Hydropower Generation in Egypt after the Operation of South Valley Project

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Abstract— **Energy crisis, thus the actually experiencing said that where energy is a very important infrastructure of the overall development of any nation. Electric power one from importance sources of energy, there are two main sources for electrical power; thermal power and hydro power. Hydropower in Egypt will be studied in this approach as operation, evaluation and affect by the new projects. the construction of High Aswan Dam (HAD) during the sixties provided decision makers in Egypt with more control over flood and drought management. Severely high flows, which used to cause major damages to river banks, agricultural lands and threat human lives and properties, are more controlled after HAD construction. HAD plays an important role in hydropower generation due to the huge amount of the discharges passing through it and the water heads over its turbines. However, the inflow discharges under go a very high variability; they vary from a maximum inflow 150 BCM/year to a minimum inflow of 42 BCM/year. This variability has an effect on the generated hydropower. In addition, more hydropower reduction may be caused by any upstream water projects which affects on turbine water discharges. One of these projects is the South Valley Project or (El-Sheikh Zayed) Project. It is considered one of the major and national water projects designed to irrigate about 540000 new feddans=56700 Acres. It uses an estimated water volume of about 5 BCM/year. In this research, effect both of the proposed project, and the multiple low inflow years on hydropower generation in Egypt are evaluated. A mathematical mass balance numerical routing and multiple regressions of hydropower, discharges, and head relationships model was developed and used to study different scenarios of inflows and heads and their effects on hydropower generation. Finally specific conclusions were drawn.**

Key Words — South Valley Project, High Aswan Dam, Hydro-power generation in Egypt, Inflow at Lake Nasser.

I. Introduction

Hydropower, by the nature of its fuel source (water) and the non-combustion way in which it captures and converts the energy of falling water into electrical energy via the water turbine and generator set, lowers the amount of carbon dioxide emitted during the production of electricity. Hydropower potential, all over the world, meet 23% of the total power of the world. Many countries in U.S.A, Asia, and Africa have an experience in hydropower development. India, China, Pakistan and Democratic Republic of Congo have used their watercourses to generate millions of Miga-watts from small hydropower plants. In Egypt, the percentage of thermal generation is higher than hydro generation but recently; the government has become more interested in hydro generation. Worthy of mentioning that the share percentage of HAD generation is more than %86 from all hydropower generation in Egypt.

The River Nile is the second longest river in the world (about 6500 kilometers long). The Nile basin consists of about three million square kilometers in different countries with a variety of different characteristics. The main water supply sources are the Equatorial Lakes, Bahr El-Gazal watershed and the Ethiopian Plateau [1]. It is the main source of water in Egypt. The water coming to Egypt is used in different purposes such as irrigation, industry, navigation and power generation.

Several researches have been made on the hydropower generation with different problems. In earlier work, the impact of upper Nile development projects on hydro energy production from High Aswan Dam was discussed in [2]. The optimal operation of the reservoir for electric generation with varied conditions such that long and short term hydrothermal scheduling, distributed regional demand in order to analyze operation characteristics of electric utilities appropriately, is presented in [3, 4, 5]. Hydrothermal optimal power flow by using the interior point method (IPM) is presented in [6]. Scheduling problems were discussed by using different methods to solve these problems; mixed-integer linear programming, dynamic programming, lagrange relaxation and neural network were presented respectively in [7 – 10]. Also, linear programming methodology for the optimization of electric power Based on the application of a linear-integer programming algorithm was presented in [11]. In the study of hydropower generation and transmission capacity expansion plans for zone B "Cote d'Ivoire, Guinea, Senegal, Gambia" of West Africa power pool, WAPP, it was two scenarios were applied; scenario I is free trade and scenario II is limited reserve trading. The outputs of the optimization problem by using dynamic model based on Economic Community of West Africa States (ECOWAS) data are presented in [12].

In this research, a new approach is used to illustrate and evaluate the effect of two different cases on the generation of hydropower from HAD turbine stations. The first is the construction of South Valley (SV) project in Upper Egypt and the second is the multiple low water inflow years to Lake Nasser, by developing a special a mathematical model. This model is based on mass balance hydrologic routing equations, and new hydropower equation. This regression equation based on actual data of water discharges, and head relationships. The calculation considered the behavior of Lake Nasser (the HAD reservoir), water inflows, out flows, all losses, and quota of Sudan from River Nile.

