Upstream Effects on Aras Cascade Hydropower Plants System

Mahdi Razi Khosroshahi[1], S. Jamshid Mousavi[1], Hosein Alizadeh[2]
1- Amirkabir University of Technology, Hafez Av., Tehran, Iran
2- Iran University of Science and Technology, Narmak, Tehran, Iran
⋮
jmosavi@aut.ac.ir

Abstract

Aras River is an international river whose water resources are shared by four countries of Turkey, Armenia, Iran and Azerbaijan. A major middle part of Aras River is exactly the border between Iran, Azerbaijan and Armenia and on this part the countries share several hydropower plant projects including two storage projects (Aras and Khodafarin) and four run-of-river projects (Megri, Gharechilar, Marazad and Ordubad). On the other hand there are some development plans in upstream countries of Turkey and Armenia which are expected to affect the energy production performance of the hydropower cascade system of Aras River. The principal motivation of this study is to demonstrate some of these effects and therefore the results are expected to be helpful for future action plans or possible hydro-political negotiations. To deal with this issue, the water resources demand-supply system of Aras River was modeled using WEAP (Water Evaluation and Planning) software. A script for hydropower simulation based on the sequential streamflow routing method was developed using scripting capabilities of WEAP. Results demonstrate that upstream projects construction will dramatically reduce energy production of the hydropower plants. We have supposed that the most influential effect of upstream development in Turkey and Armenia is 35% reduction in long-term average of Aras Dam inflow, the reality that revealed by a pervious study. Therefore based on our results, 30% decrease in the annual average of hydropower energy production of Khodafarin, Megri and Gharechilar power plants and 50% and 15% reduction in annual average of hydropower energy production of respectively Aras and Marazad power plants are expected.

Keywords: Hydropower plants cascade system, WEAP, Sequential Streamflow Routing, Aras River

1. INTRODUCTION

Transboundary issues associated with Aras River provide general perspective for effective cooperation among riparian countries including Turkey, Azerbaijan, Armenia and Iran. The existing agreements for cooperation are mostly between Iran, Azerbaijan and Armenia to develop hydropower plants (HPPs) along the shared river in the border of Iran and Armenia (Heidari, 2011). On the other hand the impact of Turkish activities in upstream of Aras River will change flow pattern and water pollution in this river. In this paper a hydro-energy simulation model is developed to assess effects of upstream activities on the hydropower cascade system performance. The famous Sequential Streamflow Routing (SSR) routine is embedded in WEAP model using scripting capabilities.

2. CASE STUDY

Aras River has high potential of hydropower development and consequently in recent years lots of hydropower projects have been under study or construction on the river. In this regard, Iran, Azerbaijan and Armenia have shared 6 main hydropower plants projects. The first one is Aras Dam and hydropower plant which is under operation since 1974 with installed capacity of 44 MW. The second storage project is Khodafarin Dam and hydropower plant whose construction is expected to be completed in 10 years. Installed capacity of Khodafarin plant is 200 MW and it consists of 2 plant units. Between these two storage projects there are four important run-of-river hydropower projects of Marazad, Ordubad, Megri and Gharechilar which are all under study now. Installed capacity of Marazad, Megri and Gharechilar are 35, 110 and 110 MW, respectively. Figure 1 shows schematic of Aras cascade hydropower plants system. There are some riparian municipal, rural and agricultural demand sites in the river system. ILF, AzLF and ALF represent tributaries flow into main body of Aras River respectively from Iran, Azerbaijan and Armenia sides. Table 1 shows long-term average of discharge of Aras River main body and its tributaries. In Figure 1, IDE, AzDE and ADE represent riparian demand sites respectively in Iran, Azerbaijan and Armenia and QEN represents minimum required environmental flow. Table 2 shows annual water requirement of these demand sites.

