The inner diameter of the penstock gradually decreases from 9.4 m to 4.0 m between the shaft and the power plant; [b]The inner diameter of the penstock gradually decreases from 9.5 m to 5.0 m between the shaft and the power plant.

Sources: Aksa (Aksa Energy Generation Incorporated Company) (2004); DSI (Department of Investigation and Planning of State Hydraulic Works) (1986); DSI (XVIIth Regional Directorate of State Hydraulic Works) (1987); DSI (Xth Regional Directorate of State Hydraulic Works) (1999); EIE (General Directorate of Electrical Power Resources Survey and Development Administration) (1986, 1990); Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company) (2008, 2009); En-Su (En-Su Engineering Consultancy Limited Company) (2008); FPGA (Euphrates Planning Group Authority) (1968); Hidrokon (Hidrokon Engineering Consultancy Incorporated Company) (2009); Ilisu Environment Group (2005); Jemas-Su (Jemas-Su Groundwater Survey and Engineering Limited Company) (2001); Limak (Limak Hydropower Plant Investments Incorporated Company) (2006); Met (Met Project Engineering Consultancy Construction Industry and Trade Limited Company) (2006); Su Yapi (Su Yapi Engineering and Consultancy Incorporated Company) (2007); Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture) (2001); Yolsu (Yolsu Engineering Services Limited Company) (2009).

Then, the naturalized flows and correlations are used to produce representative flow data for the period 1971–2000. Although the flows in the Tigris River and its tributaries are monitored by a comprehensive network of stations, for some branches these correlations remain insufficient to constitute a longer data set. In the correlation studies, the upstream–downstream relationships along river branches are evaluated using the quantities for corresponding months, and inappropriate data sets are not included. If it is not possible to calculate correlations, then the observations are extended based on the catchment area ratio between the appropriate stations. If this is also not possible, then the monthly averages of the extended or observed data sets are utilized, as detailed in Table A5 in the supplemental data online.

The equations listed in Table A6 in the supplemental data online are used to project the extended runoff rates of the stream-gauging stations to the dam axes. The flow series produced by these equations can be called historical flows at dam sites. The flows collected from the sub-catchment between reservoirs are given as input to the proposed model. Thus, the sub-catchment flow rates of a scheme are obtained by subtracting the produced historical flow series of the upstream reservoir/reservoirs from those of the project of interest. In the non-linear programming model, the outflows of the upstream schemes and the return water from the upstream irrigation systems are added to the sub-catchment flows through the flow continuity constraint, as seen in equation (8) in Table A2 in the supplemental data online. Moreover, for the maintenance of natural ecosystems, 10% of the monthly mean historical flows for the last decade at the dam axes (1991–2000) is left on the riverbed as environmental water (DSI (General Directorate of State Hydraulic Works), 2014).

The upstream–downstream irrigation and water supply schemes for each of the system reservoirs are summarized in Table A7 in the supplemental data online. The *upstream* column provides necessary information about the upstream projects regarding their gross and net irrigated areas, the irrigation modules used, the assumed rate of return ratios and the domestic water demand rates. The *downstream* column is reserved for the abstractions supplied by the outflows of the projects. In addition, the abstractions supplied directly from the system reservoirs are listed in the *reservoir* column.

In these calculations, the net abstractions are used for the upstream irrigations under the assumption that 20% of the demand will return to the riverbed (Ilisu Hydropower Consultants, 1983). This rate of return is 15% for the Batman–Silvan Projects (Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture), 2001). For the Garzan irrigation scheme, the monthly

Table 3. Results of the operations for the Tigris hydropower system.

Produced energy (GWh)												
Months												
10	11	12	1	2	3	4	5	6	7	8	9	Total
Without constraint on Silopi and Nusaybin–Idil–Cizre irrigations												
63.6	388.4	435.3	475.3	462.4	567.1	1028.3	826.7	649.9	1303.0	979.7	192.2	7371.8
With constraint on Silopi and Nusaybin–Idil–Cizre irrigations												
55.8	391.6	435.3	475.7	442.7	562.8	1028.3	856.0	661.8	1300.6	939.1	192.2	7342.0
With constraint on Silopi and Nusaybin–Idil–Cizre irrigations and reduced storage of the Ilisu Reservoir												
57.6	323.2	400.9	410.5	339.6	412.7	853.0	997.8	824.3	988.5	672.6	188.9	6469.6