In other words, our approach is a new method which uses depending on the actual field data to study the hydropower generation state in Upper Egypt in case new water projects and multiple low inflow years. Many different scenarios are to be implemented are adopted to illustrate these effects.

II. River Nile Resources

Egypt is completely dependent on the Nile River for its water resources. Most of these water resources are originated outside its borders. The average annual rainfall amounts are indeed very low, with almost zero values in Egypt. The desert of Egypt is arid with a dry atmosphere and considerable seasonal as well as diurnal temperature variation in Upper Egypt. Temperatures often exceed 38^{o} C at Aswan, where daily maximum temperature is 47^{o} C in June for example, indicating high evaporation losses along the Nile and the reservoir. The natural flow from the Nile during the low flow season is too insufficient to meet the demands of our country in this period. Due to the construction of High Aswan Dam, water availability to irrigate desert areas increased [13]. The Nile flood can be as high as 150 BCM/year and as low as 42 BCM/year. The major contribution to the Nile River water is coming from the Ethiopian Plateau through the Blue Nile and Atbara during the period from August to December, while following this period, most of the water supply comes from the White Nile and its tributaries. The available monthly discharges inflow data and water levels were used in this approach. The annual water inflow is shown in Figure 1.

III. High Aswan Dam

The High Aswan Dam (HAD) is a rock-filled dam constructed across the Nile at a distance of 7 km south of Aswan. The height of the dam is about 111 m above the riverbed. Its width is 980 m at the bottom and l0 m at the top. Water is discharged through the power plant and excess water is discharged through the spillway. Since the construction of the dam, Lake Nasser has been formed. It is a huge man-made lake of 500 km length and an average width of about 12 km which form a surface area of about 6000 km^2. It has been used for continuous water storage upstream the High Aswan Dam since May, 1964. The High Aswan Dam Reservoir (HADR) is the second largest in the world. It contains a powerhouse with **12** generating units from **Frances Turbine** type with a runner diameter of 6.3 m rated at 185 MW. Each turbine is under a head range of 60 to 76 m, "while the water level in the reservoir upstream the turbines is ranges between 175 m at the beginning of the water year in August and 165 m or less in the drought seasons, the height of turbines is 108 m, so the head on the turbines can be calculated as 175-108 = 67 m" in the normal operation case. For a corresponding range of discharges between 270 to 345 m^3/sec, [14]. The total nominal installed capacity of HAD is 2100 MW. Associated with the generating units are emergency low-level outlets for releasing water when downstream needs exceed the flows that can be handled by the turbines.

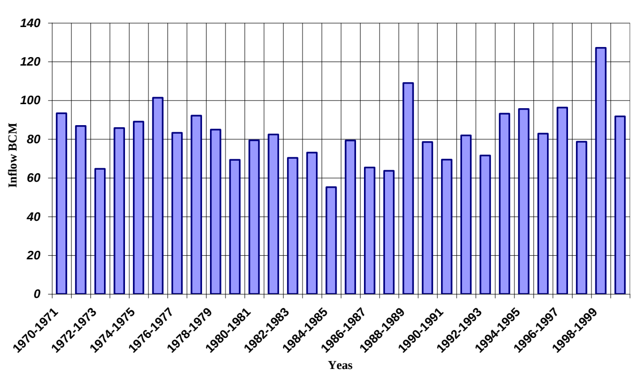

Fig. 1. Natural annual Inflow at Lake Nasser through four decades

IV. South Valley Project

The South Valley (SV) Project is a national major project in Egypt. It is a major water project designed to irrigate about 540000 new feddans=56700 Acres by elevating water from Lake Nasser. The estimated required water discharge is about 5.5 BCM/year taken at 265 km upstream the High Aswan Dam. This extracted huge volume from the lake has a major and magic effect on irrigating the desert land. But it, also, has some other major side effects since it is taken from a limited Egyptian share of 55.5 BCM/year. Some of these side effects are outside the scope of this research such as affecting the water management plans, water levels and discharges in addition to the cost benefit analysis issues. This research concentrates on the effects of this project and the effect of multiple low inflows on the generated hydropower from the High Aswan Dam. Mathematical models and different scenarios are considered to study these effects. Each scenario is based on the natural inflow from 45 BCM/year to 70 BCM/year.