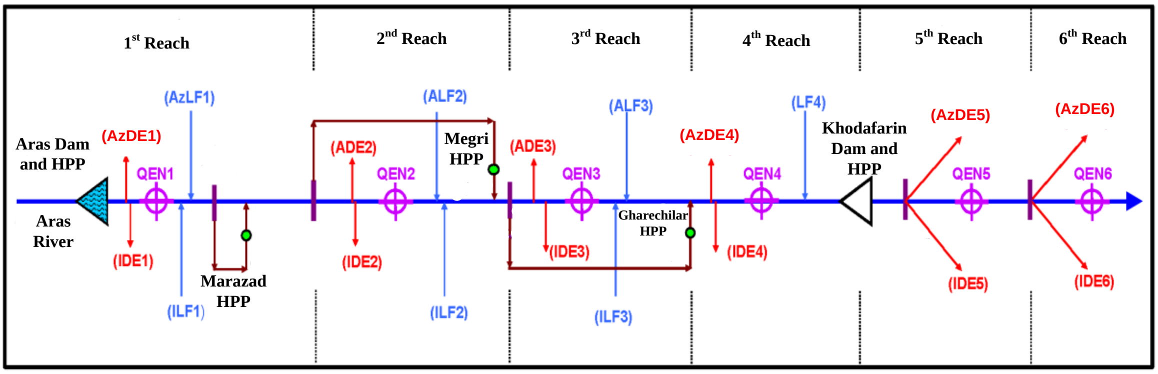

Figure 1- Aras cascade hydropower plant system

Table 1- Long-term average of Aras River and its tributaries

Tributary	Flow (cms*)	Tributary	Flow (cms)
Aras Dam Inflow	133.12	ILF2	3.60
AzLF1	9.69	ALF3	1.93
ILF1	19.80	ILF3	1.62
ALF2	2.41	LF4	56.27

*cms: cubic meter per second

Table 2-Annual water requirement of demand sites

Demand Site	Annual Water Requirement (mcm)	Demand Site	Annual Water Requirement (mcm*)
AZDE1	123.09	AZDE5	830.00
IDE1	429.10	IDE5	830.00
ADE2	11.18	AZDE6	575.55
IDE2	3.14	IDE6	744.36
ADE3	3.04	QEN1,2,3,4	18 cms**
IDE3	4.68	QEN5,6	35 cms
IDE4	22.48		

*mcm: million cubic meter **cms: cubic meter per second

3. WEAP

WEAP is a microcomputer tool for integrated water resources planning. WEAP is distinguished by its integrated approach to simulating water resources systems and by its policy orientation (Sieber and Purkey, 2011). It provides a comprehensive, flexible and user-friendly framework for policy analysis. A growing number of water professionals are finding WEAP to be a useful addition to their toolbox of models, databases, spreadsheets and other software. In spite of powerful capabilities, there are limitations for hydropower systems modeling in WEAP. To improve these capabilities we developed some scripts in the scripting environment of WEAP to enable it hydropower simulation based on the traditional sequential streamflow routing methodology. It is worth mentioning that the scripting is an environment to create more powerful expressions and functions for a WEAP model and also to automate WEAP via its Application Programming Interface (API) to perform a sequence of actions.

4. Sequential Streamflow Routing

Two main approaches are used for hydro-energy analysis: 1) non-sequential or flow-duration curve (FDC) method, and 2) sequential streamflow routing (SSR) method (USACE, 1985). FDC is a relatively simple method by which forebay and tailwater elevations, generating efficiency, head loss and other important variables of interest must be assumed to be constant or to vary as a function of discharge; thus the FDC method cannot accurately simulate the storage operation at reservoir projects where head varies independently of flow and also FDC method cannot be used to analyze systems of projects. The SSR method does not have the drawbacks and limitations of the FDC method although SSR is more time consuming than FDC. In this study we have employed the SSR method.

We have developed a framework in which SSR method is embedded in the WEAP software using scripting capabilities. There are two main phases in this framework: 1) allocation and 2) simulation. In the allocation phase, a demand site node is set for each hydropower plant and appropriate equations are established to calculate the amount of hydropower water requirement of each power plant in each time step. Then in each time step based upon the calculated water requirement values, WEAP allocate water between demand sites. After allocation phase, detail simulation of energy production is done in the second phase (simulation).

