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Impacts of the southeastern Anatolia Project in Turkey on the performance of the Tabqa dam and hydropower plant in Syria

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Abstract Water resources systems development in the upper parts of a river basin can have major impacts on downstream users. This paper analyses the impacts of development of the southeastern Anatolia Project (Turkey), commonly called GAP, on the Euphrates downstream riparian countries, Syria and Iraq, and especially on the performance of the Tabqa dam in Syria. A two-stage modelling approach has been adopted. First, the operating rules of the largest GAP reservoirs are optimized and then simulated using a stochastic dual dynamic programming (SDDP) model to get, among other results, time series of simulated discharges at the borders with Syria and Iraq. This process is repeated for three development scenarios of the GAP. In the second stage, the reservoir operating policies of the Tabqa hydropower plant in Syria are derived from a stochastic dynamic programming (SDP) model and then simulated over a planning period of 50 years using the time series of inflows produced by SDDP for each development scenario. The analysis of results reveals, amongst other things, that if GAP is completed as planned, the risk of not meeting the annual Syrian energy target increases substantially (up to 60%).

Key words Euphrates; large scale optimization; reservoir operation; Stochastic Dual Dynamic Programming (SDDP); Stochastic Dynamic Programming (SDP); upstream/downstream trade-off

INTRODUCTION

The southeastern Anatolia Project (GAP) is a multidimensional water resources development project in the Turkish part of the Euphrates-Tigris River basin. It involves the construction of 22 dams, 19 hydroelectric power plants with an installed capacity of 7526 MW, and the irrigation of 1.7 million ha. With the completion of the Ataturk reservoir, Turkey has now enough storage capacity to control the headwaters of the Euphrates and to potentially divert huge volumes of water for irrigation.

The downstream riparian countries, Syria and Iraq, are concerned with the modification of the hydrological regime of the Euphrates River and its impact on the production of hydroelectricity from their hydropower plants and on the availability of water for irrigation purposes. This is especially important for Syria as Tabqa, its largest reservoir and hydropower plant (14.1 km^3, 800 MW), is located immediately downstream of the Turkish border. In the Tigris River basin, the problem is less acute as the Turkish contribution to Tigris flows is much smaller than to the Euphrates.

In response to the complaints formulated by its downstream neighbours, Turkey emphasizes the positive effects its storage capacity can have for the downstream countries by augmenting low flows during severe droughts and by absorbing flood waters. This study assesses the performance of the Tabqa reservoir and hydropower plant and quantifies the positive and negative effects of the altered hydrological regime on hydropower generation and on the reliability in meeting downstream water demands. The performance is evaluated for several development scenarios of GAP in Turkey, where each scenario is characterized by an irrigation area and by a set of dams, which define the GAPs storage capacity and its ability to alter the natural flow regime, mainly through irrigation water withdrawals and the decisions to release water for power generation. The assessment presented in this paper builds on the analysis by Tilmant *et al.* (2007a).

This paper is organized as follows: the next section presents the optimization algorithms (SDP and SDDP); then the system description and background information about GAP and the different scenarios are presented; followed by a discussion of simulation results; and finally conclusions.

METHODOLOGY

To perform the analysis, a two-stage modelling approach has been adopted. First, the operating rules of largest GAP reservoirs are optimized and then simulated using a stochastic dual dynamic programming (SDDP) model. One of the important results is a time series of simulated discharges at the Syrian border. This process is repeated for each GAP development scenario described in the third section. In the second stage, Tabqa reservoir operating policies are derived from a stochastic dynamic programming (SDP) model and then simulated over a planning period of several years using the time series of inflows produce by SDDP for each GAP development scenario. Those simulations are analysed to evaluate the influence of the level of development of GAP on the performance of the Tabqa dam in Syria.

