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Project Title: OPTIMIZATION OF TARBELA DAM RULE CURVE FOR FLOOD CONTROL AND MAXIMUM POWER GENERATION

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BE Civil Engineering Project titled

OPTIMIZATION OF TARBELA DAM RULE CURVE FOR FLOOD CONTROL AND MAXIMUM POWER GENERATION

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Has been accepted towards the partial fulfillment of the requirements for

8th semester part for the BE Civil Engineering Degree

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Dedication

This Thesis is dedicated to my beloved

Parents

&

Teachers

ACKNOWLEDGEMENT

First of all, thanks to Allah for his blessings, which has enabled us to complete our part related to 8th semester. There are number of people without whom this might not have been written, and to whom we are greatly obliged.

Last but not the least, our deepest gratitude goes to our beloved parents and project advisor who have always been a symbol of encouragement and inspiration to us. To those, who in some way contributed in this research, your kindness means a lot to us. Thank you very much.

Hamza Ahmed

Abstract

Rule curve is a criteria guideline indicating the limiting rates of the storage and release function of a dam. An optimal rule curve synchronizing with the hydrological condition of the area is necessary for efficient dam operation. To maximize the objective function of a dam such as irrigation, flood control and power generation, a dam must be operated in a systematic cycle throughout the year in order to provide maximum power production, minimal spill water, minimum water shortage in dry seasons as well as it should be capable enough to minimize the losses caused by floods by operating efficiently with early flood warning system. This is achieved when the rule curve is optimized to the highest possible level. In this project we have generated an optimized rule curve for Tarbela Dam using different Dam Parameters with the help of MATLAB specifically for flood control and maximum power generation. We have analyzed different floods of low, medium and high intensity and carried out a comparative study between the optimized and actual rule curves of Tarbela Dam. The results clearly indicate that optimized rule curve lead to considerable reduction in flood losses vis-à-vis conservation of water for optimal power generation and irrigation.

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1 Chapter 1: Introduction

1.1 Background

Floods have always been catastrophic for Pakistan. Floods have caused billions of dollars loss to the country’s economy. The present condition of Pakistan’s economy is unable to sustain the heavy destructions caused by these natural disasters. To prevent these floods, dams were created to control the violent floods but unfortunately, we were unable to generate an optimized strategy to operate these dams so that the losses are minimized to a maximum possible level and outputs such as irrigation and power are maximized to highest potential of the dams using all the available resources.

Floods have wreaked havoc for years leaving millions of people homeless and making thousands of acres of land arable. Pakistan had been prone to flood since its creation and it has become a catastrophe that was seemed to be uncontrollable. In addition, global warming and the ever-increasing climate change are the main reason for the catastrophic flood losses and its frequency has been increasing ever since. Pakistan has faced number of serious flood events.

The increasing climate changes in the recent years have left the coastal and urban communities more vulnerable and flooding has increased more than before. Flood damages are increased mainly because of the increase of the flow of main rivers and flash floods have greatly flooded the Secondary and Tertiary Rivers or Hills. Riverine flooding, flash floods in Secondary and Affluent Rivers/ Water that directs from the hills, Coastal flooding which is due to typhoons and City/Town flooding due to continuous downpour and undesirable storm evacuation provisions, these all pile up to cause major flood damages. The history of flood and losses related to floods are enlisted in the table below.(Ministry-of-Water-Resource-Pakistan 2017)

Table 1: History of floods and losses

HISTORICAL MAJOR FLOOD EVENTS EXPERIENCED IN PAKISTAN

Sr. No.	Year	Direct losses (US$ million) @ 1US$= PKR 86	Lost lives (No)	Affected villages (No)	Flooded area (Sq-km)
1	1950	488	2,190	10,000	17,920
2	1955	378	679	6,945	20,480
3	1956	318	160	11,609	74,406
4	1957	301	83	4,498	16,003
5	1959	234	88	3,902	10,424
6	1973	5134	474	9,719	41,472
7	1975	684	126	8,628	34,931
8	1976	3485	425	18,390	81,920
9	1977	338	848	2,185	4,657
10	1978	2227	393	9,199	30,597
11	1981	299	82	2,071	4,191
12	1983	135	39	643	1,882
13	1984	75	42	251	1,093
14	1988	858	508	100	6,144
15	1992	3010	1,008	13,208	38,758
16	1994	843	431	1,622	5,568
17	1995	376	591	6,852	16,686
18	2010	10,000 @ 1US$= PKR 86	1,985	17,553	160,000
19	2011	3730* @ 1US$= PKR 94	516	38,700	27,581
20	2012	2640** @ 1US$= PKR 95	571	14,159	4,746
21	2013	2,000^ @ 1US$= PKR 98	333	8,297	4,483
22	2014	440^^ @ 1US$= PKR 100.89	367	4,065	9,779
23	2015	170[#] @ 1US$= PKR 105.00	238	4,634	2,877
24	**2016**	**6**[#] @ 1US$= PKR 104.81	**153**	**43**	-
25	**2017**	**-**	**172**[!]	**-**	-
Total		**38,171**	**12,502**	**197,273**	**616,598**

* Economic Survey of Pakistan 2011-12

** Thomson Reuters Foundation (http://www.trust.org/item/20130909134725-rm708/)(Agriculture sector)

^^ Economic Survey of Pakistan (2014-15)

Based on PIDs & FLA's interim reports related to irrigation, drainage & flood protection infrastructure only

! Source: NDMA

Referring the 6 years of the past, the overall damages caused by floods have reached a mammoth of US$ 38.171 Billion taking count the lives that have been lost and rise up-to 12,502 people and out of these losses 50% direct losses have been ascribed to major floods in the recent six years after 2010.(Ministry-of-Water-Resource-Pakistan 2017)

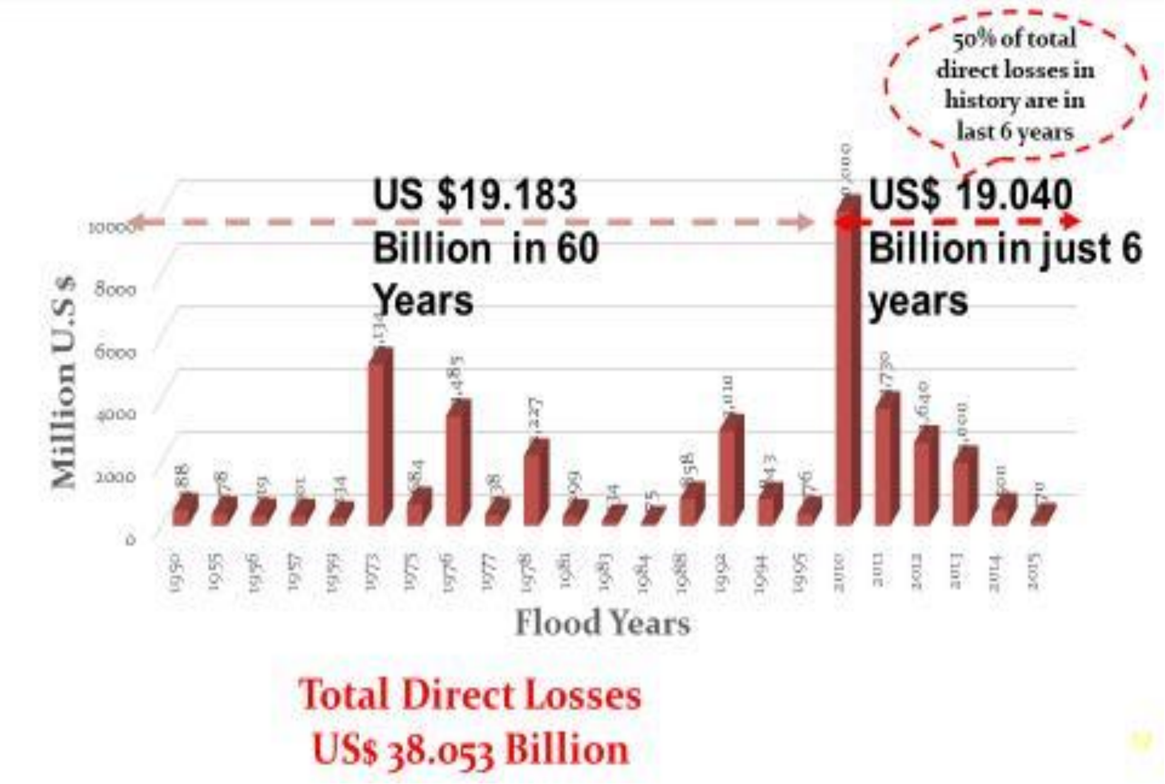


Figure 1: Losses to the economy of Pakistan with respect to the years.

1.2 Integrated Approach in Flood Management

Flood management has played a key role to minimize the catastrophic effects of flood and has protected many people along their socio-economic daily activities in flood plains as they faced the wrath of flood. However, in the past flood risks have been minimized by the structural measures. But when we consider the strategies, the use of structure means alters the environment of mother-nature and can cause massive harm to habitat, bio-diversity and greenhouse output.

Moreover, the structural means are vulnerable to failing when extra-ordinary or unpredicted event occurs. Besides, environmental deprivation is likely to hamper human routine, life, food & health security. Therefore, we there was need of concept change from orthodox flood management to integrated flood management.

Integrated Flood Management (IFM) works under the Integrated Water Resource Management (IWRM) and provides a concept that considers the human security and sustainable development against flood risks. This overall approach has led to flood management which plays a key-role in sustainable development and reduction of poverty. IFM helps us to reduce the loss of life and land from flood events and focus to maximize the overall benefits derived from flood plains.

1.3 Tarbela Reservoir

Tarbela is the largest earthen dam and also the largest by constructional mass. Constructed on the Indus River in the districts Swabi and Haripur of province Khyber Pakhtun Khwa (KPK), the dam is about 30 km and 105 Km from the cities of Swabi and Islamabad, respectively.

The dam has a head of 143 meters. It helps to form the Tarbela Reservoir, having surface area of approximately 250 square kilometers. The construction of the dam was completed in 1976 with the main purpose to store water from Indus River which will help in the Irrigation, minimization of flood and production of hydroelectric power.

However, it is primarily used in the generation of electricity. Tarbela dam was constructed with a capacity of 3478 MW.. In the past, a lot of floods have hit Tarbela dam in which it failed to serve its purpose to control the destructive waters. These floods are the sole reason of our study on this dam.

1.4 What is a Rule Curve?

Water resources issues are becoming more and more critical day by day and their prime cause is the change in global climate and use of land which has significantly increased due to overall population increment and growth in economy. However, for water resources management we require demand and supply management mechanism. In supply management we basically improve the efficiency of reservoir operation and this helps us without any physical changes in reservoir.

Normally, it’s the integral function of all objective functions selected in order of their preference to help water discharge from the reservoir considering the downstream requirements and need for long term purposes.

Rule curve is a criteria guideline indicating the limiting rates of the storage and release function of a dam. An optimal rule curve synchronizing with the hydrological condition of the area is necessary for efficient dam operation. To maximize the objective function of a dam such as irrigation, flood control and power generation, a dam must be operated in a systematic cycle throughout the year in order to provide maximum power production, minimal spill water, minimum water shortage in dry seasons as well as it should be capable enough to minimize the losses caused by floods by operating efficiently with early flood warning system. This is achieved when the rule curve is optimized to the highest possible level.

The rule curves have its purposes into two main areas: (Kangrang, Prasanchum et al. 2018)

- **Firstly,** Changes in the conditions of hydrology due to the variation caused by the climate change such as increased/decreased inflow coming in the reservoir and the precipitation over the catchment area
- **Secondly,** the need of water in the downstream portion of the dam for economic, engineering and domestic purposes is changing because of increasing domestic demand & agricultural growth.

The reservoir should be managed in such a way that the water to be released can be used for various domestic uses with the application of the planned technique till there is no change in the parameters from the original. However, if there is some difference in the values in the future than the planning phase, the efficiency of the rule curve may change.

1.4.1 Assumptions:

The assumptions that the rule curve follows, depend on sustaining the head of the catchment to cater-for the changes in hydrological conditions. Furthermore, downriver rule curve suppositions also depend on sustaining the head of the catchment to manage the variations in hydrological statistics. Downriver water allowance is based on the interval of time, which is usually 1 year. The primary objective is to minimize the risk of water shortages and floods in the reservoir basin and the low-lying areas. In the dry season it is necessary to maintain water head in order to minimize risk of water level falling below the minimum storage required. On the contrary water should be released from reservoir during rainy season to avoid overflow and to cater the extra inflow to reservoir. To achieve this goal the rule curves of reservoir are optimized to provide optimal solution for long-term operation.

1.5 Problem Statement:

The topographical landscape of Pakistan suggests that our country is prone to floods and other natural calamities. These floods have devastating effects and have caused loss of billions of rupees and precious lives. The reason behind the catastrophic effect of these floods is not the intensity but the lack of awareness about water resource management. Rule curve optimization is one of the strategical measures of managing the water entering the reservoir. Tarbela Dam being the largest reservoir in Pakistan does not have adequate management for its water release. Therefore, the prime concern of this study is to optimize the rule curve which will help limit the floods in Tarbela Dam.

1.6 Objective of study

There are 2 principal objectives of this thesis:

- To control the floods at maximum level.
- To use flood water for maximum power generation

1.7 Scope of research

The scope of this study is to mitigate the devastating effects of floods to the existing assets of the country and to reduce these risks in case of such floods in future by not releasing the flood water in an uncontrolled manner. This projects opts to the maintenance of a flood emergency cushion for forecasted floods and not only releasing this water in an organized mechanism with a discharge below flood level but also to further enhance the benefits, using the flood water for power generation and irrigation when the dam inflows are low and water consumption and requirements are high.

2 Chapter 2: Literature Review

2.1 Flood Dynamics in Pakistan

Pakistan is located between the latitudes of 24N and 36N. And has a population of around 207.774 million. The area that Pakistan encompasses is about 796000-kilometer square. It is a land of vast mountains with ever high peaks ranging up-to a height of 28,000 feet and rivers with peak flood discharge of million (10^6) cusecs. The Himalayan Mountain Ranges bounds the Tarbela Dam from the North. The northern mountains have an influence on the rainfall of Pakistan. The northern mountain barrier by intercepting the monsoon winds influences the rainfall pattern in Pakistan.