irrigation water demands are taken from the Garzan irrigation module (FPGA (Euphrates Planning Group Authority), 1968). The Batman–Silvan irrigation module is utilized for the Batman–Silvan and Kabakli irrigation schemes (Suis and Sial (Suis Project Engineering and Consultancy Limited Company and Sial Geosciences Survey and Consultancy Limited Company Joint Venture), 2001). The water demand rates of the Ergani irrigation scheme are taken from the Ergani irrigation module (DSI (Xth Regional Directorate of State Hydraulic Works), 1999). For the Devegecidi, Dicle–Kralkizi, Gozegol, Bespinar, Kirkat (Gercus) and Goksu irrigation schemes, the Tigris irrigation module is used (FPGA (Euphrates Planning Group Authority), 1968).

Results and discussion

The integrated Tigris operation plan

The operations of the Tigris hydropower system are optimized to maximize the total energy production. The initial and ending storage values of the system reservoirs are constrained to be equal to the dead volumes. In the non-linear programming model, the monthly means of the flow data sets from 1971 to 2000 are utilized as inputs during the 12-month operation period. The total energy production for this integrated system operation plan is found to be 7371.82 GWh/year, as detailed in Table A8 in the supplemental data online.

Downstream of the Tigris hydropower system are the Silopi and Nusaybin–Idil–Cizre irrigation schemes, which cover an area of 121,000 ha (Ilisu Environment Group, 2005). They represent a demand of approximately 767.30 hm^3/year of water, which is planned to be supplied by Cizre Reservoir located immediately downstream of Ilisu Dam (Ilisu Hydropower Consultants, 1983). Because of the inadequate storage capacity of this reservoir, the outflows of the Ilisu Project are used to enable Cizre Dam to supply the irrigation water demand.

The operational results are analyzed to confirm whether the power releases from Ilisu Reservoir are sufficient to supply the downstream irrigation demand, and it is found that the releases do not meet the demand all the time (see Figure A1 in the supplemental data online). Thus, a minimum release constraint is integrated into the algorithm to ensure that

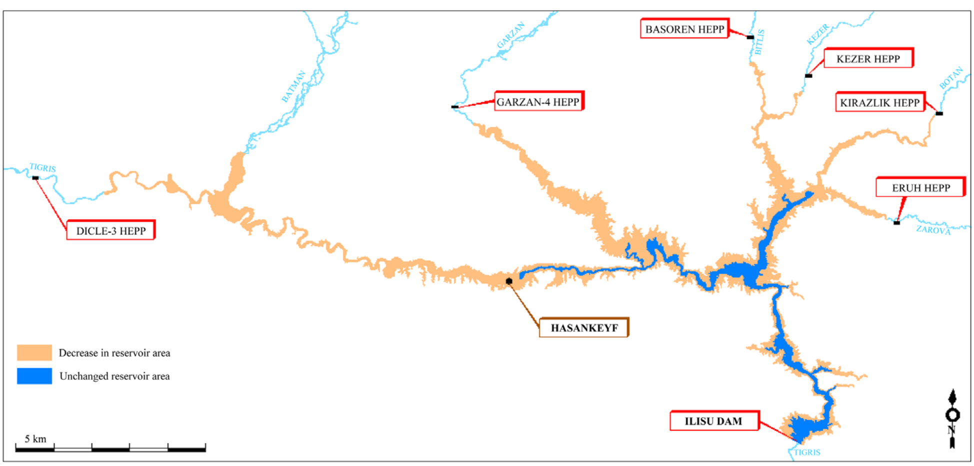

Figure 2. Ilisu Dam and HEPP Project.

the outflows of Ilisu Reservoir are sufficient to supply the water demands of the Silopi and Nusaybin–Idil–Cizre irrigation areas.

The optimization study is repeated with this additional constraint. The total energy production of the system is found to decrease to 7342.01 GWh/year, as expected (Table 3). The objective function value obtained in the first run is the maximum energy that can be produced by the system, and the imposition of an additional constraint regarding the system releases leads to a decrease in energy production.

The Ilisu Dam and HEPP Project in the integrated Tigris operation plan

When the results of these two system runs are compared with the operational results obtained in the planning stages of the system reservoirs, it is found that several power plant units will not be used after the commissioning of the irrigation schemes and that there is no need for large storage capacities for some of the projects, as in the case of the Ilisu Project (Ilisu Environment Group, 2005). Figure A2 in the supplemental data online presents the monthly storage variations for Ilisu Reservoir. Although these results are obtained using the average flows in the optimization algorithm, it is expected that the situation will be the same with real flow rates. These circumstances were also previously noted by Yalcin and Tigrek (2015), who claimed that the flow regulation capability of the upstream reservoirs eliminates the need for the enormous storage of Ilisu Reservoir.