The SDP algorithm

Stochastic dynamic programming (SDP) and its extensions are widely used optimization techniques to determine optimal operating policies (Labadie, 2004). The objective of a reservoir operation problem optimization is to derive optimal release decisions as a function of variables describing the state of the system. In this study, the system's status at the beginning of each time period is given by the storage level and the hydrological inflow (Tejada-Guibert *et al.*, 1995).

In SDP, release decisions are determined by solving a functional equation, which maximizes the sum of the immediate f_t and future benefits F_{t+1} for each period of time:

$$F_t^*(s_t, q_t) = \max_{r_t}\left\{ f_t(s_t, q_t, r_t) + \underset{q_{t+1}|q_t}{E}\left[F_{t+1}^*(s_{t+1}, q_{t+1})\right]\right\} \tag{1}$$

for $t = 1, 2, ..., T$

where T is the planning period; t the current period; q_t is the total inflow to system in period t; s_t the storage at the beginning of period t; r_t the total release during period t; $f_t(s_t,q_t,r_t)$ the benefit from system operation during the current period t; $F_t^*(s_t,q_t)$ the expected future return from the optimal operation of the system from period t to the end of planning period T (cost-to-go function); $\underset{q_{t+1}|q_t}{E}[\cdot]$ is the conditional expectation operator for q_{t+1} given a specific hydrologic state q_t. The most important constraints are the mass balance equation, the upper and lower bounds on releases and storage:

$$s_{t+1} = s_t + q_t + C(r_t, l_t) - e_t - i_t \tag{2}$$

$$\underline{s}_{t+1} \leq s_{t+1} \leq \overline{s}_{t+1} \tag{3}$$

$$\underline{r}_t \leq r_t \leq \overline{r}_t \tag{4}$$

where l_t represent spillage losses; C is the system connectivity matrix ($C_{j,k}$ = 1(−1) when reservoir j receives (releases) water from (to) reservoir k; e_t are the evaporation losses; i_t are the irrigation water withdrawals in the reservoir; $\underline{s}$ and $\overline{s}$ are minimum and maximum storage volume, respectively; $\underline{r}$ and $\overline{r}$ are minimum and maximum release, respectively.

Considering an infinite-horizon, periodic, and stationary problem, the optimal solution is obtained when release decisions generated by the SDP algorithm of equation (1) reach steady state. The model is said to converge when the change in the cost-to-go function from one cycle to the next becomes nearly constant for each point of the discrete state space domain. In this study, the time span of a period is one month, and one cycle corresponds to one year. The resulting steady-state release policy r_t^* and cost-to-go functions $F^*(s_t,q_t)$ constitute the sets of solutions that can be used by reservoir operators to derive an optimal release policy.

Unfortunately, the applicability of SDP is limited to small-scale problems involving three to four reservoirs with variable heads. In fact, adding reservoirs or states variables generates an exponential increase in the time and memory required to find a solution to the recursive equation (1). This well known problem, called "the curse of dimensionality", does not allow us to use SDP to derive the policies for the hydro system in the Euphrates as the number of reservoirs is too large. However, new algorithms such as stochastic dual dynamic programming (SDDP), introduced by Pereira (1989), or neuro dynamic programming, introduced by Castelletti *et al.* (2006), are able to overcome this SDP limitation.

The SDDP algorithm

SDDP is an algorithm that removes the computational burden found in traditional SDP, making possible the integrated analysis of large-scale water resources systems involving multiple reservoirs. SDDP can be seen as the combination of SDP and nested Benders decomposition, with the former being able to handle a large number of stages, but not a large state space, whereas the latter can handle large state space but not a large number of stages. In the SDDP algorithm release decisions are chosen so as to minimize the operating costs of a hydrothermal electrical system (see Pereira, 1989; Pereira & Pinto, 1991; Tilmant & Kelman, 2007b, for a detailed description of the SDDP algorithm).