The river Indus along with its tributaries i.e. Sutlej, Beas, Ravi, Chenab and Swat, Kabul besides other are secondary and tertiary rivers creating a great river system which are feed by the snow melting and concentrated rains in the catchment areas. The rivers flowing in Pakistan make it a backbone to the economy of Pakistan. These rivers can be flooded thereby causing massive destruction across the country causing mammoth damages in the Private and Public sector and loss of hundreds of lives. Peak Floods alongside landslides and glacial movements can sometimes be a reason for the formation of natural dams that are temporary of nature.

Pakistan has had very diversified type of fluctuating climate. It has a very hot and very dry climate but there have been great variations in them for some last years. The districts and urban hubs situated near the river banks are more vulnerable to confront different types of floods i.e. Flash Floods, Riverine flood especially in Punjab and Sindh. These floods cause massive damages and losses to acres of land, cultivated crop making it arable and this had a devastating effect to the monetary loss of billions to the economy.

The riverine floods are caused due to the perennial rains in the river catchments during monsoon, these rains can sometimes be aided by flows due snow melt. Monsoon that originates in the Bay of Bengal causes concentrated heavy rainfalls at the base of the gradual increasing Himalayas, these heavy downpours generates catastrophic floods in rivers and their affluent. Sometimes there can be high floods in the rivers which can be a result of the natural dams that are formed temporarily and by landslides or glacial movements with their following collapse.

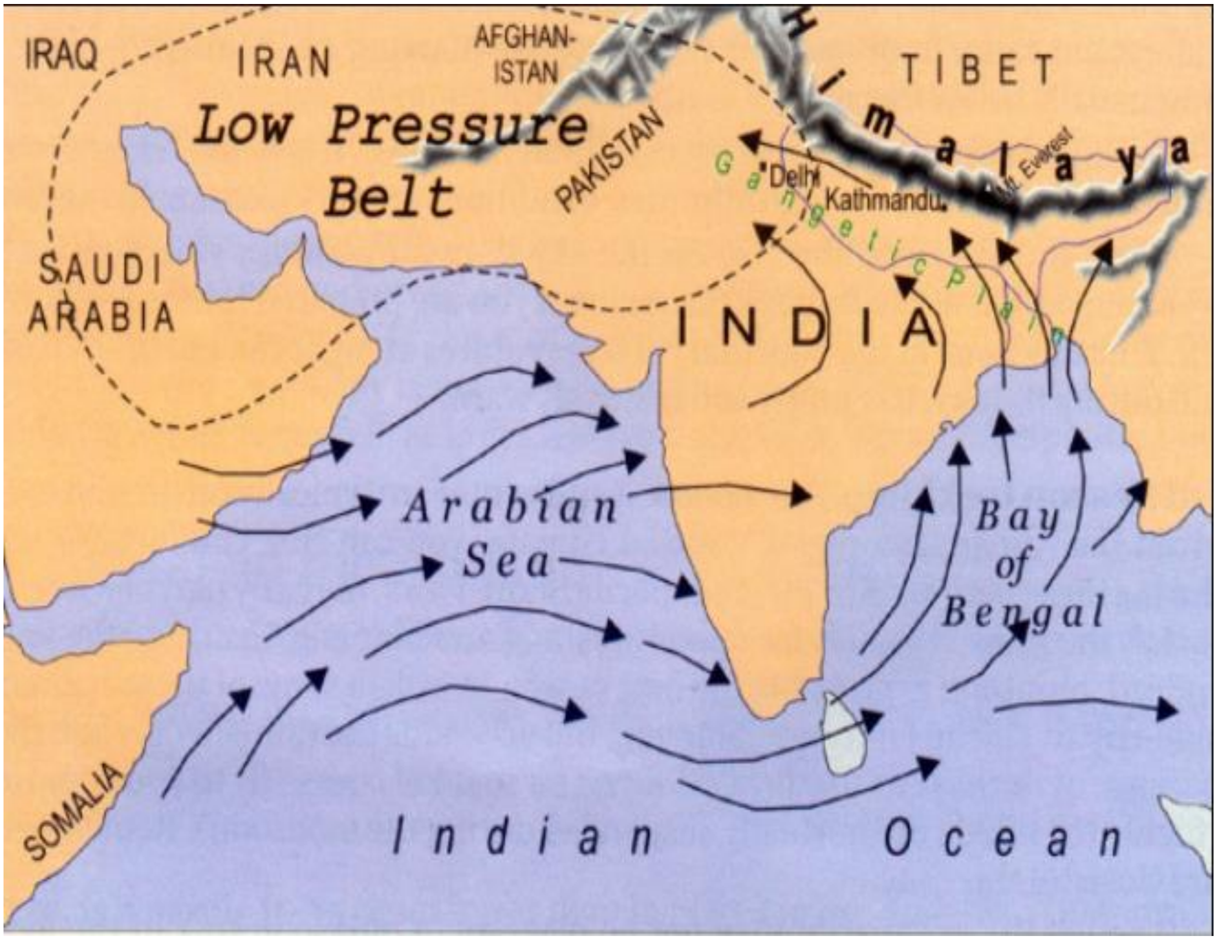


Figure 2 Monsoon Entering Pakistan

One of the mammoth hazards for Pakistan is the flooding of the Indus River and their affluent. Floods tend to usually occur during the Months of June till October (summer season).Thereby, majorly affected are the Kharif crops. However, there are some cases in which the flooded lands do not dry up and cause subsequent loss to the Rabi crops.

Major rivers i.e. Indus, Chenab, Ravi, Sutlej and Secondary Rivers that are Kabul, Swat and Neelum etc. cause flooding of low-lying areas adjoining the beds harming irrigation and communication networks, following land erosion alongside the river banks. Punjab and Khyber Pakhtunkhwa come in the upper plains of Indus basin, the inundation of water over the banks will turn back uniting the main river channels again.

However, Sindh comes in the lower plains where River Indus is flowing at greater elevation than lands adjoining it. Thereby we have bounded the rivers with embankments along both the sides. If flood breaches the embankments, then water overflows and does not return to the river again. This results in greater time of flooding and land under water resulting in severe damages to the adjoining bodies, cultivated crops and infrastructure in the overall terrain whether private or public.

Sometimes, there can be a breach to the embankment by the floods due to their exceptionally high level. Barrages of Punjab and Sindh were remodeled and rehabilitated to standard requirements, based on return of past 100 years. So far, the Kalabagh Barrage has been rehabilitated and Head-Soleimani Barrage is almost completed. Panjnad Barrage aims to be completed by March of 2019 for its capacity enhancement while Khanki-Trimmu and Baloki barrages are near the finishing stages. The capacity of Guddu Barrage was reduced by 1,500,000 cusecs to 900,000 cusecs. Sukkur Barrage will however be rehabilitated on the basis of its capacity to 1,200,000 cusecs. Kotri Barrage does not require rehabilitation as it was rehabilitated 1988.(Ministry-of-Water-Resource-Pakistan 2017)

2.1.1 Impact of Global Warming & Climate Change on Flood Management

The entire world is facing havoc due to change in climate. The largely affected areas due to change in climate will be of third world countries, Pakistan being one of them. And since Pakistan is on the verge of developing, so it is more vulnerable to the effects of this change. Current studies indicate an increase in the number of glaciers that are melting in South Asia which might result in devastating floods in our country and neighboring territories in the near future. Our economy is already facing immense losses because of damages and abasement to Mother Nature.

Pakistan lies in the global list of top ten countries facing regular and vigorous variations in climatic events like floods, dry spells, typhoons, perennial showers, record breaking temperatures, etc. Because of the increasing concentrations of CO_2 and gases like chlorofluorocarbons in the environment, the average global temperature is constantly increasing. The study for last century indicated an increase of 0.6 degree centigrade and current studies anticipate an increase of 1.0^o C to 4.0^o C towards the end of this century.(Ministry-of-Water-Resource-Pakistan 2017)

The current extreme climatic disasters recorded for our country are the floods wrecking diverse regions in the monsoon season. From 2010 onwards, every year Pakistan witnessed floods which resulted in immense destruction of valuable property and precious lives. Such events are causing serious threats to the water security of the country. The flow to the Indus River system will also be affected by the temperature change in the northern region of country.

2.1.2 The Challenges of Flood Management

Currently the biggest environmental challenge for Pakistan is the climate change causing disastrous situations such as floods, dry spells, hunger, destitution, agricultural land degradation, deforestation and desertification. The alarming future constraints include relocation of monsoon precipitation zone from North-east to North-west, heavy monsoon precipitation in little period of time, variability in monsoon behavior and uncertain flash floods. What needs to be done is to inform masses about these natural calamities and their happenings, so they are able to take mitigating and preventative measures

From past events it has been clearly observed that the adopted practices of flood management are not as worthy as they might seem to be. So, it is essential to devise new plans to subsist more effectively with the dangers of floods and variations in climate change. The exponential increase in population and elevated construction activities in floodplains makes them more vulnerable to the risk of flooding. In developing countries where agriculture is the backbone of economy, floodplains are their major asset directly relating to their food and livelihood security(Tariq and Van de Giesen 2012).

2.1.3 2010 Flood in Pakistan

The flood of 2010 appeared to be the most devastating flood of all times in Pakistan causing a damage of enormous 43 Billion US$ to the national economy in terms of houses, crops, fertile lands, property, important buildings and government installations.

It carried a peak inflow 781000 cubic feet per second (ft^3/sec). Obviously, the dam wasn’t designed for such heavy inflows for longer times, so it failed to perform, and it caused massive inundation in the suburbs thereby, causing a massive loss to the economy and land making it arable. It affected

Swabi , Nowshera and Swat districts in Khyber Pakhtunkhwa (KPK). It affected the Indus river basin and almost 20 percent of Pakistan total land area was affected badly while the death toll was about 2000. Floods also resulted in destruction of property, infrastructure loss, and livestock. (Ministry-of-Water-Resource-Pakistan 2010)

Tarbela dam was designed to carry a net inflow of 240000 cusecs. But 2010 flood carried a precipitation value of 10.8 inches over a 24-hour period, which was more than an average annual precipitation of 3.17 inch. It was also noted that 2010 had a massive rainfall of 13 inches throughout the country thereby wreaked havoc of flood.

The 2010 flood caused a serious blow to the power infrastructure of Pakistan. More than 9,000 transformers and lines for power transmission, power houses and feeders in various areas were damaged by the flood. One of the main power houses namely Jinnah Hydro Power was overwhelmed by flood water resulting in power shortage of 3.135 gigawatts.

The flood water resulted in deficiency of clean drinking water and proper sanitation due to which different life-threatening diseases such as gastroenteritis, diarrhea, cholera etc. commonly known as Black Death diseases inhibited the flood-hit areas making flood victims vulnerable to new risks. The first incident of cholera was recorded in Swat District on 14th August thereby leaving millions of victims vulnerable. At this stage they were already infected by gastroenteritis and severe diarrhea. Furthermore, cases of malaria outbreak were also reported.

A report from International Red Cross depicted unexploded explosives such as landmines, artillery shells, and grenades etc. were carried away downstream by the flood water from military camps in Azad Kashmir and FATA and dispersed in lower regions leaving IDPs more endangered. Surveys by United Nations approximated about 800,000 people were unreachable and the only source for aiding them was through air transport. More than 35 helicopters were required to transport necessary supplies to increasing number of victims out of which many were those sheltering in mountainous northwest region where the road infrastructure had been swept away by flood water.(IRFC 2010)

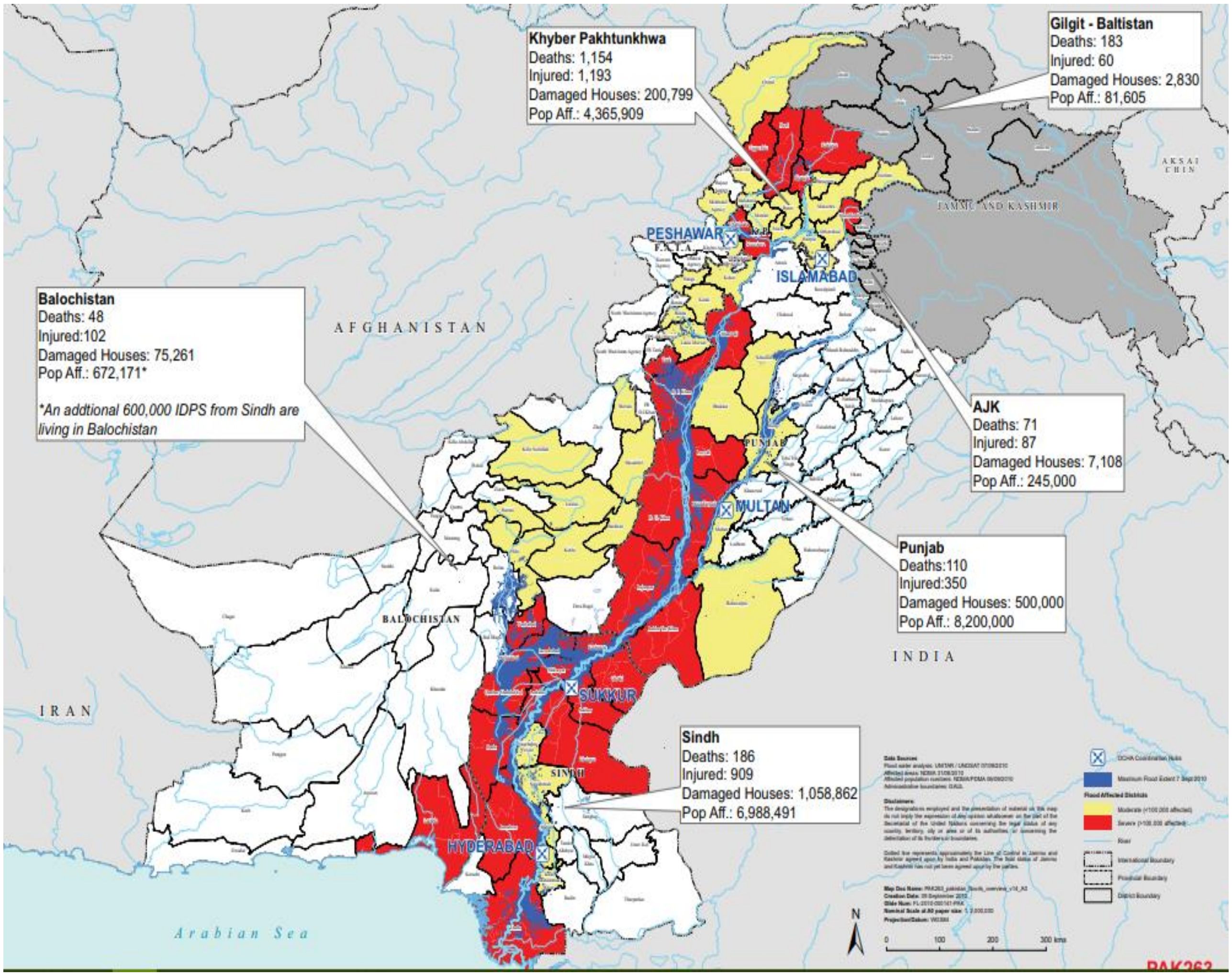


Figure 3 2010 Flood losses(OCHA 2010)

2.2 Hydropower

Hydro-Electricity is production of electric power using the force produced by water falling under the action of gravity. Potential head present in the reservoir is the reason we have hydroelectric power that actually is running a turbine and generator. The Power that is generated depends upon the discharge and the change in head between the reservoir and discharge. This difference of elevation is referred as head.