V. The Developed Model

There are many mathematical models that can be used to predict the relation between the electrical power and water. This is a numerical that model is developed with special conditions to achieve some requirements such a relation. It is developed by the researcher particularly to study, analyze, and present the effect of the new SV project operation and multiple low water inflow years on the electric generation of the HAD power station. The special characteristics conditions of the model and the proposed simulation are considered as

1- The release discharge should be controlled during all time steps..
2- The upstream Water level should be controlled to avoid any water level exceeding 182.00 m.
3- The unique simulation of dam operation conditions.
4- The evaporation loss functions are governed by both lake water levels and meteorological conditions.
5- Seepage losses are governed by lake water levels.
6-Toshka spillway and South Valley Canal are about 265 km from upstream the High Aswan Dam.

Also, used model considers a unique because it is developed based on , multiple regressions of hydropower, discharges, and head relationships, mass balance hydrologic routing equations with special conditions related to the nature of the location and other reasons such as:

- In this study the special complicated nature of the problem since the storage volume reach up to 162 BCM/year with a length of about 500 Km and the existence of many types of outflows (point and non-point outflows) at different locations

- The major task is to simulate the actual occurring scenarios rather than indicating the optimal scenarios (for example by using dynamic programming) so the developed approach was used in this study to analyze the actual occurring conditions for different cases.

The developed model has different modules which are illustrated in (Figure 2). It can be briefly summarized as follows:

A. Hydropower Module

In this module, a new equation for turbines generation was created as flowing:

There are many trials to create this equation, they can be concluded as two trials; first one, data for every month separately was used to generate relation between power generations, head on turbines and discharge though these turbines. Second one; all data for all years from 1990 to 2000 were used to generate a anther relation as shown in figure 2. There are two formulas for the two trials. formula of first trial relation is represented as the hydropower global equation, "$P = (Q * H_1)/C$. ". formula for second trial, data for all years was represented as linear equation "$P = C_1 * Q + C_2 * H_t + C$" was showed in equation (1). The results of two formulas were compared with actual generated power; the result as; percentage of error for formula 1 gives **3.6** and the error for formula 2 gives **0.286**, the percentage of error for trial 2 is smaller than percentage of error smaller than formula of trial 1. Also correlation factor was given as 0.991. So the equation which is used in the study is second trial.

$$\mathbf{P = -689.41 + 0.167 * Q + 9.62 * H_1} \quad \textbf{Gw.h} \qquad (1)$$

$R^2 = 0.991$ (the correlation factor for the equation)

Where:
H_1 is the head acting on the turbines (m).
Q is the outflow discharge through the turbines (m.m^3/month.), and it is the discharge for reservoir.

C1, C2 are Coefficients & C is Constant

B. Inflow Generation Module:

In this module, the computations of inflow hydrograph are performed. These computations are based on the historical monthly distribution of similar and close value inflow floods to form an inflow hydrograph of the required amount and more

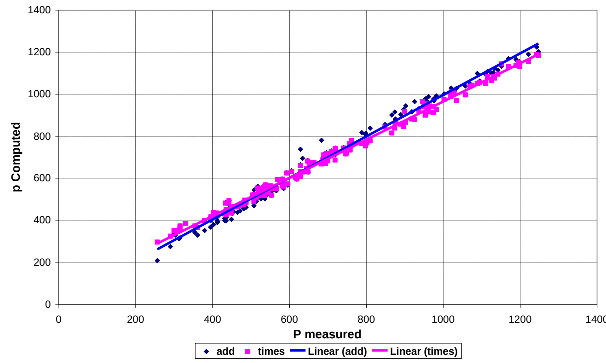

Fig. 2. Tow formulas for first trial and second trial

realistic distribution.