SYSTEM DESCRIPTION

The southeastern Anatolia Project (Turkey)

As mentioned in the introduction, GAP is a multidimensional water resources development project, which aims to improve the entire economy of the southeastern Anatolia region in Turkey. This will be achieved by boosting agricultural production by 300% and providing 22% of Turkey's viable hydroelectric potential. This project is one of the largest water resources development projects in the world, involving the construction of 22 dams, 19 hydroelectric power plants with an installed capacity of 7526 MW, and the irrigation of 1.7 million ha. In this study, only the largest reservoirs and hydropower plants are incorporated in the SDDP model. Figure 1 only shows the topology of the GAP in the Euphrates River and the characteristics of the largest reservoirs involved in the analysis. A detailed description of the GAP project can be found in Kolars & Mitchell (1994) and Tilmant *et al.* (2007a). As explained in the two previous references, the different scenarios analysed here essentially depend on the irrigation areas and the reservoirs they are associated with, and thus the level of development of the GAP project. Table 1 lists the characteristics of the three scenarios.

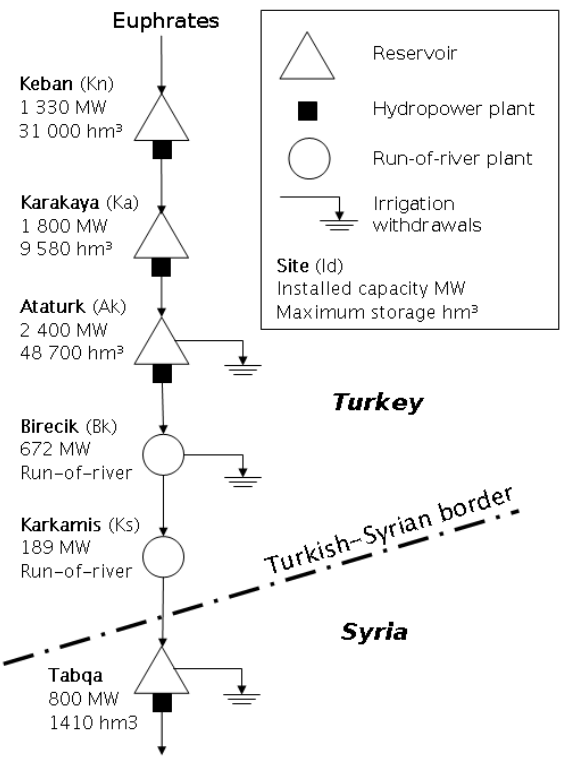

Fig. 1 Large reservoirs in the upper part of the Euphrates River basin.

Table 1 GAP development scenarios.

Scenario	High	Medium	Low
Irrig. area (10^6 ha)	1.70	0.83	0.20
Irrig. efficiency (%)	60	60	40
Dams	All	All	All without Ks, Bk
Inst. capacity (MW)	8300	7910	5838

The Syrian system

With the construction of the Tabqa dam in the 1970s, Syria planned to considerably develop irrigation along the Euphrates. The Tabqa reservoir has a storage capacity of 14.1 km^3, but due to its geographical location and the large area of its reservoir, the annual evaporation losses are significant (around 1.5 km^3 year^{-1}). The installed capacity of the hydropower plant is 800 MW and the annual target for energy generation is 1600 GWh.

Irrigation is another important operating objective. Whereas only 280 000 ha of irrigated lands were developed by the mid 1980s (Kolar & Michell, 1991), considerable developments have been observed since the early 1990s. Beaumont (1996, 1998) estimated an irrigation area around 475 000 ha by the year 2000. Data on irrigation water usage in the Euphrates River basin are taken from Beaumont (1998), Kliot (1994) and Kolars & Mitchell (1994) who suggest 10 000–12 000 m^3 ha^{-1} year^{-1}. These figures have been confirmed using the irrigation model CROPWAT and the climatic database CLIMWAT (Allen *et al.*, 1998) by Tilmant *et al.* (2007a). Most of the irrigation water withdrawals take place in the summer, from June to August.