The quantity of power generated related directly to the head of water. Water to the turbine is taken through the large pipe called penstock. This water owing to its potential energy will rotate the turbine blades which in turn will rotate the turbine generator shaft. The rotation of the shaft generates power in the form of electricity which is then supplied by means of power lines.(Kishor, Saini et al. 2007)

A generating station from which water head is usually converted in the form of potential energy to secure definite amount of Power is called Hydro Electric Power Station.

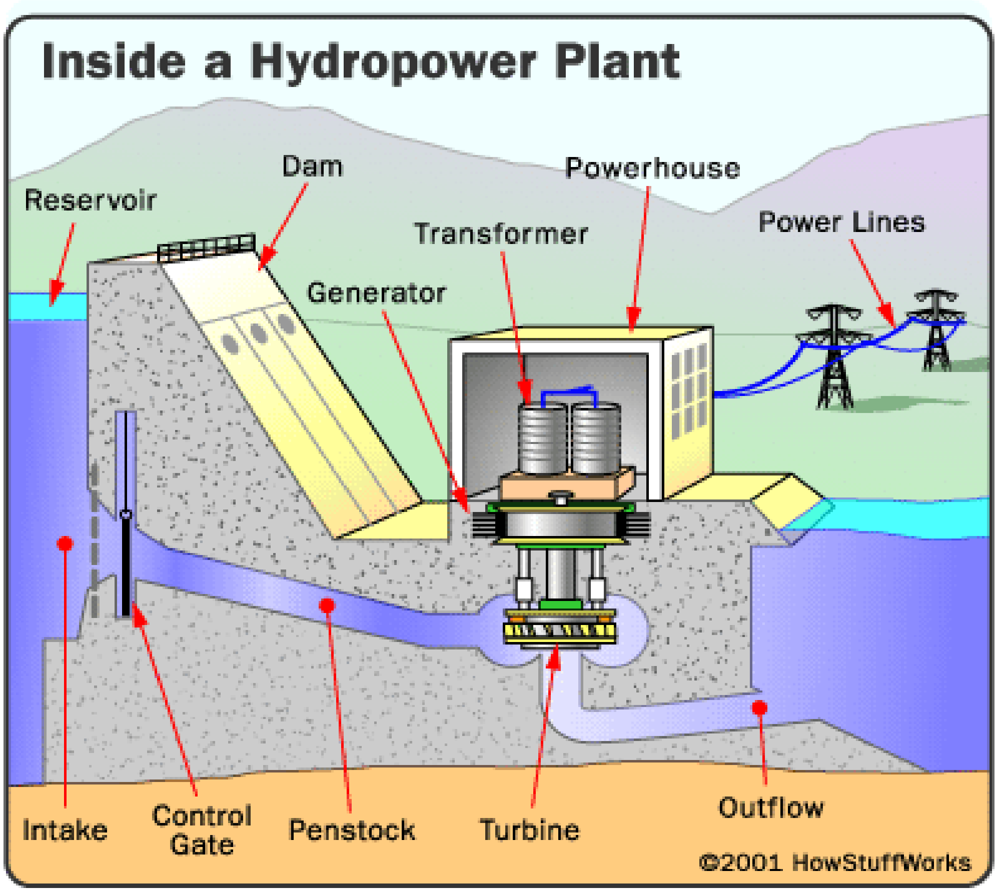
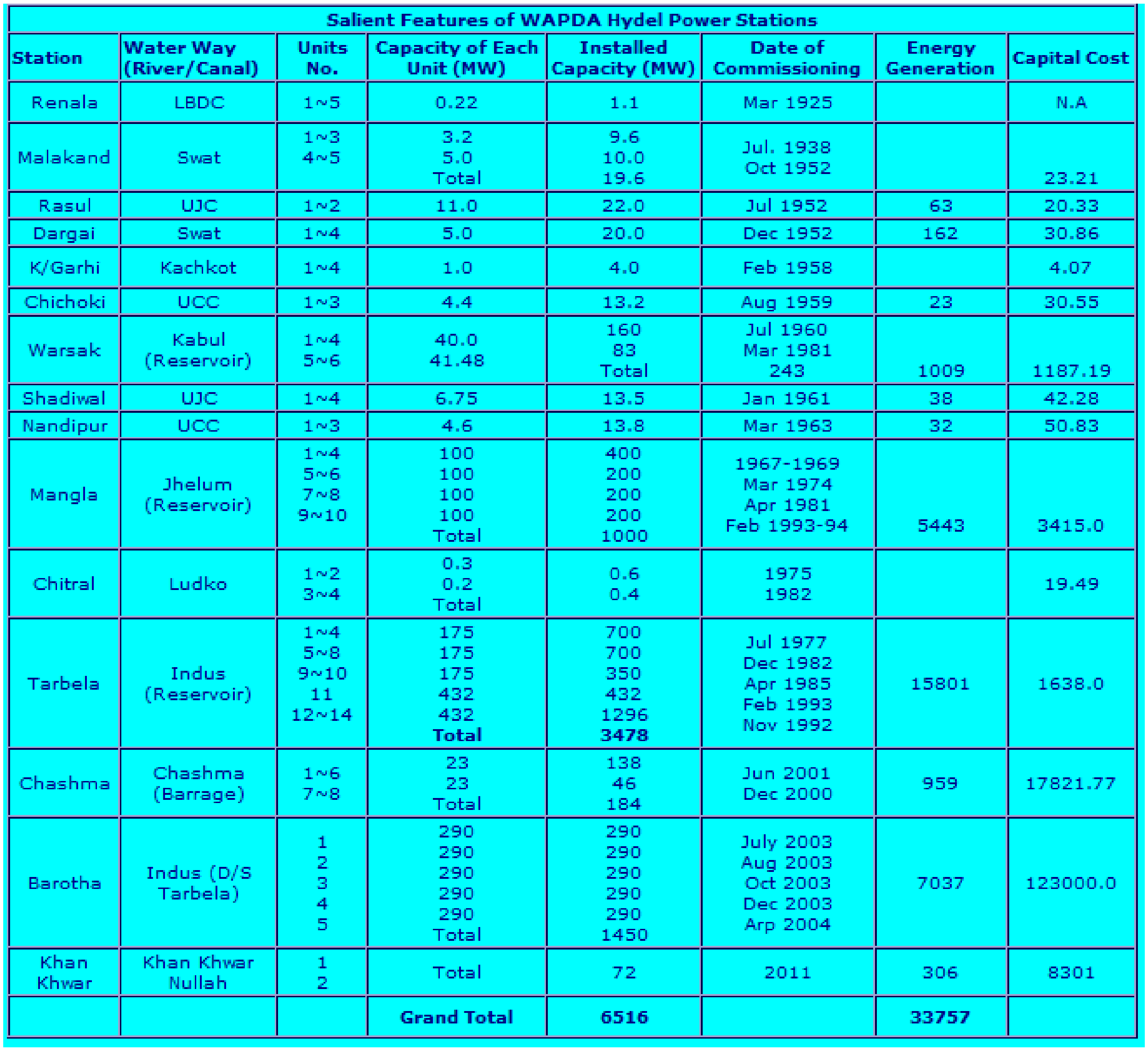


Figure 4 Hydropower Plant

2.2.1 Generation of Hydropower in Pakistan

Pakistan has always had a good potential for generating electricity from water. Pakistan does have a potential of 40,000 MW out of which economic hydro-potential can be met for 20,000MW. The overall capacity for the 13 hydro-power station is 6444MW which is 35.88% of the total generating Capacity of WAPDA. One of the main power sources of our country is Hydroelectric power, but sporadic dry spells tend to decrease hydropower generation. WAPDA is responsible for country’s major hydroelectric power plants as shown in table below.(Shakeel 2012)

Table 2 Salient Features of WAPDA Hydro Stations



Salient Features of WAPDA Hydel Power Stations

Station	Water Way (River/Canal)	Units No.	Capacity of Each Unit (MW)	Installed Capacity (MW)	Date of Commissioning	Energy Generation	Capital Cost
Renala	LBDC	1~5	0.22	1.1	Mar 1925		N.A
Malakand	Swat	1~3 4~5	3.2 5.0 Total	9.6 10.0 19.6	Jul. 1938 Oct 1952		23.21
Rasul	UJC	1~2	11.0	22.0	Jul 1952	63	20.33
Dargai	Swat	1~4	5.0	20.0	Dec 1952	162	30.86
K/Garhi	Kachkot	1~4	1.0	4.0	Feb 1958		4.07
Chichoki	UCC	1~3	4.4	13.2	Aug 1959	23	30.55
Warsak	Kabul (Reservoir)	1~4 5~6	40.0 41.48	160 83 Total	Jul 1960 Mar 1981 243	1009	1187.19
Shadiwal	UJC	1~4	6.75	13.5	Jan 1961	38	42.28
Nandipur	UCC	1~3	4.6	13.8	Mar 1963	32	50.83
Mangla	Jhelum (Reservoir)	1~4 5~6 7~8 9~10	100 100 100 100 Total	400 200 200 200 1000	1967-1969 Mar 1974 Apr 1981 Feb 1993-94	5443	3415.0
Chitral	Ludko	1~2 3~4	0.3 0.2 Total	0.6 0.4	1975 1982		19.49
Tarbela	Indus (Reservoir)	1~4 5~8 9~10 11 12~14	175 175 175 432 432 **Total**	700 700 350 432 1296 **3478**	Jul 1977 Dec 1982 Apr 1985 Feb 1993 Nov 1992	15801	1638.0
Chashma	Chashma (Barrage)	1~6 7~8	23 23 Total	138 46 184	Jun 2001 Dec 2000	959	17821.77
Barotha	Indus (D/S Tarbela)	1 2 3 4 5	290 290 290 290 290 Total	290 290 290 290 290 1450	July 2003 Aug 2003 Oct 2003 Dec 2003 Arp 2004	7037	123000.0
Khan Khwar	Khan Khwar Nullah	1 2	Total	72	2011	306	8301
			Grand Total	**6516**		**33757**	

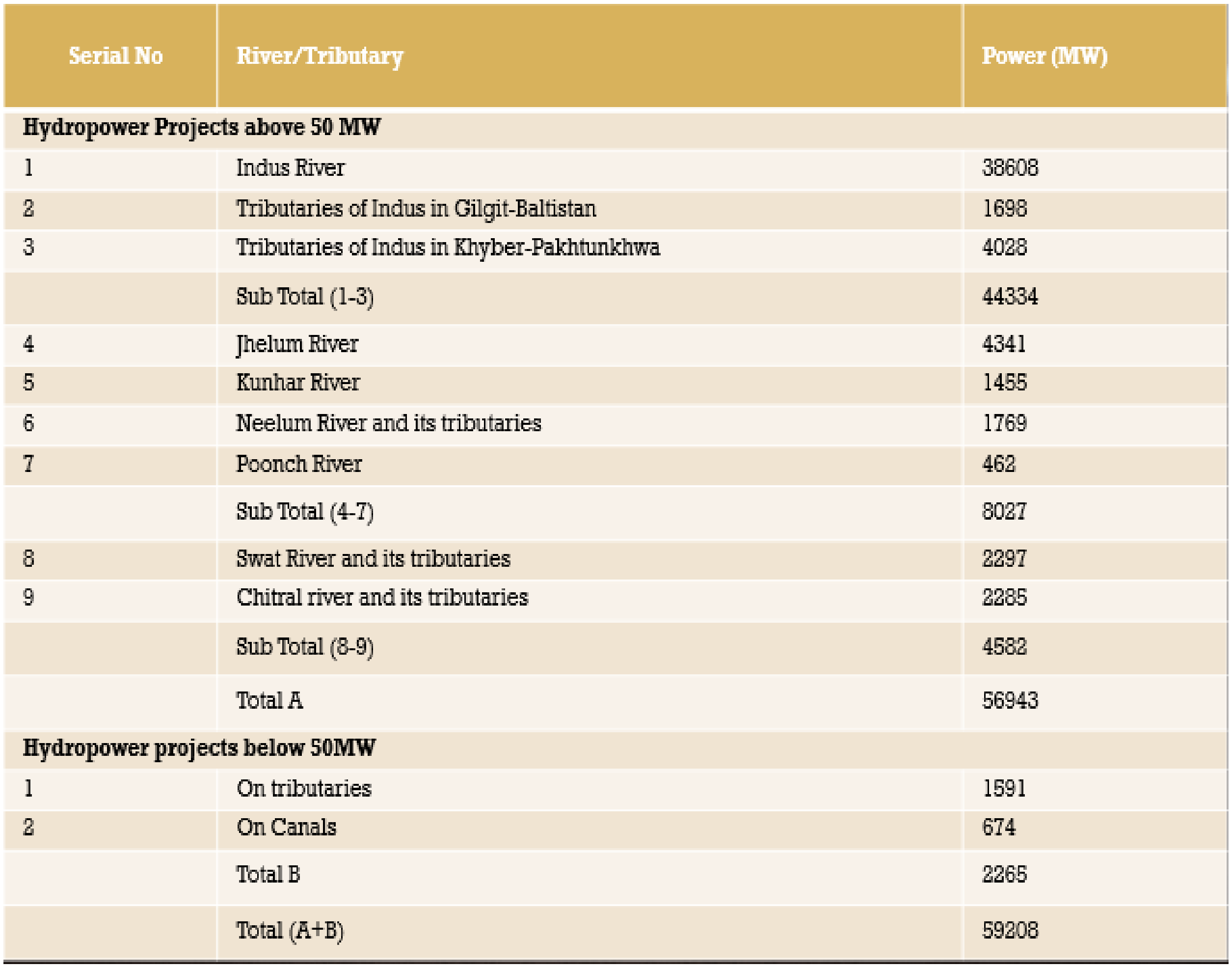
2.2.2 Potential for Pakistan’s Hydro Energy:

This country by the grace of Almighty Allah has been gifted with sufficient sources of water out of which Pakistan could only tap 13% of it.