The Ilisu Dam and HEPP Project has been under debate for more than half a century because of concerns regarding the inundation of archaeological sites around Hasankeyf. To protect this ancient settlement from inundation, the maximum water level must be lowered from 525 to 457 m, as presented in Figure 2 (Yalcin and Tigrek, 2015). The energy loss caused by such a decrease and the capability of this reduced level of storage to supply downstream water needs can be analyzed using the proposed non-linear programming model. However, before such a trial is performed, it is necessary to assess its dead storage volume.

The basin applications in Turkey have appeared to commission the farthest downstream dams first. In addition to Ilisu Dam, Alkumru Dam on Botan Creek and Garzan Dam on Garzan Creek are the other instances of this application in the Tigris Basin (Figure 1). Thus, the dead volume calculations are performed accordingly, resulting in enormous dead-volume allocations and significant loss of hydropower potential (Tigrek and Aras, 2011). The dead storage volume of Ilisu Reservoir is estimated as 3078.7 hm^3 at a level of 485 m (Ilisu

Table 4. Comparison of the operations for the Garzan subsystem.

Optimized system	Operation years	Inflow values	Special case	Produced energy (GWh)			
				Aysehatun	Kor	Garzan	Total
Tigris	1	Mean	–	177.81	108.69	166.76	453.26
Tigris	1	Mean	With constraint on Silopi and Nusaybin–Idil–Cizre irrigations	170.80	109.65	168.23	448.68
Tigris	1	Mean	With constraint on Silopi and Nusaybin–Idil–Cizre irrigations and reduced storage of the Ilisu Reservoir	186.52	108.80	167.02	462.34
Garzan	1	Mean	–	212.98	124.90	149.60	487.48
Garzan	30	Historical	–	211.41	119.07	177.19	507.67

Environment Group, 2005). This design is based on the calculations for the existing upstream conditions at that time (Ilisu Dam and HEPP Engineering and Consultancy Services Consortium, 2008).

To investigate the dead storage required for the scenario corresponding to the full development of the Tigris Basin, the sediment transport analysis conducted by EIE (General Directorate of Electrical Power Resources Survey and Development Administration) (2000) using the data collected at the Cizre sediment-gauging station (Station Id: EIE 2606) in the vicinity of the dam site is utilized. The results of this analysis indicate that the suspended sediment yield in the basin is 733 ton/year/km^2, and the submerged specific weight is 1.31 t/m^3. Under the assumption that the bed load is 25% of the suspended sediments, the total sediment load in the basin is determined to be 699 m^3/year/km^2. The total area controlled by the upstream projects is 23,016.8 km^2. By subtracting this area from the total drainage area of Ilisu Reservoir, a region of 13,391.2 km^2 is identified as the catchment that contributes to sediment transport. Thus, the amount of sediment that will be deposited in the reservoir during the economic lifetime of the project is found to be 468.31 hm^3 (see Table A9 in the supplemental data online). Assuming the horizontal deposition of sediments across the reservoir, this volume will reach a level of 446.81 m after 50 years, as depicted in Figure A3 in the supplemental data online.

The operations of the Tigris hydropower system are reoptimized based on the reduced storage of Ilisu Reservoir considering the downstream irrigation schemes. The objective function value is found to be 6469.61 GWh/year, representing a reduction of approximately 12% in the total energy production (Table 3). Figure A4 in the supplemental data online presents a comparison of the monthly storage variations for the existing and reduced-capacity versions. Although there is a 93% decrease in the active volume, the reduced storage capacity remains sufficient to supply the irrigation water demand. This result illustrates the efficacy of integrated operations for flow regulation.

The state of the Garzan subsystem in the integrated Tigris operation plan

In this study, the operations of the Tigris hydropower system are optimized for three cases: neglecting the downstream irrigation demands (NID), considering the downstream irrigation demands (ID) and considering the downstream irrigation demands with the reduced storage capacity of Ilisu Reservoir (ID-RC). The total amounts of energy produced by the Garzan subsystem are found to be 453.26, 448.68 and 462.34 GWh/year for NID, ID and ID-RC respectively (Table 4).