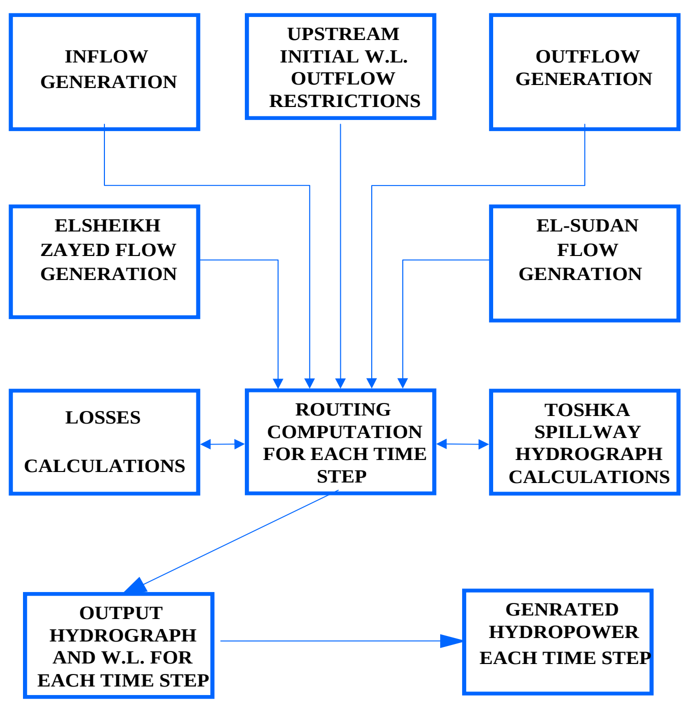

Fig. 3 Developed Model

C. Outflow generation module:

The proposed outflow hydrograph down stream the High Aswan Dam is computed using this module. The module computations are based on the water requirements for different months, the restrictions of the allowable maximum outflow down stream the dam, and the maximum allowed water levels upstream the dam. So the basic outflow hydrograph is composed from the historical data and water demand and water discharges and levels restrictions.

D. The Upstream Water Level and Outflow Restrictions Module:

This module monitors both; the upstream water level and the outflow down stream the dam. The task of this module is to ensure that the maximum water level upstream the dam is not exceeding the maximum limit during any time step and, also, to avoid increasing of the outflow discharge down stream the dam higher than the safe limits if possible.

E. South Valle y (SV) Project Outflow Computation Module:

This module is based on the computations of the proposed project outflow hydrograph. The proposed hydrograph computations are introduced. According to the water requirements of the cultivated area based on the requirements of similar crops cultivated on similar environment.

F. Sudan Abstraction:

This module is based on the historical data available for Sudan abstraction during different conditions. During the study, different scenarios are simulated using different Sudan abstraction conditions.

G. Losses computation module:

The major Lake Nasser losses are the evaporation and seepage losses. They are both incorporated in the model by this module. The evaporation losses are computed according to lake water levels, surface area, climatic conditions and time of the year. The computation equation was developed based on actual measurements. They can be stated in general form as following:

$$\mathbf{EL = \boldsymbol{f}\,(w.l., M)}$$

Where
EL Evaporation losses m.m^3/day
w.l. Lake Nasser water level (m)
M Month of the year
For the seepage losses, the empirical regression functions for seepage losses and water levels are used for this part as following:

$$\mathbf{S = 0.038\,(H - 110)}$$

Where:
S: the flow in BCM/month to the ground water in Lake Nasser
H: the storage level in metre.