The hydro energy generation in our country reaches 100,000 Mega Watt with determined sites of 59000 Mega Watt.

Hydropower potential is mainly relying on the hydrological changes and the requirement for irrigation. The catchment elevations are comparatively low during early summer, so the turbines have to be operated for comparatively lower heads resulting in lower electricity generation. In Monsoon season we have our dams at maximum levels thereby we can attain maximum production of power. For the months of December till February, the agricultural demands are very low comparatively for this reason very low power output is generated.

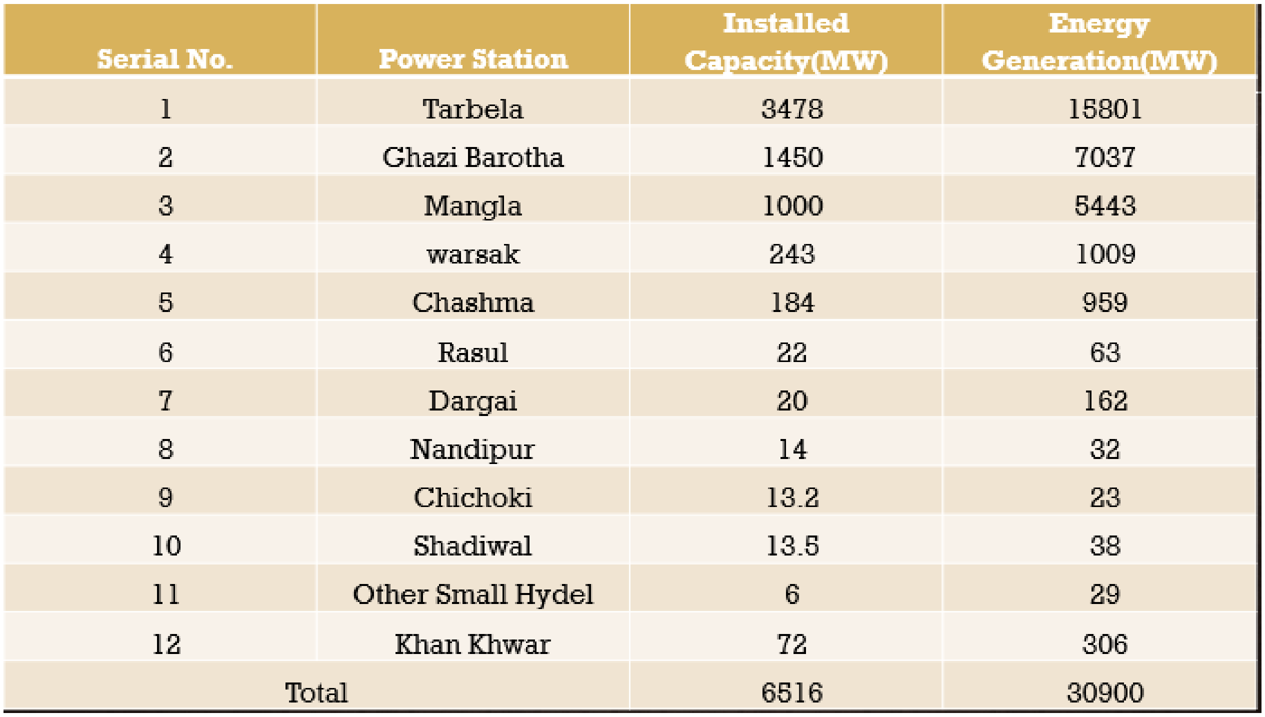
Table 3 Hydro power Potential River-wise(WAPDA 2011)



Serial No	River/Tributary	Power (MW)
Hydropower Projects above 50 MW		
1	Indus River	38608
2	Tributaries of Indus in Gilgit-Baltistan	1698
3	Tributaries of Indus in Khyber-Pakhtunkhwa	4028
	Sub Total (1-3)	44334
4	Jhelum River	4341
5	Kunhar River	1455
6	Neelum River and its tributaries	1769
7	Poonch River	462
	Sub Total (4-7)	8027
8	Swat River and its tributaries	2297
9	Chitral river and its tributaries	2285
	Sub Total (8-9)	4582
	Total A	56943
Hydropower projects below 50MW		
1	On tributaries	1591
2	On Canals	674
	Total B	2265
	Total (A+B)	59208

This table represents the hydro power generation capacity of the major rivers of Pakistan and their tributaries. Our area of concern lies in Indus River and the land scape it covers. From the table it can be observed that the power generation potential of Indus River is 38608 MW but we are flushing almost 85% of its water into sea without using its potential. A serious consideration of this subject is required and immediate actions are needed. If we use the complete potential of the Indus River alone, it can solve our present energy crisis and will reduce the electricity cost by at least 70%. This is indeed a blessing for or country. And if the power generation potential of all the rivers is used we will be having no electricity shortfall at least for next 50 years.

Table 4 Hydropower Stations In operation (WAPDA 2011)



Serial No.	Power Station	Installed Capacity(MW)	Energy Generation(MW)
1	Tarbela	3478	15801
2	Ghazi Barotha	1450	7037
3	Mangla	1000	5443
4	warsak	243	1009
5	Chashma	184	959
6	Rasul	22	63
7	Dargai	20	162
8	Nandipur	14	32
9	Chichoki	13.2	23
10	Shadiwal	13.5	38
11	Other Small Hydel	6	29
12	Khan Khwar	72	306
Total		6516	30900

This table shows the current production of hydro power by all the hydropower projects in Pakistan making a total of 6516 MW. In reference to the previous table we understand that Pakistan possesses a hydro power generation potential of nearly 60000 MW, the ratio of current generation to the potential is very low. So instead of installing temporary and expensive sources of power generation which is the irony of the present times, we should switch on to Hydro power generation which is a long lasting a cheap solution to the current energy crisis in Pakistan.

2.3 Tarbela Dam

Pakistan major energy producing dam, namely **Tarbela Dam** is the world's biggest Earthen Rock Filled Dam and it has been filed as the greatest water development resources and is a part of Indus Basin Project which was completed in 1976. The Dam bounds the river Indus referred as the "Abbasin" or the father of the river at a distance of 130 Kilometer to the North West of Islamabad, in Distt Swabi KPK

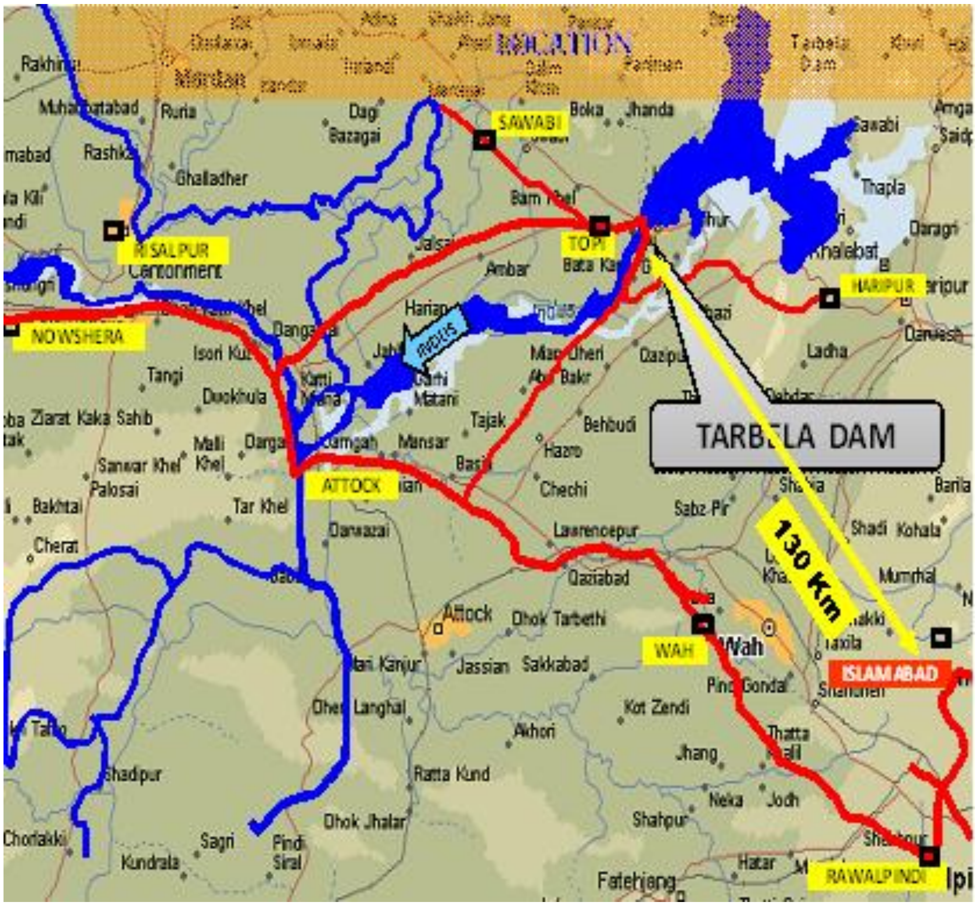


Figure 5 Tarbela Dam Location

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2.3.1 Reservoir

On an average 90% of the annual river flow is originating from the snow melt that basically forms a part of Tarbela Reservoir. The remaining of the runoff comes from the precipitation in the Catchment area of 4,000sq. miles which lies at the upstream of dam site. Precipitation proves to be critical for flood production factor of the basin.(Ahmad 2012). The 81-kilometer catchment area constructed and designed has an overall bounding capacity of 11.6 million acre-ft (MAF) at the highest lake elevation for 472 meters a storage capacity of 1.9 MAF at the lowest head of 396 meters and an overall capacity of 9.7 MAF.(WAPDA)

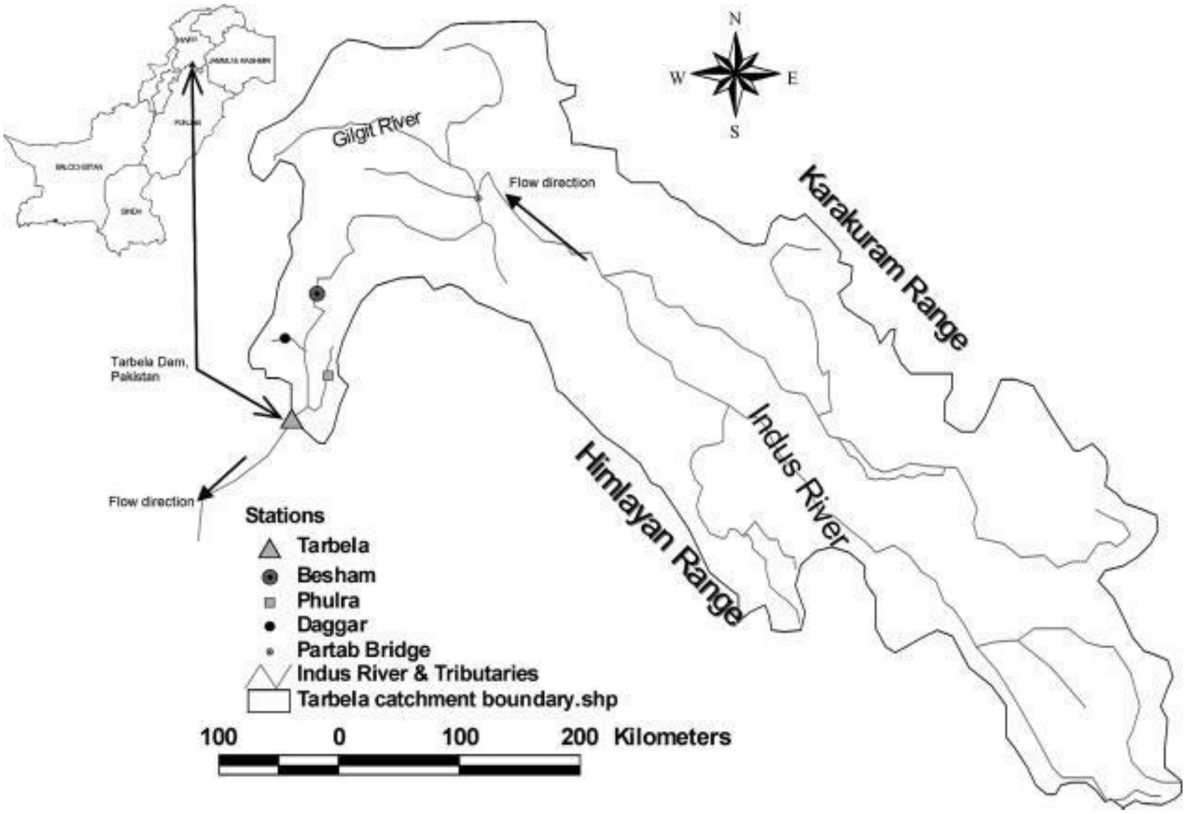
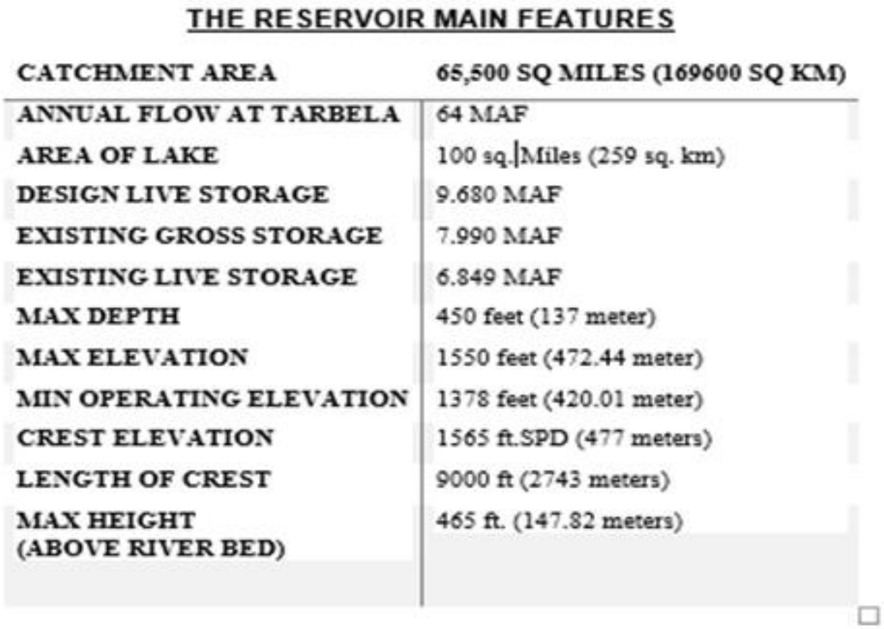