ANALYSIS OF SIMULATION RESULTS

The SDP algorithm has been used, considering water withdrawals for irrigation in the Tabqa reservoir as a priority so that the analysis will focus on energy production and consequently on downstream water availability. To maintain minimum flow for downstream users, essentially Iraq, an additional constraint has been activated: if enough water is available, monthly release cannot be less than 300 m^3 s^{-1}, which corresponds to the minimum flow that should cross the Iraqi border according to an outdated agreement between the three riparian countries. In the absence of a new agreement on the sharing of the Euphrates, we will use this minimum flow as a target value.

Fifty years of operation of the Tabqa reservoir are simulated (600 months) by a forward-moving re-optimization method of the optimal policy calculated by the SDP algorithm (Tejada-Guibert *et al.*, 1993), making possible the statistical analysis of performance indicators such as the risk faced by Syria of not meeting its energy generation objective (1600 GWh year^{-1}).

Energy generation

Figure 2 displays the empirical cumulative density functions of annual energy generation for each GAP scenario. Examination of Fig. 2 reveals that if the GAP project is fully implemented (high GAP scenario development), the risk of not meeting the annual Syrian energy target increases up to 60%. In the case of the medium GAP development this risk becomes 34%, and reduces to 16% for the current situation (low GAP scenario development).

Table 2 shows the basic statistics associated with these results. Another statistical indicator used is the resilience. This can be expressed as the probability that if a system is in an unsatisfactory state, the next state will be satisfactory (Loucks & van Beek, 2005). Resilience increases from 29% (high GAP scenario development) to 75% (low GAP scenario development) showing again that the current situation is more flexible and sustainable than the full GAP project implementation.

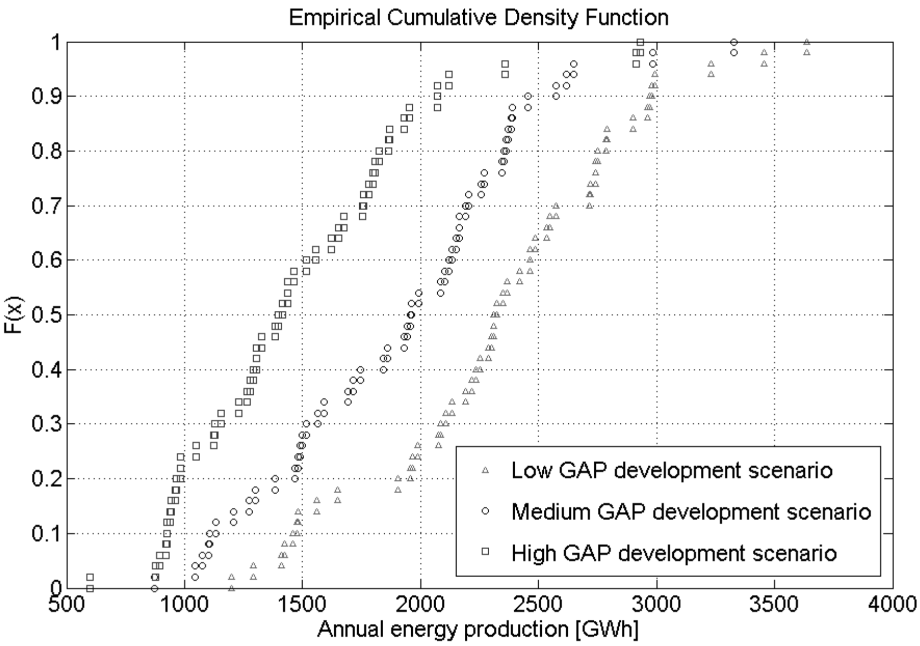

Fig. 2 Empirical cumulative density function of annual energy production at Tabqa for the three GAP development scenarios.

Table 2 Simulation results (Annual energy production—Tabqa).