To investigate the maximum energy that can be produced by the Garzan subsystem, the operations of the subsystem are optimized on a monthly basis for a 30-year period using the extended historical inflow series from 1971 to 2000 and for a one-year period using the monthly means of the extended data sets. Accordingly, the energy production capacities of this subsystem are found to be 507.67 and 487.48 GWh/year for long- and short-term operations respectively (Table 4). These results mean that the amounts of energy produced by the Garzan subsystem in the optimized operations of the entire system are lower than its production capacity. The reason for this situation is that the entire system optimization algorithm aims to maximize the energy production of the Tigris hydropower system, not its individual components.

Policy implications

The integrated operation plan of 30 dam and eight pond projects can only guarantee to supply the downstream irrigation demand when a minimum release constraint is added to the optimization algorithm. Thus, it is unlikely to satisfy this demand through sequential single-reservoir simulation model applications. Satisfying the irrigation demands in the region is the key for the success of the GAP. For this reason, the independent dam operation policies applied in the basin put the water supply and, therefore, the success of the GAP in jeopardy.

The issue becomes more complicated because the Tigris–Euphrates is an internationally shared basin. Although the water allocation problems among the stakeholder countries are not on the agenda due to the political ambiguity and war situation in Syria and Iraq, how will Turkey determine the amount of flow rate to be committed to these countries? Of course, the impacts of these releases on the GAP should also be evaluated. The proposed optimization model will be useful in developing water resource-management strategies in the region.

Another important question is: which dam's operational policy will be responsible for unmet water demand? Based on the findings of this study, the answer cannot be the most downstream project, Ilisu. Although the Ilisu Project has an enormous reservoir capacity, it may be inadequate to supply the regional and international water needs due to the operational policy of the upstream reservoirs. Moreover, possible long dry periods may further contribute to the unmet demand risk. Therefore, an integrated approach that allows the operation of all the reservoirs, ponds and transfer channels as a system should be adopted, and the manner in which reservoirs are operated in terms of the volume and timing of water releases to meet downstream water demands has to be regulated in terms of an integrated operation plan.

It is obvious that possible decreases in the energy production levels of the subsystems can be experienced due to the integrated operation strategy, as in the case of the Garzan subsystem. However, it should be recognized that the intent of the integrated system operation plan is not to optimize the income of its individual components but rather to maximize the energy production of the entire system while satisfying the water demands in the basin. In addition, the production of the system components cannot reach the levels predicted in their planning stages under the existing single-reservoir operational policies.

With this purpose, a governmental or private-sector organization responsible for determining the basin operational management strategy and regulating the operations of the system reservoirs has to be instituted. This organization should be responsible, at the same time, for allocating the revenue obtained over the integrated system operations among stakeholders. The same organization should also be able to determine the alternative operation policies under the uncertainties associated with future hydrological conditions, and improve these policies on the issues of effective usage of water, plant modifications and selection of crop type according to flow regimes, storage in the reservoirs and energy prices.

Conclusions

In this study, an optimization model that considers the integrated operation of cascade hydropower schemes with domestic, industrial, agricultural and environmental needs is presented, and its non-linear objective function and constraints are described. The optimization model is used to analyze the operational policies for the Tigris hydropower system, which consists of 15 energy, nine irrigation and four multipurpose reservoirs. The energy potential of the basin is evaluated in an integrated operation plan, and the volume and timing of water releases from reservoirs are optimized with consideration for upstream and downstream uses and demands. The results show the advantages of this integrated operation model in terms of effective use of water for demands and power generation.

The integrated model is also used in evaluating the overall systems response to changes in individual components of the system. The outcomes of the examinations of the existing development plan of the basin within the framework of the integrated operation model demonstrate that several plant units of the system reservoirs will not be utilized after the completion of the ongoing irrigation projects. For instance, there is no need for the enormous reservoir volume of the Ilisu Project, causing Hasankeyf with its countless ancient monuments to be inundated, due to the flow-regulation capability of the upstream reservoirs. Although this regulation capability eliminates the need for such a reservoir, it remains insufficient to supply demands in the basin without an integrated operation plan.

It is too difficult to apply a management plan providing integration among planning, construction and operation due to the existing and ongoing projects in the basin, but attention must focus on how to operate cascade reservoir systems composed of state- and private-sector-owned reservoirs. It is clear that such an integrated operation model can only be implemented through a catchment- or even a tributary-based management policy enacted by a governmental or private-sector organization that takes full responsibility for system operations under supportive legislation.