Figure 6 Location of the Tarbela Reservoir and important river gauging stations in the catchment

Table 5 Tarbela Reservoir Main Features(WAPDA)



THE RESERVOIR MAIN FEATURES

CATCHMENT AREA	65,500 SQ MILES (169600 SQ KM)
ANNUAL FLOW AT TARBELA	64 MAF
AREA OF LAKE	100 sq. Miles (259 sq. km)
DESIGN LIVE STORAGE	9.680 MAF
EXISTING GROSS STORAGE	7.990 MAF
EXISTING LIVE STORAGE	6.849 MAF
MAX DEPTH	450 feet (137 meter)
MAX ELEVATION	1550 feet (472.44 meter)
MIN OPERATING ELEVATION	1378 feet (420.01 meter)
CREST ELEVATION	1565 ft.SPD (477 meters)
LENGTH OF CREST	9000 ft (2743 meters)
MAX HEIGHT (ABOVE RIVER BED)	465 ft. (147.82 meters)

2.3.2 Flood Limits

Flood Limits for Tarbela are as follows: - (Ministry-of-Water-Resource-Pakistan 2010)

Table 6 Tarbela Flood Limits

Flood Stage	Discharge (cfsx1000)
Low	250
Medium	375
High	500
Very High	650
Super High	800

Senior Engineer (S&H) will issue Flood Warning on the receipt of inflow data from upstream gauging stations to Government, Civil and Project Authorities as laid down in the Flood Management Procedure

2.3.3 Spill Ways

- **Service Spillway** has 7 gates (50 ft wide x 61 ft high) with water releasing capacity of 650,000 cusecs
- **Service Spillway** has 9 gates (50 ft wide x 61 ft high) with water releasing capacity of 850,000 cusecs(WAPDA)

Figure 7 Tarbela Spillways

2.3.4 Power generation Tarbela

GENERAL(WAPDA)

Table 7 General Specifications of Tarbela Power Units

Total Number of Units	14
Total Installed Capacity	3478 Mega Watt (MW)
Installed capacity from units 1-10	Each produces175 Mega Watt i.e. Total 1750 MW
Installed capacity from units 11-14	Each produces 432 Mega Watt i.e. Total 1728 MW
Installed capacity for TUNNEL-1	Each of the 4 Units make up of 175 MW
Installed capacity for TUNNEL-2	Each of the 6 Units make up 175 MW
Installed capacity for TUNNEL-3	Each of the 4 Units make up 432 MW

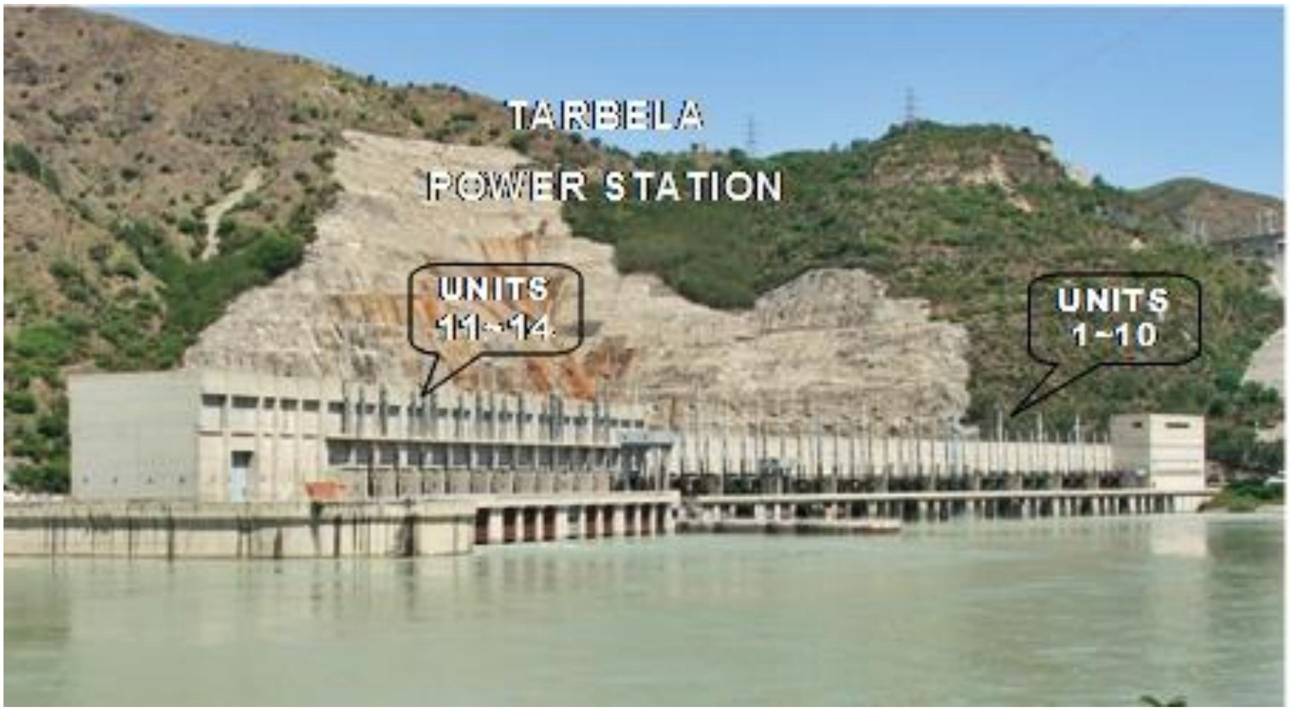


Figure 8 Tarbela Power Units

2.3.5 Tunnels

Each tunnel is of half a mile in length. Furthermore, these tunnels (1, 2, 3 and 4) are being utilized for the upkeep of energy requirement Water releasing capacity for each tunnel at maximum reservoir head is approximately 90,000 cusecs. The discharge flows through the structure losing potential head and joins the river.

In addition, a fifth tunnel has been added to aid the water release for irrigation demand up to the capacity of 80,000 cusecs at peak reservoir head.(WAPDA)

Figure 9: Tarbela Tunnel

2.4 Mathematical Optimization

A mathematical optimization problem in which some function is maximized or minimized relative to a given set of alternatives. *The function that is to be minimized or maximized is called the objective function* and the feasible region is the pair of alternatives which is also referred to as constraint region.(Kelley 1999). This process can be implemented to the reservoir management for the purpose of controlling flood at the downstream areas of the basins.

2.4.1 Optimization Techniques

2.4.1.1 Linear Programming

Linear programming is the one which confronts with the programming problems in which the objective function to be optimized and all the connections between the variables needed must be linear i.e. of exponential 1. Any Linear Programming complication has an objective function and a number of restraints. Furthermore, these restraints directly relate to the set of conditions for which work can result the desired objective function. Whenever one wants to achieve a desired objective, it will be realized that the environment does present some constraints. (Professor_Hossein_Arsham)

Whenever you want to solve decision-making complications as a linear program, the below given requirements are to be met.

1. In every case objective function should be linear. This means each of the variable are raised by the exponent of one (variable^1). Whether we add or subtract (not necessary for division or multiplication).
2. The objective function is either maxima or minima.
3. The objective function should always represent the aim of the decision-maker.
4. Restraints should be linear.

2.4.1.1.1 Linear Programming Problem Formulation Process and Its Applications

Linear program always consists of four parts whether any type i.e. combination of decision variables, the overall parameters, the final objective function, and a set of restraint. (Professor_Hossein_Arsham). For the formulation of the given complication in a numerical way, one must learn to know the complication. (i.e., Devising a mental model) by iteratively studying the overall complications.

In order to have a strong understanding of the complication, one must ask the following generic queries:

1. What are **controllable inputs** (**decision variables**)? Give a definite description on the decision variables precisely.
2. What are the **parameters** (**uncontrollable variables**) used? These are commonly the given definite mathematical values. Give the definition of the parameters accurately and carefully, assigning descriptive names.
3. What is the **objective**? What is the **objective function**? And what result does the decision maker want? How does the objective relate to the decision variables? Is it a maxima or minima complication? The objective represents the aim given by the governing body.
4. What are the **restraints** being faced? Goals to be met? Will there be an inequality or equality in the type of restraint? What are the relations between variables? Note them out in descriptive manner prior to the numerical manner.

One needs to keep in mind that the feasible region does not have to do anything with the maxima or minima. These maxima and minima of any linear programming methodology are obtained from

2 different sources. The objective function is in accordance to the desire of the user, and for the restraints as they help to mold the practical region are generally decided from the stake holder’s environment taking in regard some limitations and guidelines on attaining his/her goal.

2.4.1.2 Dynamic Programming

When we take mathematics and computer science under discussion, dynamic programming is used to break down sub-problems into smaller problems. Dynamic Programming can be applied to the complications that show characteristics’ of overlapping in a sub-problem which are very minute in size than the original complications.(S. Dasgupta 2006). If the method can be applied, it is usually very less time consuming and there by much faster than orthodox methods. However, the main idea generally for the use of dynamic programming is very simple. Generally, the basic approach is to first reach out to the sub-problems and solving them, after that they are to be combined to reach the overall complex problem. Most of the time, the sub-problems are overlapping and same. In dynamic programming we aim to solve the sub-problems, thereby minimizing the computation time. This can be very much useful when we have sub-problems that are exceptionally complex. Top-down dynamic programming basically gives an idea about the storage of solutions because sub-problem is usually part of complicated problem. Bottom-up dynamic programming involves developing a complicated calculation in a recursive way by simple computation. (Cormen, Leiserson et al. 2001)

Dynamic programming is useful for mathematical optimization and a computer programming. However, dynamic programming can be used to simplify the complicated problem by breaking them down into smaller parts. There are some decision problems which cannot broken down into smaller problems, however, decisions that stretch to various points in time can be often broken apart recursively; Bellman referred this as "Principle of Optimality". Similarly, when computer science is in discussion, we usually take a complex problem that can be broken down into fragments then this problem is said to have a optimal substructure. For dynamic programming to be applied we need to nest recursively the sub-problems in to the larger problem and we can make a link between the values of both the complex and the sub problems. This relationship used is called the “Bellman equation.”

2.4.1.2.1 Dynamic Programming to be used in Computer Programming

A Dynamic problem must have two attributes so that it can be applied to optimal substructure and overlapping sub-problems. This strategy is known "divide and conquer" instead of "dynamic programming" when the concurring problems are thereby very small than the complex problems. This is therefore, “quick sort”, and determining all possible matches of a general expression as they are not described as dynamic programming problems.

Optimal substructure means the sub-problems considered have an optimal solution. Consequently, the first step is to examine that the complexity has an optimal substructure so that dynamic programming can be applied. We can describe the optimal substructures by the use of recursion. For example, if we take two points u to v. Then the sub-structure is the shortest path from u to v that is P. Now, if we take any intermediate point w on this path, for P to be exactly the shortest path, then the path P1 from u to w and P 2 from w to v will be the shortest paths between the correlating points. Therefore, it will be very easy for one to formulate a solution for the shortest path in a recursive manner, which is what the Bellman-Ford algorithm does. Figure 10 shows another problem of Finding the shortest path in a graph using optimal substructure; a straight line indicates a single edge; a wavy line indicates a shortest path between the two vertices it connects (other nodes on these paths are not shown); the bold line is the overall shortest path from start to goal

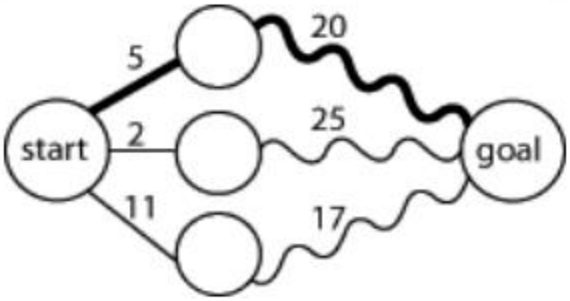


Figure 10 Optima Substructure Problem

Overlapping sub-problems gives an idea that the margin of sub-problems should be small, this implies that the recursive algorithm must solve any sub-problem and present its solution, and then for another same sub-problem solve it iteratively, instead of developing a new sub-problem.