In the allocation phase, hydropower water requirement (in mcm) is determined based upon the energy production equation as below

$$WR_t = \frac{P_{\max} \times PH_t \times ND_t}{2725 \times \eta \times h_{n,t}}, \tag{1}$$

where t is the monthly time step index, $P_{\max}$ is installed capacity (MW), PH_t is number of peak hours per a day, ND_t is the number of the days which the time step includes, η is the generating efficiency, $h_{n,t}$ is net head.Net head is estimated using average forebay elevation (FBE_t), tailwater elevation (TWE_t) and head loss ($h_{l,t}$) as below equation

$$h_{n,t} = FBE_t - TWE_t - h_{l,t}. \tag{2}$$

All of the variables in the equation (2) are average values over the time step, e.g. FBE_t is estimated as average of forebay elevation at the beginning and the end of the time step. These variables can be calculated by means of *Expressions* capability of WEAP where at each time step quantity of a variable can be calculated by an analytical function of some other variables calculated in previous time steps. Therefore for instance FBE_t can be approximately estimated using forebay elevation at the beginning of time step which is equal to forebay elevation at the end of the previous time step. However this approach may not be accurate enough. Therefore we propose an iterative procedure to calculate accurate hydropower water requirement which is based on both beginning and end of time step forebay elevation. At first iteration of this procedure, the hydropower water requirement value at each time step and each power plant site is estimated using the forebay elevation of preceding time step and then WEAP is run using these approximated hydropower water requirement. When WEAP is run for the first iteration complete time series of forebay elevation are stored and thus an approximate record of end forebay elevation will be available at each time step. Therefore in the other iterations, hydropower water requirement value at each time step and each demand site is calculated using forebay elevation values at the beginning and the end of the time step. This procedure continues and new series of forebay elevation are stored after each iteration to be used in the following iteration. This iterative procedure converges when hydropower water requirement time series or forebay elevation time series of an iteration do not differ from what calculated in the previous iteration. Sum of the difference of two preceding time series is defined as a convergence measure (criterion).Figure 2illustratesconvergence rate of the proposed iterative procedure.

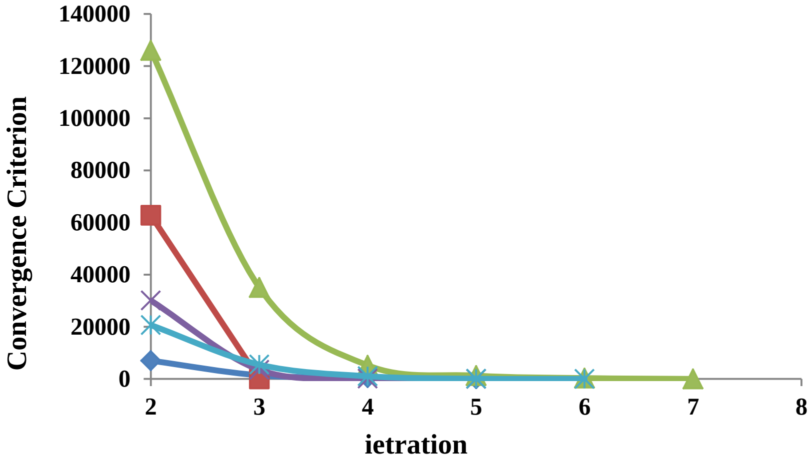

Figure 2.Convergence of the proposed iterative procedure

Second phase of the SSR method is simulation where detail hydro-energy simulation is implemented. One of the major outputs of the allocation phase is volume delivered to each demand site, especially hydropower plant nodes, to supply its water requirement. From these water volumes time series of turbine discharge of each power plant is calculated in the simulation phase. The other major output of allocation phase is time series of storage volume of the reservoirs (or forebay elevation) from which time series of net head is calculated in the simulation phase. To calculate the net head at each time step of each power plant site, specific tail water level and head loss as functions of turbine discharge can be considered. After determination of the flow and net head, generated power and energy can be simulated. Finally some important variables such as actual plant factor, generating hours and reliability of energy production are calculated.