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References

Aksa (Aksa Energy Generation Incorporated Company). (2004). *Kor Barajı ve HES fizibilite raporu* [Kor Dam and HEPP feasibility report]. Istanbul: Aksa Energy Generation Incorporated Company.

DMI (General Directorate of State Meteorological Works). (2009). *Monthly total precipitation, monthly mean temperature and monthly total evaporation records*. Ankara: General Directorate of State Meteorological Works.

DSI (Department of Investigation and Planning of State Hydraulic Works). (1986). *Bitlis-Güzeldere Projesi ön fizibilite raporu* [The Bitlis-Guzeldere project pre-feasibility report]. Ankara: Department of Investigation and Planning of State Hydraulic Works.

DSI (General Directorate of State Hydraulic Works). (2007). *Akım gözlem istasyonları, aylık toplam akımlar (1954–2000)* [Flow gauging stations, monthly total flows (1954–2000)]. Ankara: General Directorate of State Hydraulic Works.

DSI (General Directorate of State Hydraulic Works). (2009). *Turkey water report*. Ankara: General Directorate of State Hydraulic Works.

DSI (General Directorate of State Hydraulic Works). (2014). Retrieved May 25, 2014 from https://www.dsi.gov.tr/

DSI (Xth Regional Directorate of State Hydraulic Works). (1999). *Dicle Havzası, Ergani Projesi planlama raporu* [The Tigris Basin, the Ergani project planning report]. Diyarbakir: Xth Regional Directorate of State Hydraulic Works.

DSI (XVIIth Regional Directorate of State Hydraulic Works). (1987). *Bitlis-Garzan Projesi, Ayşehatun Barajı ve HES planlama raporu* [The Bitlis-Garzan Project, Aysehatun dam and HEPP planning report]. Van: XVIIth Regional Directorate of State Hydraulic Works.

EIE (General Directorate of Electrical Power Resources Survey and Development Administration). (1986). *Dicle Nehri, Botan Çayı istikşaf raporu, yayın no: 86–53* [The Tigris River, Botan Creek reconnaissance report, publication no: 86–53]. Ankara: General Directorate of Electrical Power Resources Survey and Development Administration.

EIE (General Directorate of Electrical Power Resources Survey and Development Administration). (1990). *Bitlis Çayı istikşaf raporu, yayın no: 90–62* [Bitlis Creek reconnaissance report, publication no: 90–62]. Ankara: General Directorate of Electrical Power Resources Survey and Development Administration.

EIE (General Directorate of Electrical Power Resources Survey and Development Administration). (2000). *Türkiye akarsularında sediment gözlemleri ve sediment taşınım miktarları, yayın no: 20–17* [Suspended sediment data and sediment transport amounts for surface waters in Turkey, publication no: 20–17]. Ankara: General Directorate of Electrical Power Resources Survey and Development Administration.

EIE (General Directorate of Electrical Power Resources Survey and Development Administration). (2003). *Aylık ortalama akımlar (1935–2000)* [Monthly mean discharges (1935–2000)]. Ankara: General Directorate of Electrical Power Resources Survey and Development Administration.

Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company). (2008). *Garzan Barajı ve HES revize fizibilite raporu* [Garzan dam and HEPP revised feasibility report]. Ankara: Enersu Engineering Consultancy Construction Industry and Trade Limited Company.

Enersu (Enersu Engineering Consultancy Construction Industry and Trade Limited Company). (2009). *Sirvan Barajı ve HES revize fizibilite raporu* [Sirvan dam and HEPP revised feasibility report]. Ankara: Enersu Engineering Consultancy Construction Industry and Trade Limited Company.

En-Su (En-Su Engineering Consultancy Limited Company). (2008). *Dipni Barajı ve HES Projesi fizibilite raporu* [The Dipni Dam and HEPP Project feasibility report]. Ankara: En-Su Engineering Consultancy Limited Company.

FPGA (Euphrates Planning Group Authority) (1968). *Dicle Havzası istikşaf raporu* [The Tigris Basin reconnaissance report]. Diyarbakir: Euphrates Planning Group Authority.

Guven, B. (2014). *Çözümün ve işsizliğin anahtarı GAP oldu* [GAP has been the key of solution and unemployment]. Retrieved October 12, 2014, from https://www.turkiyegazetesi.com.tr/gundem/191122.aspx

Hidrokon (Hidrokon Engineering Consultancy Incorporated Company). (2009). *Çetin Barajı ve HES fizibilite raporu* [Cetin Dam and HEPP feasibility report]. Ankara: Hidrokon Engineering Consultancy Incorporated Company.