For example, if we consider the method for developing the Fibonacci series in a recursive way; Fi = Fi-1 + Fi-2, with base case F1 =F2 =1. Then, F43 = F42 + F41, and F42 = F41 + F40. Now F41 is being solved in sub-structure of both F43 as well as F42 making it recursive. Even though the total number of sub-problems is actually very small in number, we end up solving the same problems in an iterative way if we refer to this recursive solution that is orthodox in nature. Dynamic programming does take possibility of the fact and computes each sub-problem only a single time. It must be kept in mind that the sub-problem is smaller than the larger problem by an additive factor. However, if they are smaller by a multiplicative factor, it will not be categorized as dynamic programming. This can be done by the following methods (Cormen, Leiserson et al. 2001). Figure 11 shows the subproblem graph for the Fibonacci sequence. The fact that it is not a tree indicates overlapping subproblem

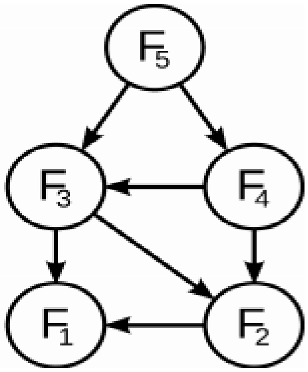


Figure 11 Overlapping Subproblem

- **Top-down approach**: This is the foremost criterion of the recursive formulation of any complexity. If we can numerically solve the main problem recursively taking the solutions of its sub-problems and if they are concurring, then we can place the solution in a table having a certain index or can be memorized. If the sub-problem is attempted to be solved, the table is checked whether it is already filled or not. If a solution has been taken in the index, thereby it can be used promptly or else the sub-problem has to be solved and added to the table.

- **Bottom-up approach**: This case is quite interesting. Once we try to record a solution of a problem in a recursive way, with the help of its sub-problems. Our approach can then be of bottom up fashion where we can solve the sub-problems first then use the solution recorded to achieve the solutions to bigger problems. This is usually a step to step process where solutions to bigger problems can be achieved by using solutions to smaller sub-problems.

Some programming does have the ability to store up the solutions for further use. This can be done by means of certain set of arguments which is done to achieve speed in the overall call by need process. Languages such as Scheme, Perl make it possible to be portable, however some such as C++ etc. require some special extensions. Some languages have a recursive way of memorization which is a system built in process this can only be possible for functions that are readily transparent.

2.4.1.3 Dynamic Programming Vs Linear Programming

For linear programming to be very much possible it is usually required for the objective functions and the constraints to be linear. It is therefore important for one to study solving methods where linear assumptions are unreasonable or inappropriate.

Whereas, one of the most widely and commonly used mathematical method for solving the linear and non-linear problems for optimization is Dynamic programming. The term "dynamic" is derived in most applications from the mere fact that this method is used to derive a process of optimal decisions that are adapted to changes in scenario that tends to occur dynamically over time.

In layman terms, the basic idea is to solve the problem in a backward manner from the end towards the very start of the problem. In other words, the method being used is very Recursive of its nature. In this the solution, the problem is broken down in smaller parts that are very much traceable and simple to solve. These sub-problems in-turn solved help us to reach the main problem. Taking in mind linear programming, the dynamic programming solution does not require any linearity in its assumptions. Likewise, this method can be applied to very number of spans of problems. The diversity can be taken into account. However, we cannot ignore the fact that the formulation of the complex and diverse problem will be highly specific. And for this, it is said that dynamic-programming formulation is a work of art.(De Farias and Van Roy 2003)

2.4.1.4 Genetic Algorithm

Genetic Algorithms can be considered a methodology that is based on the natural selection and genetics. Genetic Algorithms basically involves coding the decision variables of search problems that can be taken into strings of finite length with alphabets of certain cardinality. The basic candidates for the search of problems are the chromosomes and the alphabets are called as genes whereas the information that rests in the genes is called alleles. For example, let us consider the daily life of sales-man and take the traveling of the salesman as a problem then a chromosome will represent a pathway, and a gene will represent the target area. Considering the orthodox optimization methods, Genetic Algorithm works by coding the parameters, instead of using these parameters themselves. (Sastry, Goldberg et al. 2005)

To formulize an up-to mark solution and to apply natural selection, we require a filter to differentiate what is an up-to mark solution from incorrect solutions. This filter may be any objective function that can be a numerical model or some computer-based simulation where we can consider it to be a subjective function in which we are able to choose better solutions instead of bad ones. We can measure the comparative fitness by the help of fitness measure, which the genetic algorithm will use to generate up to mark solutions.

One more necessary concept of Genetic Algorithm is the notion of population. Contrary to orthodox searching techniques, genetic algorithm depends on a population given by candidate solutions. The quantity of the population is generally a parameter entered by the user. Scalability and efficiency of genetic algorithm largely depends on the population. For example, limited population densities might lead to substandard solutions which are not up-to the mark. While considering huge population sizes may lead to non-essential cost of valuable computational time.

2.5 Regression Modeling:

When we discuss and come to do statistical modeling, regression is a process to establish relationships between independent and dependent variables. When our prime focal point is of a more complex problem, then this includes complicated modeling techniques to establish these relations. Being more specific, regression is a modeling technique between two independent and one dependent variable such that it tells how the dependent variables varies relating the independent varies whether one is fixed, or both are variable.

However, generally regression modeling estimates the average value of the dependent variable with respect to the independent variable that is fixed or generally gives a general value referring to independent variables.

Regression analysis is commonly adopted for prognosis and forecasting, where its use has considerable overlap with the field of programmed learning. It is also used to study relationship between independent variables and dependent variables and their effects on each other.

2.6 Model for Reservoir Optimization-Simulation With Sediment Evacuation (ROSSE)

In this model genetic algorithm-based optimization capabilities were utilized and rooted the sediment evacuation module into the simulation module. However, the sediment evacuation module was executed using the Tsinghua university flushing equation.(Khan and Tingsanchali 2009)

2.6.1 Objective Function

ROSSE model is able to optimize the rule curve based on below mentioned objective functions:

a) Minimizing of deficits of Irrigation

b) Maximum Sediment Evacuation

c) Maximization of the Power generated

d) Net economic benefits to be maximized from irrigation supply, power production, storage increased by sediment evacuated. .

2.6.2 Framework

There are three modules which are interconnected in apart of taking the input and output modules. The model is based on generation-by-generation basis and runs on it. The 1st generation's rule curve was generically assumed, however, succeeding generation curve was produced through the help of Genetic Algorithm. Only a pair of two rule curves at maximum can be replaced, including the first rule curve by the already present pair of rule curves. The simulation module calculates discharge, power and flood damage for the pair of "rule curves." And with the help of the sediment module we are able to calculate the sediments resting and evacuated from the catchment. The Genetic Algorithm module uses information gathered from simulation and sediment modules namely; release, power generated, sediment evacuated and flood damage, for the calculation of the objective function of each set of rule curves. Penalties are applied for the calculation of the fitness value to the objective function for each constraint violation. The GA operators, namely selection, crossover and mutation, based on the fitness value calculated are applied to generate a new and better population of the rule curves. The generation-by-generation cycle continues till the criterion is fully accepted.

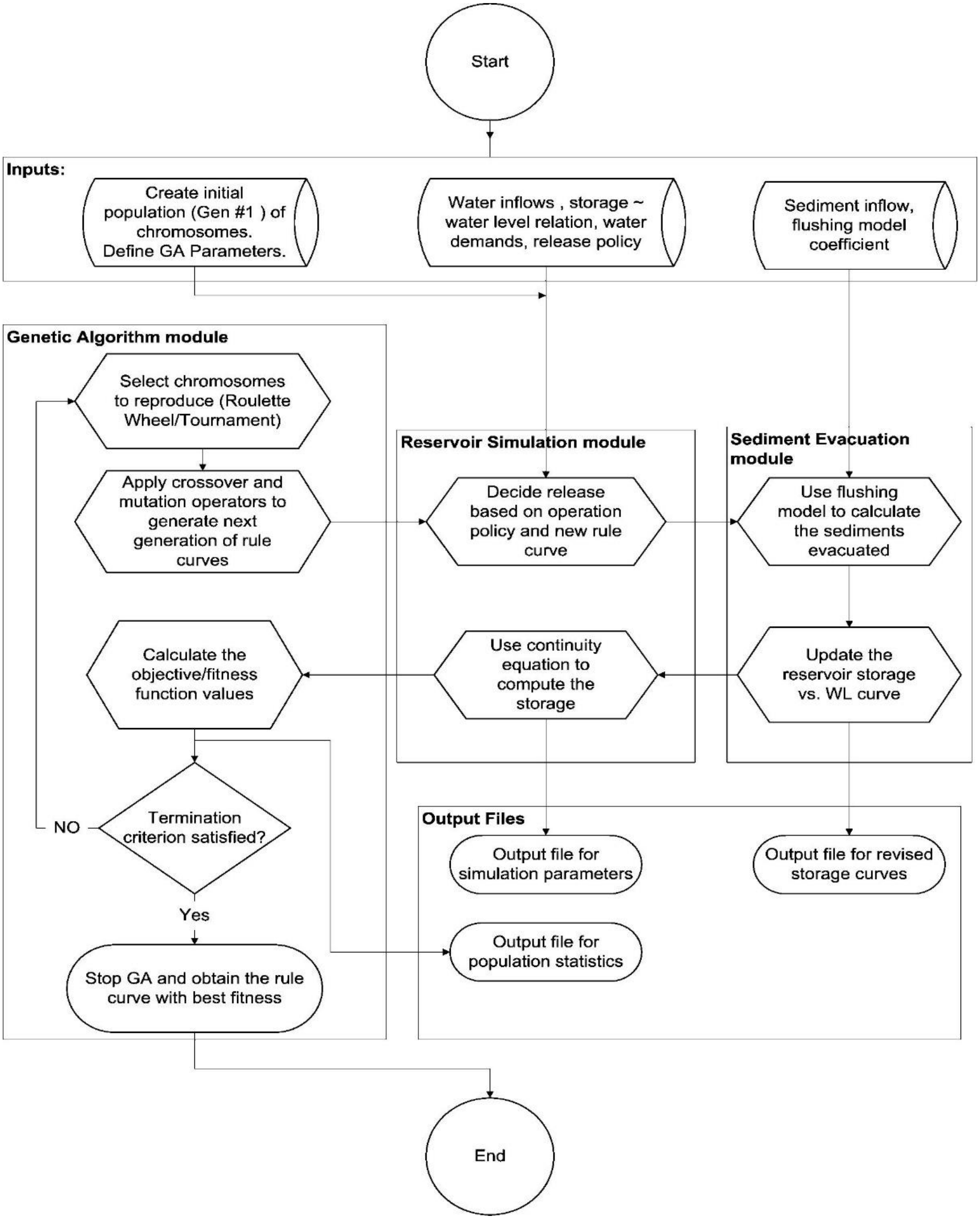


Figure 12 ROSSE Model

2.6.3 Analysis and Results:

The Tarbela reservoir rule curve was optimized by the application of ROSSE model to optimize, the greatest reservoir with unceasing sedimentation problems and complications. “Rule curves” were optimized to obtain a maximum advantage to the economy from the overall water discharged. The discharged water was helpful for irrigation, power production, sediment evacuation, and further for minimization of flood loss purposes. The already present rule curves and overall proposed rule curves for 8 scenarios developed for different policy options overall a total of nine rule curves were compared. These optimized rule curves have showed an increase in the total individual economic advantages ranging from 9 to 248% over the already present rule curves. There was a reduction of 38% shortage of irrigation supply during the simulation period. And increase in sediment evacuation enhanced the reservoir sustainability.

2.6.4 Conclusion

The studies result that if the operation policy and rule curve are modified, it’s very much possible to increase the catchment sustainability and maximize the total economic advantages. This developed formulation technique and the overall model can be helpful for optimization of rule curves of different catchments having sedimentation problems.

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3 Chapter 3 Methodology

3.1 Prologue

The first step of methodology was to collect the data of dam inflows, outflows, catchment precipitation data, power generation data, flood losses, flood affected area data and stage relation curve. After the collection of data, we generated scattered plots of data, removed the errors and uncertainties and then derived relationships between these parameters by multiple linear regression. The data was further refined by removing ambiguous values that caused abrupt peaks. The data was further refined by creating residual plots and removing the data that had higher difference from the regression model. To generate the curve, we modeled a program on MATLAB using Dynamic Programming involving all the parameters discussed above. We then devised rule curve for the past years' flood discharge data and compared the discharges of the actual floods with the discharges generated by our model.