5. SCENARIOS

To assess the upstream effects, three scenarios are defined in this study. Given that the Aras Dam and power plant are located at upstream side of the cascade hydropower system (Figure 1) and knowing that inflow to Aras Dam is one of the biggest flows which enters the system and also it is the only flow which will be affected by upstream development plans in Turkey, all of three scenarios are about Aras Dam inflow. For the first scenario, which is an extreme optimistic scenario, it is assumed that historical time series of Aras Dam inflow is exactly repeated in the future. For the second scenario, which is building upon a detail study considering whole the international Aras basin (Yekom Consult of Engineers, 2007) and therefore is expected to be the most probable scenario, it is supposed that the long-term average of Aras Dam inflow is reduced by 35% of the historical record. Finally an extreme pessimistic scenario is also defined for which it is assumed that the Aras Dam inflow is also decreased so that its long-term average is reduced by 50% of the historical record.

6. RESULTS

Based upon available 35-year hydrologic historical records, the performance of Aras cascade hydropower plant system was studied under the scenarios' condition. Some of important results are reported here. Figure 3 show annual total energy production for each hydropower plant and under each scenario. For business as usaul scenario, i.e. Scenario 1, the results show that annual total energy is 113.9, 930.4, 279.5, 763.7 and 785.7 GWh (Giga Watt hours) respectively for Aras, Khodafarin, Marazad, Megri and Gharechilar HPPs. Comparing Scenario 1 and Senario 2 results, one can realize that upstream develpoment in Turkey has such serious negative consequences for energy production that 61 GWh (53%) and 257 GWh (28%) reduction is expected respectivley for Aras and Khodafarin HPPs. Also for Marazad, Megri and Gharechilar HPPs, annual total energy decreases about 42.0 (15%), 228.5 (30%) and 219.4 (28%) GWh. In total, a decline of 808 GWh (28%) in the annual average (total) energy of the casecade system is expected for the most probable senario, i.e. scenario 2. For Scenario 3, i.e. the worst case, a decrease of 1182 GWh (41%) in annual total energy (coparing to Scenario 1) is anticipated. Furthure details about Scenario 3 is that the decline in annual total energy is 79.5 (70%), 375.6 (40%), 69.3 (25%), 334.0 (44%) and 323.8 (41%) GWh respectively for Aras, Khodafarin, Marazad, Megri and Gharechilar HPPs. Given that for Aras HPP the most relative decline in energy production is seen, it can be deduced that Aras HPP is the most vulnarable HPP in the cascade system and therefore furthur future actions should be taken to restrict these deterimental.