VI. Different Applied Scenarios

There are two tables [I, II] in this section explaining the different parts in this study. The Inflow values are ranging from 45 BCM to 70 BCM, where 45 BCM represents the actual minimum inflow discharge. Table I describes the different studied scenarios for the first part where the outflows are different from one scenario to the other; they all have an upper limit of 55.5 BCM which represent the Egyptian Share according to Egyptian / Sudanese treaty of 1959. The three cases, a, b, and c differ from each other. Case (a) describes the condition where the SV project is not working whereas case (b) illustrates the condition of the operation of the SV Project is working and the out flows through the HAD turbines are kept the same. This means that additional water volumes are taken from the reservoir to account for the consumed water volumes by the project. The water head over the turbines is reduced due to the extracted water volume. This case represents reduction on the water head over the turbines while keeping same turbine discharges. As for case c, it represents the conditions where the SV project is working and the outflows through the HAD turbines are reduced by the amount of water that the project abstracts annually 5 BCM. This means that water discharges through the turbines are reduced and the head is kept the same as the case a. Table II represents the second part of the study. This part includes six scenarios. In the first scenario the water inflow is 45 BCM and the outflow as the same. Scenarios from 2-6 represent differed inflow in five cases a, b, c, d, and e where the reservoir water level is different and the outflow through the HAD is of a constant value equal to 50.5 BCM/year. It is worthy of mentioning that the reservoir minimum water level is 165 m this value results from an accumulative inflow reduction through a number of consecutive years. This reduction results in a reduction in water head on the turbines, a matter which will affect the power generation negatively.

TABLE I
DIFFERENT STUDIED SCENARIOS
FOR THE FIRST PART

S	Annual Inflow (BCM)	Study Case annual outflows (BCM)		
		Case (a) Qz=0.	Case (b) Qz=5.5 BCM	Case (C) Qz=5.5 BCM
1	45	45	45	45 –Qz
2	50	50	50	50-Qz
3	55	55	55	55-Qz
4	60	55.5	55.5	55.5-Qz
5	65	55.5	55.5	55.5-Qz
6	70	55.5	55.5	55.5-Qz

TABLE II
DIFFERENT STUDIED SCENARIOS
FOR THE SECOND PART

S	Annual Inflow **(BCM**	Study Case Water Levels (m)				
		A	B	C	D	E
1	45	175	172	170	168	165

2	50	175	172	170	168	165
3	55	175	172	170	168	165
4	60	175	172	170	168	165
5	65	175	172	170	168	165
6	70	175	172	170	168	165

VII. The Model Results and Analysis

In the study of two different parts; ***the first part*** represents the effect of the SV Project and includes six flow scenarios, the result are shown in figures (3, 5). ***The second part*** represents the effect of multiple low inflow years on power generation, it studies the effect of different initial water levels (165 m to 175 m) for different inflow discharge (45 BCM to 70 BCM) the results are shown in figures (4, 6, 7, & 8). The results of the two parts of the study have been analyzed. The results of the 1st part are shown in table "III" where all scenarios with cases a, b, and c, are presented. Table IV illustrates the hydropower percentages resulting in cases (b) and (c) are compared with case (a).

TABLE III
SCENARIOS (1- 6) SUMMARIZED RESULTS FOR GENERATED HYDROPOWER IN FIRST PART

S	total annual generated power (Mw)		
	Case A	**Case B**	**Case C**
1	6755	6695	5917
2	7604	7544	6766
3	8451	8392	7613
4	8601	8545	7764
5	8673	8619	7835
6	8832	8781	8018

TABLE IV
SCENARIO (1-6) SUMMARIZED RESULTS FOR GENERATED HYDROPOWER IN FIRST PART

S	Annual Power Percentage (%) from case a	
	Case B	Case C
1	99.11	88.38
2	99.22	89.69
3	99.3	90.73
4	99.35	90.86
5	99.38	90.91
6	99.42	99.31

TABLE V
SCENARIO (1) SUMMARIZED RESULTS FOR GENERATED POWER FOR PART 2

S	total annual generated power (Mw)				
	A=165	B=168	C=170	D=172	E=175
1, Q=45	6196	6582	6838	7092	7471
2, Q=50	6312	6683	6930	7174	7544
3, Q=55	6422	6780	7019	7255	7616
4, Q=60	6528	6873	7104	7334	7685
5, Q=65	6629	6962	7186	7410	7752
6, Q=70	6726	7048	7263	7484	7817

TABLE VI
SCENARIO1, SUMMARIZED RESULTS FOR PERCENTAGE OF REDUCTION IN GENERATED POWER, PART 2

	percentage of generated power compared with case a			
s	case a	case b	case c	case d
1	17	11.9	8.4	5.1
2	16.3	11.4	8.1	4.9
3	15.7	10.97	7.84	4.74
4	15	10.6	7.6	4.6
5	14.5	10.2	7.3	4.4
6	13.95	9.83	7	4.3