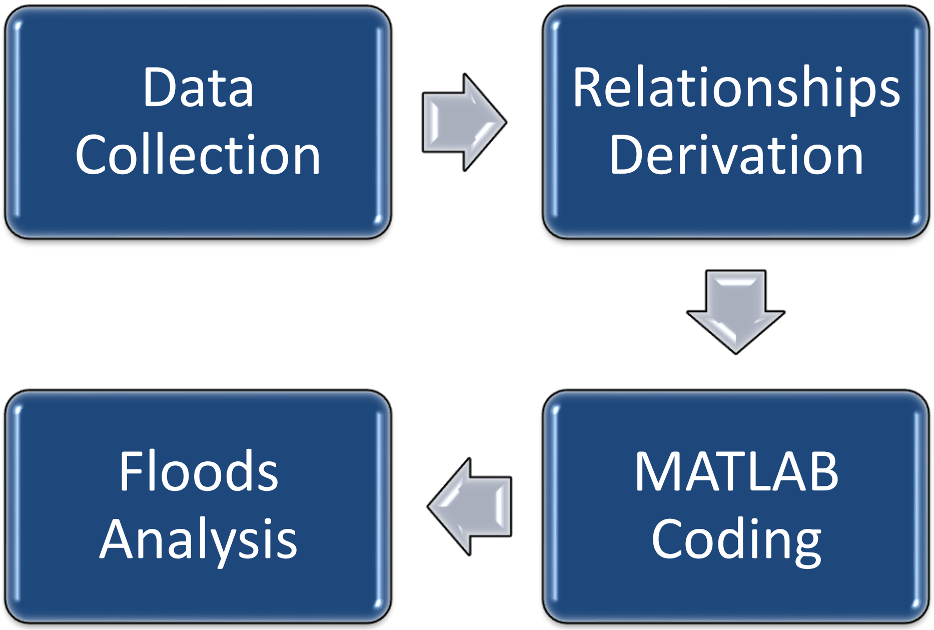


Figure 13 Flow Chart of Methodology

3.2 Data Collection

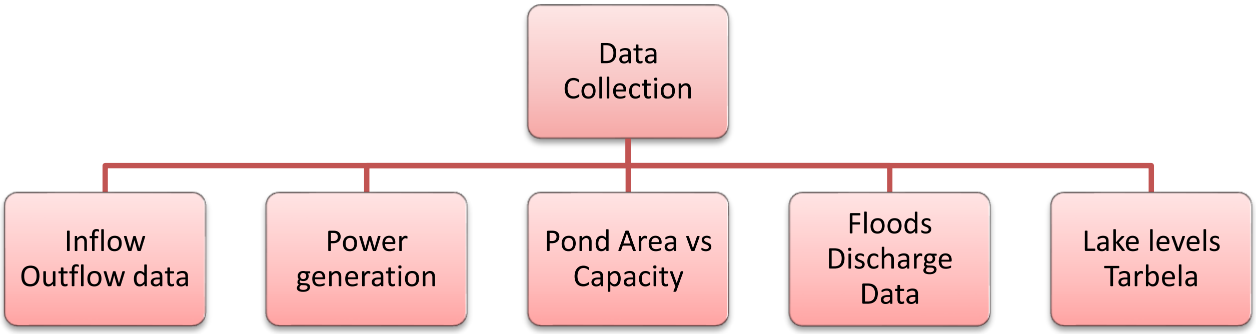


Figure 14 Flow Chat for Data Collection

3.2.1 Inflow and Outflow Data

The first step involved in data collection was to collect the inflow and outflow data of the reservoir. The daily inflow data available for last 43 years starting from 1975 up till 2018 obtained from Tarbela Dam Authorities is tabulated as under:

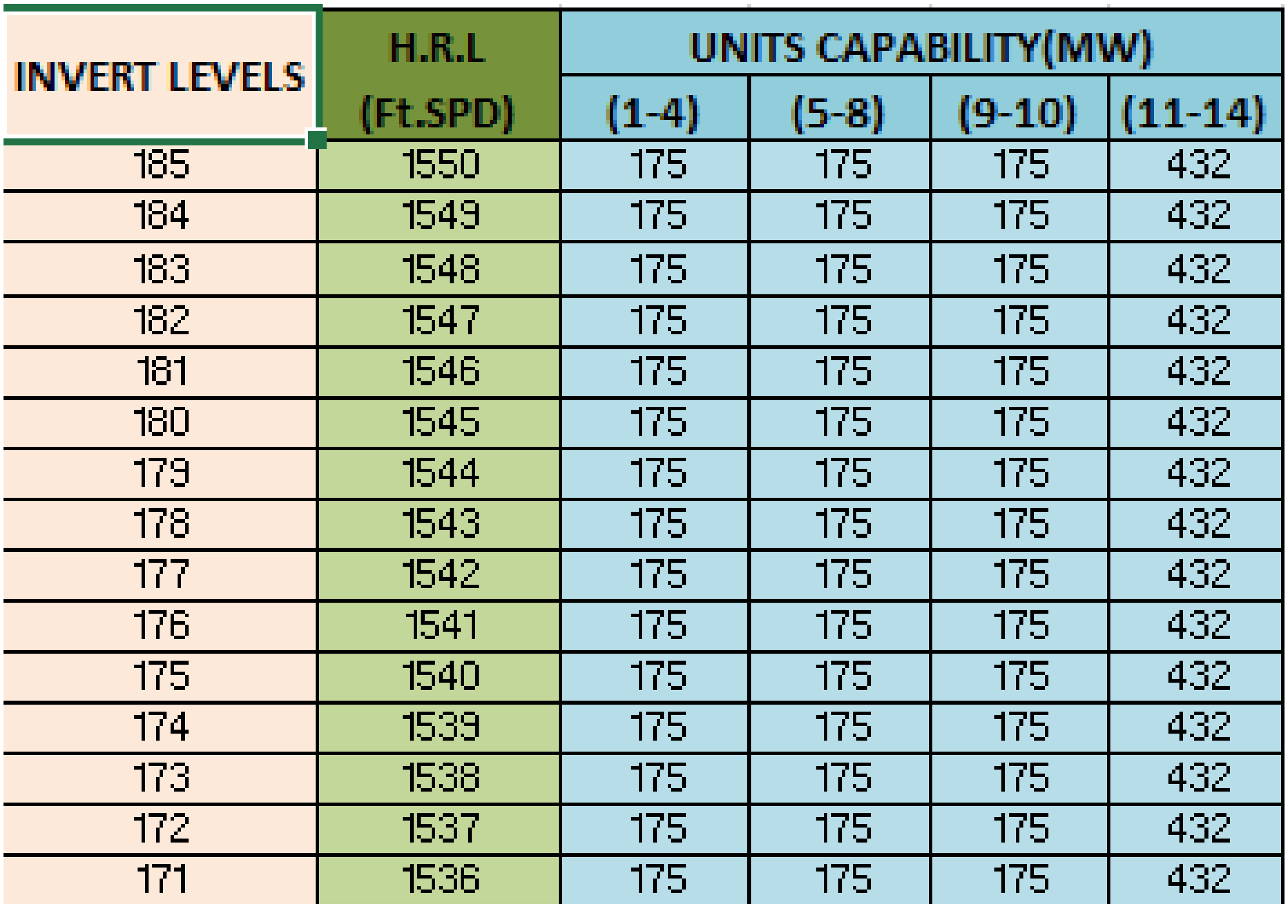
Table 8 Inflow Outflow Data

Month	January		February		March		April		May	
Date / Year	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
	(Cfs x 1000)		(Cfs x 1000)		(Cfs x 1000)		(Cfs x 1000)		(Cfs x 1000)	
04-1975	15.9	14.9	14.0	0.0	15.6	16.0	24.9	23.0	38.7	37.2
05-1975	15.4	14.7	13.9	0.8	20.6	16.9	24.1	23.1	40.3	37.3
06-1975	15.1	14.4	13.9	2.2	19.8	17.9	24.9	23.2	39.8	37.3
07-1975	15.0	14.4	14.0	1.5	18.4	18.2	26.3	23.3	38.2	39.7
08-1975	15.0	14.3	14.4	4.9	17.7	18.2	26.2	24.7	34.3	37.3
09-1975	15.1	14.7	14.9	7.3	17.2	18.2	25.3	25.3	32.4	27.9
10-1975	15.1	14.7	15.6	9.5	16.4	17.6	23.1	24.1	33.2	34.2
11-1975	15.1	14.7	15.1	9.8	15.7	16.7	22.4	23.4	34.7	34.2
12-1975	15.0	14.7	14.8	11.8	16.6	16.6	22.3	23.3	36.0	37.0
13-1975	15.1	14.7	14.9	12.8	16.3	16.6	21.8	23.3	37.8	37.3
14-1975	15.1	14.8	18.1	14.1	16.3	16.1	21.7	23.2	43.7	39.7
15-1975	15.1	14.5	16.1	14.8	15.7	16.0	20.6	23.1	51.3	40.3
16-1975	15.1	14.5	15.0	15.0	15.1	15.0	20.7	22.2	67.4	40.9
17-1975	15.0	14.8	14.9	15.0	15.1	15.5	21.2	21.7	95.5	40.5

3.2.2 Power Generation Data

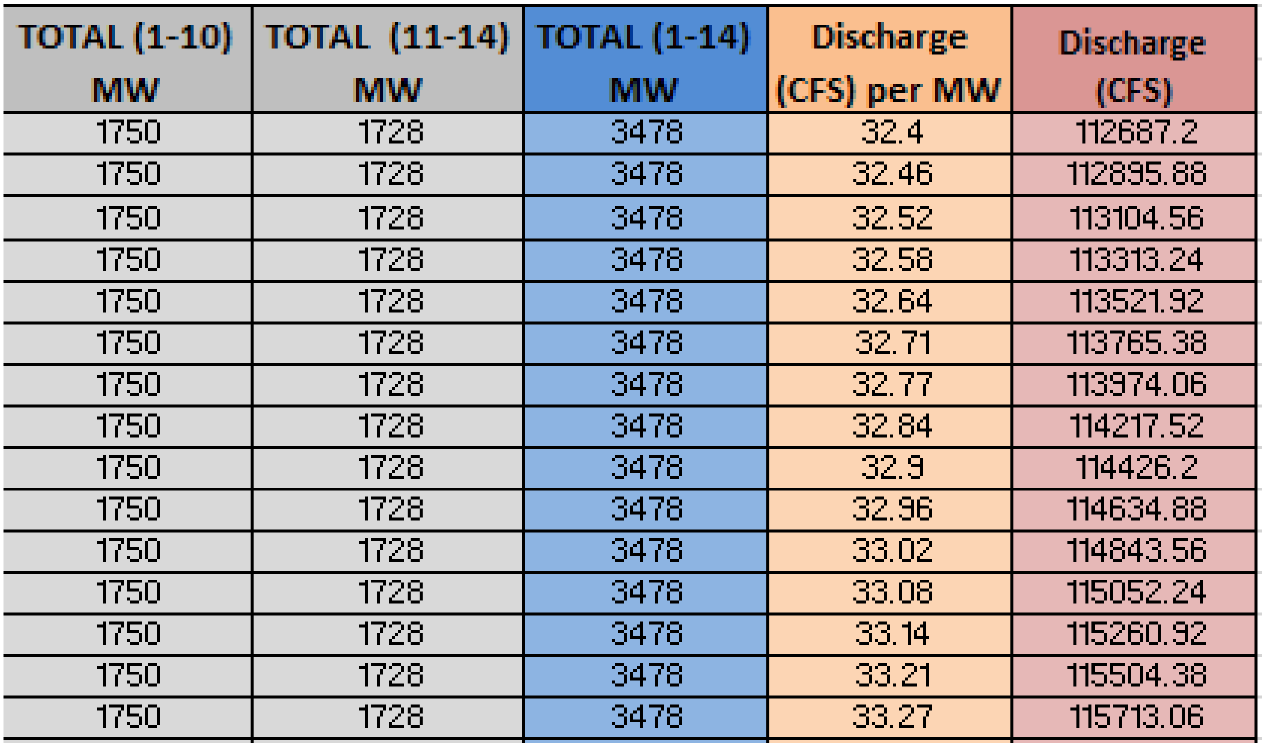
The power generated by these turbines is directly dependent on the elevation of reservoir from the mean sea level. The higher the elevation, the greater will be the amount of power generated and lower will be the discharge required per megawatt and vice versa. The reason behind this is that higher elevation levels create higher heads and velocity of the water through tunnels resulting in maximum power generation possible.

Table 9 Tarbela Invert Levels, Elevation and Individual Turbine Capacity



INVERT LEVELS	H.R.L (Ft.SPD)	UNITS CAPABILITY(MW)			
		(1-4)	(5-8)	(9-10)	(11-14)
185	1550	175	175	175	432
184	1549	175	175	175	432
183	1548	175	175	175	432
182	1547	175	175	175	432
181	1546	175	175	175	432
180	1545	175	175	175	432
179	1544	175	175	175	432
178	1543	175	175	175	432
177	1542	175	175	175	432
176	1541	175	175	175	432
175	1540	175	175	175	432
174	1539	175	175	175	432
173	1538	175	175	175	432
172	1537	175	175	175	432
171	1536	175	175	175	432

Table 10 Tarbela Total Power, Discharge per MW and Total Discharge



TOTAL (1-10) MW	TOTAL (11-14) MW	TOTAL (1-14) MW	Discharge (CFS) per MW	Discharge (CFS)
1750	1728	3478	32.4	112687.2
1750	1728	3478	32.46	112895.88
1750	1728	3478	32.52	113104.56
1750	1728	3478	32.58	113313.24
1750	1728	3478	32.64	113521.92
1750	1728	3478	32.71	113765.38
1750	1728	3478	32.77	113974.06
1750	1728	3478	32.84	114217.52
1750	1728	3478	32.9	114426.2
1750	1728	3478	32.96	114634.88
1750	1728	3478	33.02	114843.56
1750	1728	3478	33.08	115052.24
1750	1728	3478	33.14	115260.92
1750	1728	3478	33.21	115504.38
1750	1728	3478	33.27	115713.06

The trend of the power generation does not remain the same for all the values of elevation. The generated power remains the same for all the heads between 1550 ft and 1532 ft that makes the trend of power generation curvilinear. The only factor that causes the difference between these power values at elevations in the interval 1550 ft till 1532 ft is the total discharge or the discharge per megawatt. For lower elevations, the power generation trend remains almost the same down to the dead level. This combination of nearly linear and curvilinear trend makes the prediction of the total power generated, a difficult task to achieve.