Scenario	High	Medium	Low
Average [GWh]	1474	1908	2323
Std deviation [GWh]	501	538	560
Minimum [GWh]	599	875	1198
Maximum [GWh]	2929	3330	3636
Reliability [–]	0.38	0.66	0.84
Resilience [–]	0.29	0.53	0.75

Downstream water flow

The empirical cumulative density functions of monthly release of the Tabqa dam is presented in Fig. 3 for each GAP development scenario. The particular shape of the functions is due to the hard constraint put on the release: this cannot be less than 300 $m^3 s^{-1}$ if enough water is available. This constraint is always satisfied, except for the high GAP development scenario and under very dry years corresponding to a return period of 50 years. During those particularly dry years, even the irrigation (also a hard constraint in the SDP model) cannot be fully met.

The maximum flow observed is composed of the technical maximum release flowing through the eight turbines (8×285 $m^3 s^{-1}$) and an unforeseeable inflow of water in the reservoir forcing spillage. Those floods are less important in Syria with the increase of GAP project development. This observation corroborates Turkey's argument that GAPs development storage capacity has positive effects on the downstream riparian countries by augmenting low flows during severe droughts and by absorbing flood waters.

Table 3 Simulation results (monthly release—Tabqa).

Scenario	High	Medium	Low
Average [$m^3 s^{-1}$]	442	576	707
Std deviation [$m^3 s^{-1}$]	387	543	668
Minimum [$m^3 s^{-1}$]	0	300	300
Maximum [$m^3 s^{-1}$]	2654	2977	3883

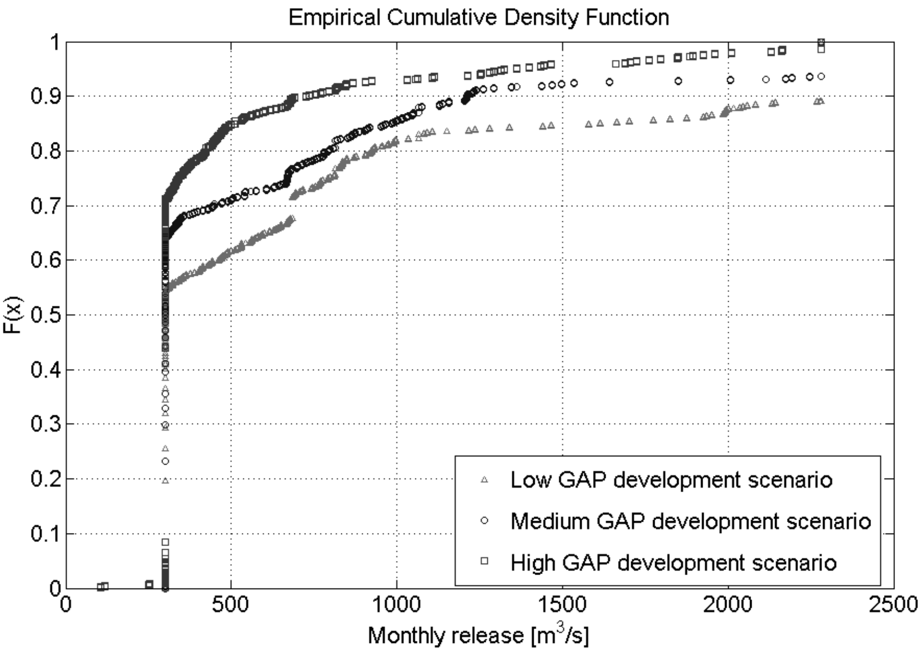

Fig. 3 Empirical cumulative density function of monthly release at Tabqa for the three GAP development scenarios.

CONCLUSION

Due to the development of new quantitative analysis tools allowing large-scale water resources system analysis, concerns can be approached more in detail and at the right scale. Stochastic dual dynamic programming (SDDP) is one such technique. Coupled with a classical SDP scheme, the analysis demonstrates that the development of the GAP project on the Euphrates will impact significantly on Syria. This is particularly true for energy generation as the GAP development scenario increases from the current situation to full project implementation. The risk of Syria not being able to meet its annual energy target may increase to 60%. Iraq, being downstream of Syria on the Euphrates, may also incur significant impacts.

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