TABLE VII
STUDY SYMBOLS

Symbol	Verification
H	Reservoir water head above a known datum. (m)
$S_a(H)$	Reservoir water surface as a function of H (m^2).
S	The volume of the reservoir storage water. (m^3)
I	Inflow in the lake (m^3/day)
O	Output of flow in the lake (m^3/day)
P	Generated hydropower (GW.h)
Q	Outflow discharge through the turbines (m^3/day), and it is the discharge for reservoir.
H_1	the head acting on the turbines (m).
Z	Q for South Valley Project (m3/day)
O=Q	Because all out flow discharges passing through turbines this is clear from actual data.
S	Scenarios
m	million

It can be concluded from these results that in case (b) the annual hydropower reduction percentages are ranging from 0.58 % for scenario (6) to 0.89 % for scenario (1) while case (c) annual hydropower reduction percentages are ranging from 8.69 % for scenario (6) to 11.62% for scenario (1). This means that case (b) has a minor effect of about 1% on the generated hydropower while case (c) has a higher effect of about 10 % on the generated hydropower.

The 2nd part results are summarized in table "V" for all scenarios with five cases (A), (B), (C), (D), and (E). Table VI illustrates the hydropower percentage resulting in cases a, b, c, d, and e. it can be concluded from these results.

The effect of (SV) project operation on the hydropower may cause a reduction of 10% of the annual generated hydropower. In case the abstracted amount of water by the project can not be compensated for this is on the one hand, on the other, the reduction in hydropower may drop to 1% in case of discharge compensation. On the other hand, discharging this amount will have a major effect on the stored reservoir water. The reservoir level will drop and the head over the turbines will drop accordingly. The effect of this will be significant major through a series of continuous low inflow years. From the results of 2nd part in the study the reduction of generated power will reach about 17% of the all annual hydropower generated, where the reduction will occur due to the reduction of water head on turbines with a constant discharge passing through turbines.