Ilisu Dam and HEPP Engineering and Consultancy Services Consortium. (2008). *Ilisu Dam and HEPP, flood hydrology and sediment transport*. Ankara: Ilisu Dam and HEPP Engineering and Consultancy Services Consortium: Colenko Power Engineering Limited, IM Maggia Engineering, Dolsar Engineering and Rast Engineering Services Limited.

Ilisu Environment Group. (2005). *Ilisu Dam and HEPP environment impact assessment report with enclosures*. Ilisu Environment Group: Hydro Concepts Engineering, Hydro Quebec International and Archeotec Incorporated.

Ilisu Hydropower Consultants. (1983). *The Cizre Dam and HEPP Project feasibility report*. Ilisu Hydropower Consultants: Binnie & Partners, Gizbili Consultancy Engineering, James Williamson & Partners, Kennedy & Donkin and COBA.

Jemas-Su (Jemas-Su Groundwater Survey and Engineering Limited Company). (2001). *Bitlis-Garzan Projesi, 1987 yılında hazırlanan Ayşehatun Barajı ve HES planlama raporunun revize bölümleri* [The

Bitlis-Garzan Project, revised sections of Aysehatun Dam and HEPP planning report prepared in 1987]. Ankara: Jemas-Su Groundwater Survey and Engineering Limited Company.

Kaplan, N. (2012). *Susuz GAP* [Waterless GAP]. Retrieved May 15, 2014, from https://www.ntv.com.tr/arsiv/id/25344895

Limak (Limak Hydropower Plant Investments Incorporated Company). (2006). *Alkumru Barajı ve HES Projesi fizibilite raporu* [The Alkumru Dam and HEPP project feasibility report]. Ankara: Limak Hydropower Plant Investments Incorporated Company.

Met (Met Project Engineering Consultancy Construction Industry and Trade Limited Company). (2006). *Eruh Barajı ve HES fizibilite raporu* [Eruh Dam and HEPP feasibility report]. Ankara: Met Project Engineering Consultancy Construction Industry and Trade Limited Company.

Murtagh, B. A., Saunders, M. A., Murray, W., & Gill, W. E. (2014). MINOS solver manual. Retrieved October 12, 2014, from https://www.gams.com/dd/docs/solvers/minos.pdf

Pro-sem (Pro-sem Engineering Architecture Consultancy Limited Company). (2008). *Pülümür Barajı ve HES fizibilite raporu* [Pulumur Dam and HEPP feasibility report]. Ankara: Pro-sem Engineering Architecture Consultancy Limited Company.

Su Yapi (Su Yapi Engineering and Consultancy Incorporated Company). (2007). *Dicle Nehri, Botan Çayı, Pervari Barajı ve HES tesisleri ön fizibilite raporu (Ek 3A)* [The Tigris River, Botan Creek, Pervari Dam and HEPP establishments pre-feasibility report (Appendix 3A)]. Ankara: Su Yapi Engineering and Consultancy Incorporated Company.

Suis and Sial (Suis Project Engineering and Consultancy Limited Company & Sial Geosciences Survey and Consultancy Limited Company Joint Venture). (2001). *GAP, Batman-Silvan Projesi planlama raporu* [GAP, the Batman-Silvan Project planning report]. Ankara: Suis Project Engineering and Consultancy Limited Company & Sial Geosciences Survey and Consultancy Limited Company Joint Venture.

Tigrek, S., & Aras, T. (2011). *Reservoir sediment management*. Leiden: CRC Press/Balkema.

Unver, I. H. O. (1997). South-eastern Anatolia integrated development project (GAP), Turkey: An overview of issues of sustainability. *International Journal of Water Resources Development, 13*, 187–208. doi:10.1080/07900629749827

Yalcin, E. (2015). *Optimisation of the Tigris river hydropower system operations* (Doctoral thesis). Middle East Technical University, Ankara.

Yalcin, E., & Tigrek, S. (2015). Hydropower production without sacrificing environment: A case study of Ilisu Dam and Hasankeyf. *International Journal of Water Resources Development*, *32*(2), 247–266. doi:10.1080/07900627.2015.1031210

Yolsu (Yolsu Engineering Services Limited Company). (2009). *Başören HES fizibilite raporu* [Basoren HEPP feasibility report]. Ankara: Yolsu Engineering Services Limited Company.