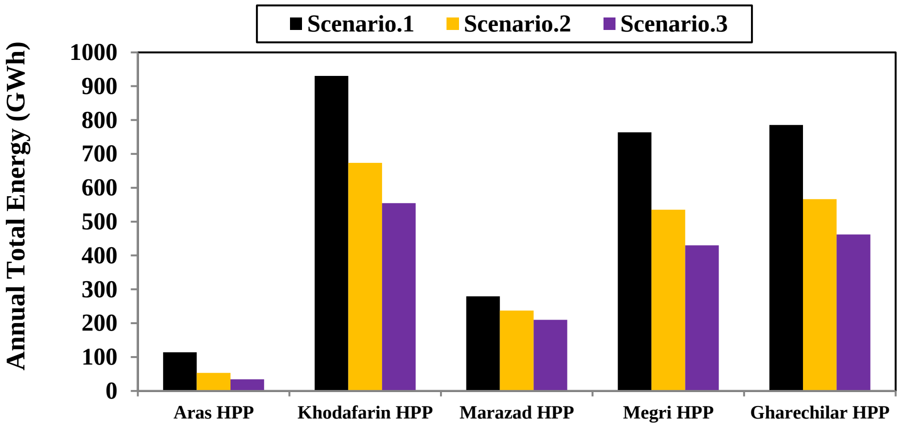

Figure 3- Annual total energy for HPPs and under different scenarios

Another important factor that reveals the performance of hydropower systems is the dependable or firm energy. In this study, the firm energy is calculated for reliability level of 90%. Figure 4 shows annual firm energy results for all HPPs under different senarios. For business as usaul scenario the results show that annual firm energy is 17.6, 325.2, 209.0, 491.6 and 510.4 GWh for Aras, Khodafarin, Marazad, Megri and Gharechilar HPPs respectively. Under upstream development condition, which is represented in this study by both of Scenario 2 and Scenario 3, annual firm energy of Aras HPP vanishes. Also dramatic fall in firm energy is seen for Khodafarin, Megri and Gharechilar HPPs under Scenario 2 so that declines of 97.7 (30%), 213.4 (43%) and 190.9 (37%) GWh are seen respectively. Under the condition of Scenario 3 and for the mentioned HPPs, the declines of 123.3 (38%), 299.4 (61%), 303.4 (59%) GWh in annual firm energy are anticipated. It is worth to note that Marazad HPP is the most robust one, given that the relative decline in firm energy level is the less with respect to the other HPPs. Furthure detail in this respect is that under Scenario 2 and Scenario 3 the annual firm energy of the Marazad HPP decrease about 37.4 (18%) and 65.3 (31%) respectively. In total, a decline of 557.1 (36%) and 809.1 (52%) GWh in the annual firm energy of the casecade system is respectively expected for Scenario 2 and Scenario 3.

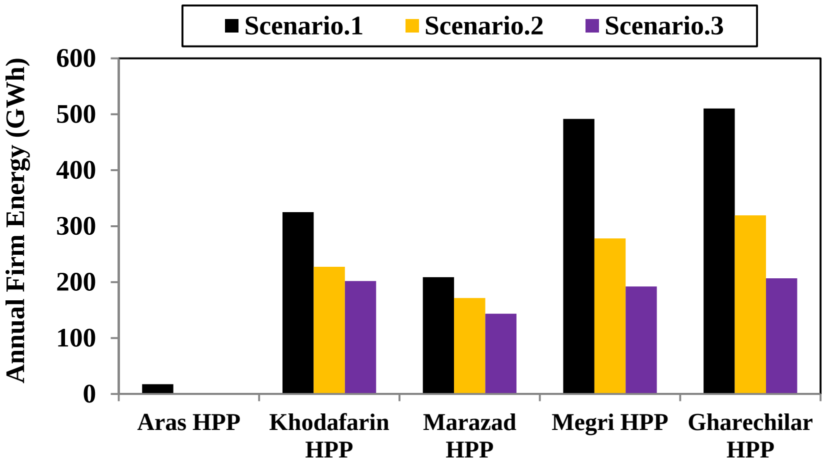

Figure 4- Annual firm energy for HPPs and under different scenarios

Actual plant factor is another important factor of power plant performance. It is worth mentioning that the storage HPPs, i.e. Aras and Khodafarin HPPs, are peaking plants and their design plant factors equals 0.25. In contrast, the run-of-river projects, i.e. Marazad, Megri and Gharehchilar HPPs, are base palnts. The actual palnt factor level has been compared for different HPPs and scenarios in Figure 5. For business as usual condition, the actual plant factor equals 31.6% and 52.4% for Aras and Khodafarin HPPS respectively and equals 89.5%, 77.0% and 80.7% for Marazad, Megri and Gharehchilar HPPs respectively. Under Scenario 2 condition, the factor decreases by 16.7%, 13.2%, 16.2%, 25.1% and 23.1% for Aras, Khodafarin, Marazad, Megri and Gharehchilar HPPs. For Scenario 3 declines of 21.7%, 18.9%, 22.2%, 35.4% and 33.6% in actual plant factor value (with respect to Scenario 1) is expected respectively. In respect to plant factor, it can be stated that Megri and Gharechilar HPPs are the most vulnarable plants and Khodafarin HPP is the most robust one.