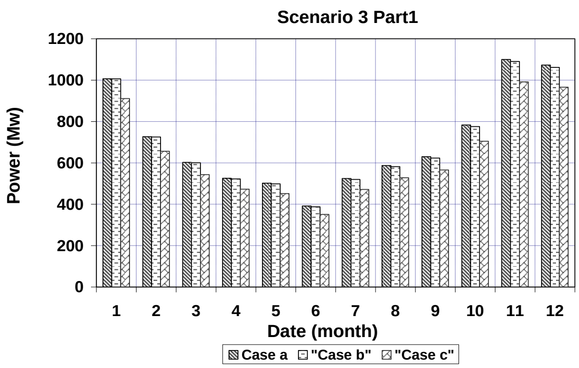

Fig. 4. Generated Power with part1

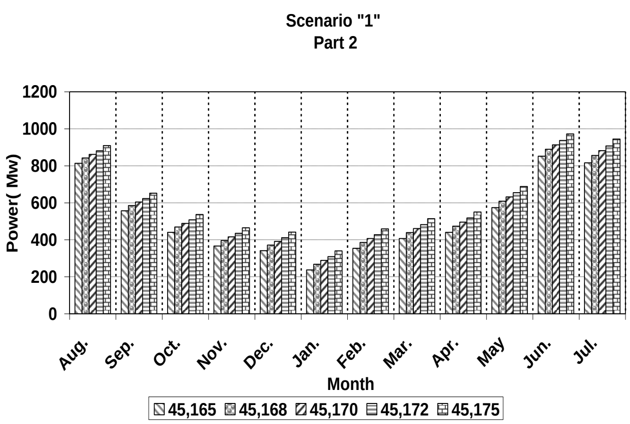

Fig. 5. Power Generation through months using Scenario 1, Part 2

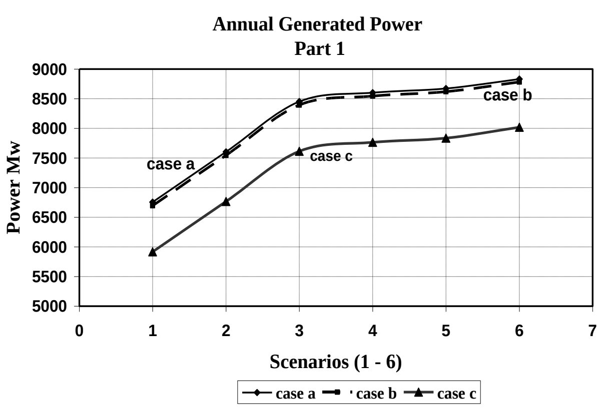

Fig. 6 Generated Power, , represented three cases, in part 1

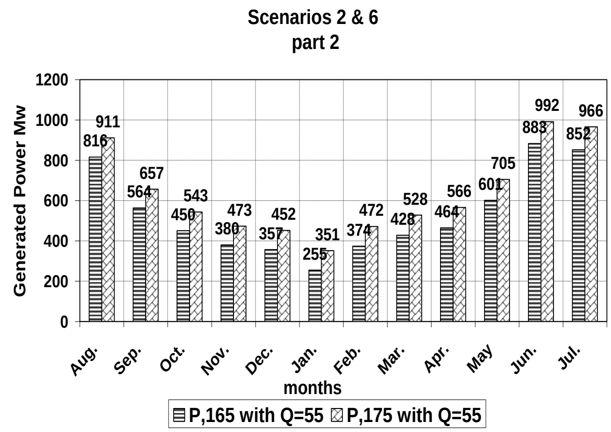

Fig. 7. Power Generation through months for part 2

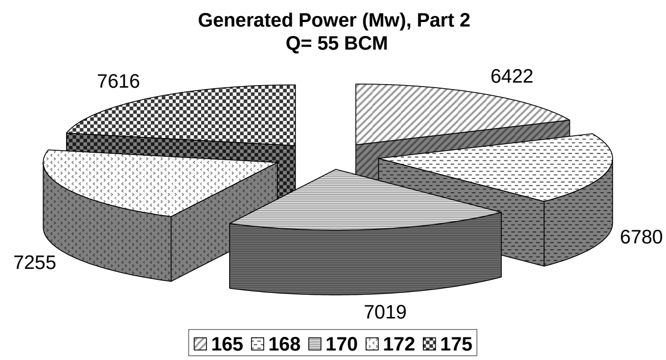

Fig .8. Generation Power at normal Operation from five cases in part II

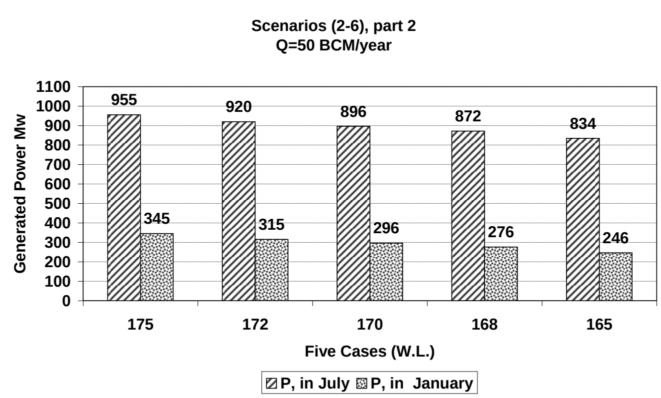

Fig. 9. Generated Power in Scenario 2, part 2

VIII. Conclusions

- The South Valley Project and consecutive low inflow year's effect on the Egyptian generated hydropower are studied during this research.
- The developed mathematical model for this analysis is based on mass balance hydrologic routing equations, multi-variant regression for hydropower, discharges, and head relationships.
- This analysis shows that the effect of SV project operation on the hydropower may reach about a relatively high value of 10% if we do not discharge more water through the turbines to compensate for the project consumption while it can drop to about only 1% if we do discharge more water (about 5 BCM/year) through the turbines to compensate for the project consumption.
- Also, in this analysis, discharging this amount will have some side effects on the generated hydropower since it drops the water head over the turbines especially for a series of low inflow years.
- On the other hand, the reduction of head on the turbines for a series of low inflow years has more effect on the power generation than the reduction in discharge. The reduction reach to 17%.
- The Egyptian government should make up arrangement for this problem especially in the current economic conditions.

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