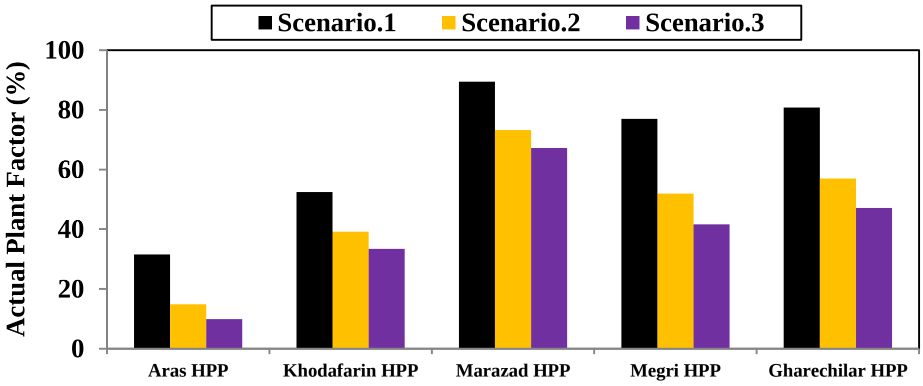

Figure 5- Actual plant factor for HPPs and under different scenarios

Figure 6 to Figure 10 show energy duration curves (EDCs) of the HPPs separately. For each HPP, EDCs of different scenarios demonstrate decline for generated energy at every level of probability in result of upstream development effects.

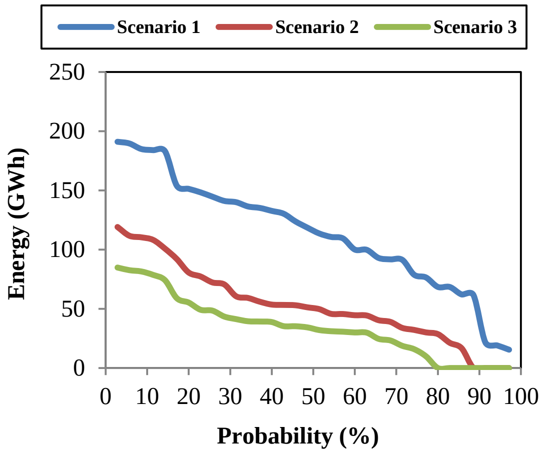

Figure 6- Energy duration curve of Aras HPP

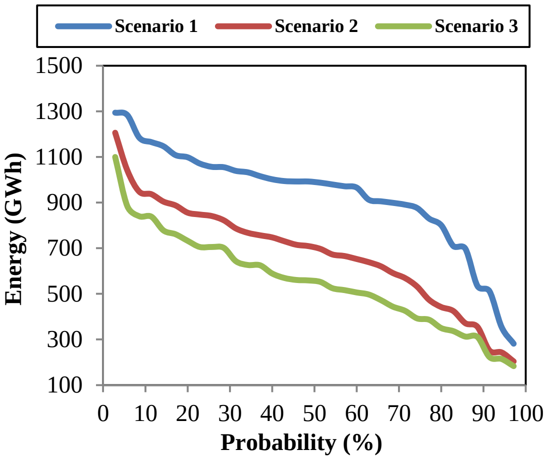

Figure 7- Energy duration curve of Khodafarin HPP

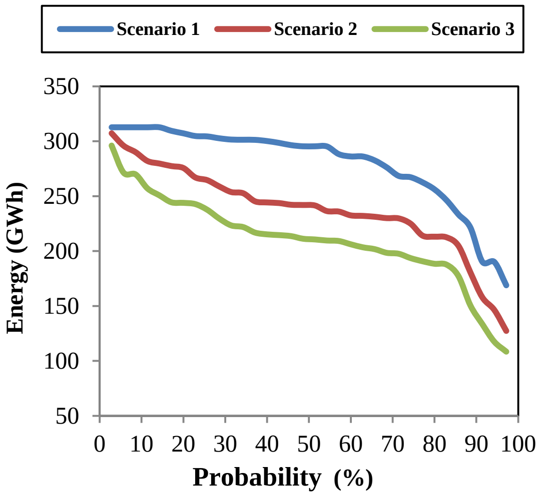

Figure 8- Energy duration curve of Marazad HPP

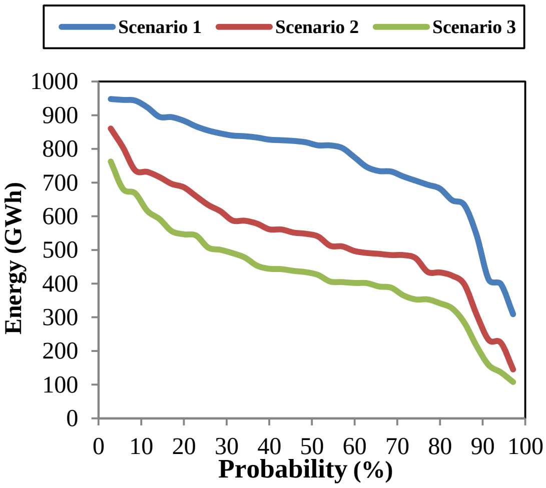

Figure 9- Energy duration curve of Megri HPP

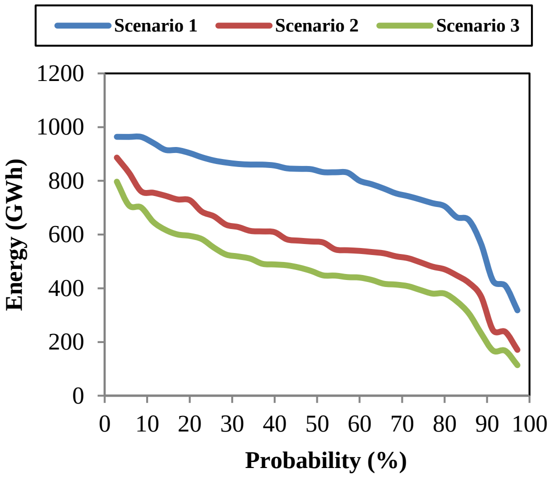

Figure 10- Energy duration curve of Gharechilar HPP

7. SUMMARY

This paper assessed effects of upstream development in Turkey on Aras cascade hydropower system which is jointly operated by Iran, Azerbaijan and Armenia. To deal with the problem, a new methodology of hydropower system modelling was developed where Sequential Streamflow Routing was embedded in WEAP software using scripting capabilities of the software. Given that upstream changes are very uncertain a scenario-based approach was taken and three different optimistic (business-as-usual), realistic (35% decrease in Aras dam inflow) and pessimistic (50% decrease in the inflow) scenarios were defined and compared. Results showed that upstream develpoment in Turkey has such serious negative consequences for energy production that declines of 808 GWh (28%) in the annual average (total) energy and 557.1 (36%) in the annual firm energy of the casecade system for the realistic scenario with respect to business as usual condition is anticipated.

8. REFERENCES

1. Afzali, R., Mousavi, S.J. & Ghaheri, A., 2008, Reliability-based simulation-optimization model for multi-reservoir hydropower systems operations: Khersan experience. *J. Water Res. Plann. Manage.* 134 (1), pp24–33.
2. Heidari, A., 2011, Aras transboundary river basin cooperation perspective. Dams and Reservoirs under Changing Challenges, Taylor & Francis Group, London, pp 429-436
3. Jalali, M.R., Azaranfar, A., Afzali, R., 2008, Development of hydropower capabilities in WEAP integrated water resources software. *3rd conference on water resources management*, Tabriz, Iran (in persian).
4. Kibaroglu et al. (Eds.), 2011, *Turkey's water policy national frameworks and international cooperation*, Springer.
5. Mahab Ghoss consulting Engineers Co., *Aras system water resources report*, 2010.
6. Mousavi S. J. and Shourian M., 2010 Capacity optimization of hydropower storage projects using particle swarm optimization algorithm. *Journal of Hydroinformatics*, Vol 12 No 3 pp 275–291.
7. Sieber J. &Purkey, D. 2012. WEAP User Guide, Stockholm Environment Institute, U.S. Center.
8. US Army corps of Engineers, 1985, *Hydropower engineering and design*.
9. Yekom Consult of Engineers, 2007, *Hydrology, water resources and water requirements report of Aras sustainable development plan*.