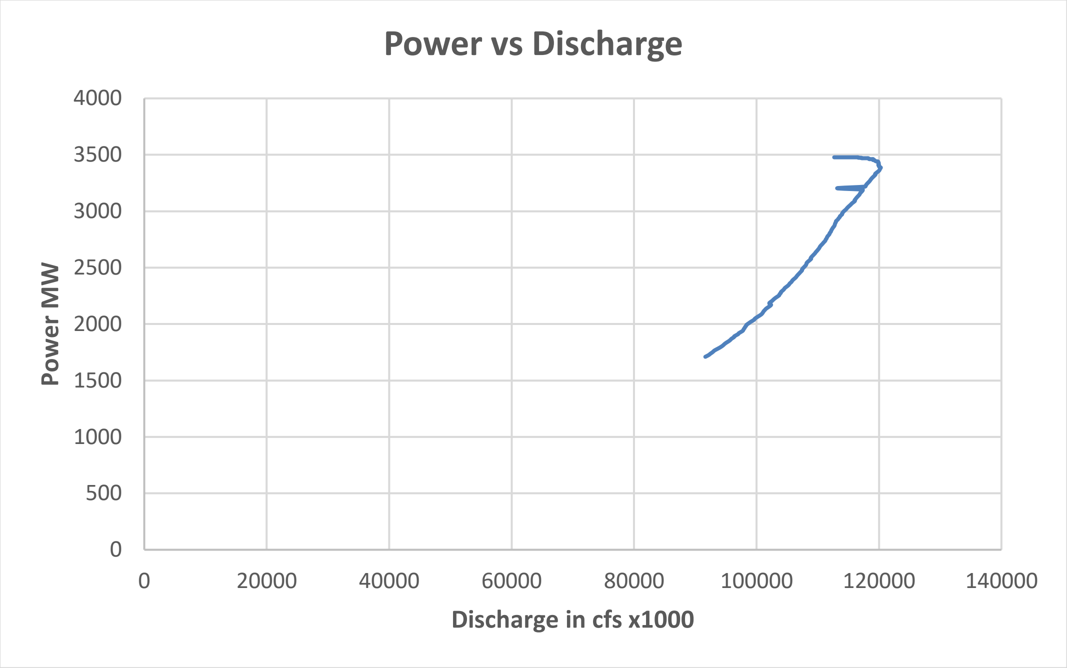


Figure 15 Power vs. Discharge plot of Unrefined Data

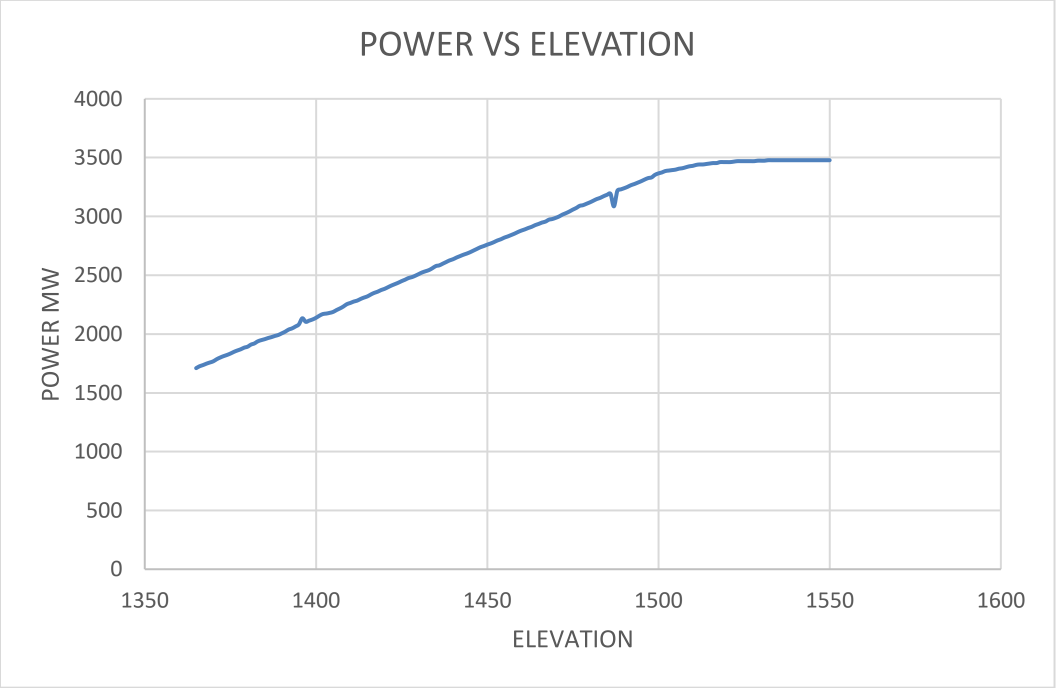


Figure 16 Power vs. Elevation plot of Unrefined Data

3.2.3 Pond Capacity vs Elevation Data

The capacity of the reservoir at each elevation is also collected. Following data shows that the reservoir capacity increases with increase of elevation and so do the water required to fill every successive single unit height of reservoir.

Table 11 Pond Capacity vs Elevation Data

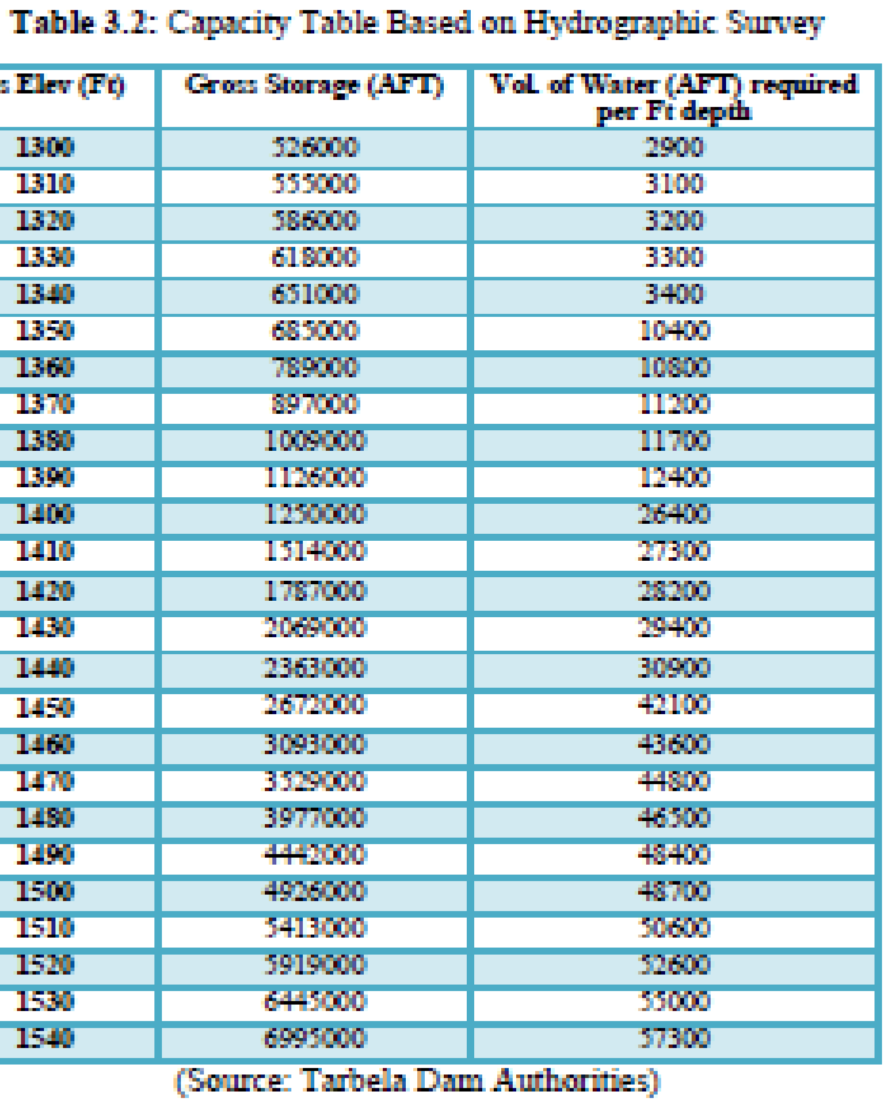


Table 3.2: Capacity Table Based on Hydrographic Survey

Res Elev (Ft)	Gross Storage (AFT)	Vol. of Water (AFT) required per Ft depth
1300	526000	2900
1310	555000	3100
1320	586000	3200
1330	618000	3300
1340	651000	3400
1350	685000	10400
1360	789000	10800
1370	897000	11200
1380	1009000	11700
1390	1126000	12400
1400	1250000	26400
1410	1514000	27300
1420	1787000	28200
1430	2069000	29400
1440	2363000	30900
1450	2672000	42100
1460	3093000	43600
1470	3529000	44800
1480	3977000	46500
1490	4442000	48400
1500	4926000	48700
1510	5413000	50600
1520	5919000	52600
1530	6445000	55000
1540	6995000	57300

(Source: Tarbela Dam Authorities)

3.2.4 Floods Discharge Data

We sorted the outflows data of past flood years. To take into account the intensity of the flood we considered the peak discharges during flood period and to account for the continual intensity we calculated average discharges for each flood season.

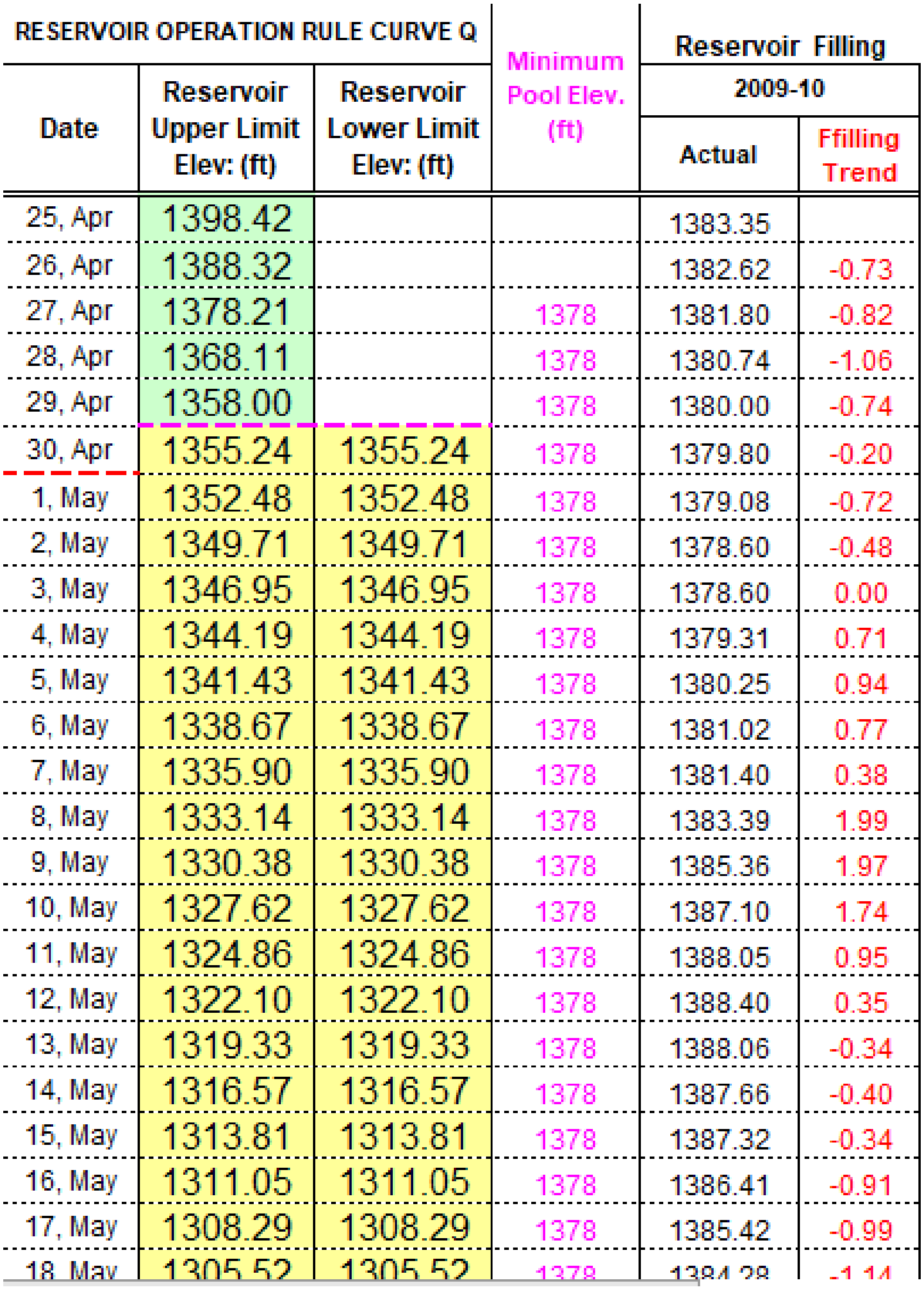
Table 12 Flood Discharge Data

YEAR	AVERAGE DISCHARGE CFS X 1000	PEAK DISCHARGE CFS X 1000
2011	167.5578947	188
2014	261.25	272
1977	262	307
1981	263.5	301
2012	269.68	284
1976	280.8636364	318
1984	281.7666667	313
1992	297.4529412	358
1975	303.6666667	413
2013	310.00625	366
1995	313.0217391	464
1978	316.0645161	396
1983	322	372
1988	332.7225806	425
1994	349.2516129	383
2010	384.0148148	557

3.2.5 Lake levels of Tarbela Reservoir

Following data shows the lake conservation levels maintained in the presently according to the current rule curve the upper limit of reservoir dictates the maximum level that can be achieved for each day. The lower limit of reservoir dictates the minimum level to which the water can be flushed in each day. The upper and lower limits of reservoir remain equal except for the flood seasons in which a cushion is provided in between them as a flood mitigation measure and to accommodate excess water during greater inflows.

Table 13 Lake Elevations data



RESERVOIR OPERATION RULE CURVE Q			Minimum Pool Elev. (ft)	Reservoir Filling 2009-10	
Date	Reservoir Upper Limit Elev: (ft)	Reservoir Lower Limit Elev: (ft)		Actual	Ffilling Trend
25, Apr	1398.42			1383.35	
26, Apr	1388.32			1382.62	-0.73
27, Apr	1378.21		1378	1381.80	-0.82
28, Apr	1368.11		1378	1380.74	-1.06
29, Apr	1358.00		1378	1380.00	-0.74
30, Apr	1355.24	1355.24	1378	1379.80	-0.20
1, May	1352.48	1352.48	1378	1379.08	-0.72
2, May	1349.71	1349.71	1378	1378.60	-0.48
3, May	1346.95	1346.95	1378	1378.60	0.00
4, May	1344.19	1344.19	1378	1379.31	0.71
5, May	1341.43	1341.43	1378	1380.25	0.94
6, May	1338.67	1338.67	1378	1381.02	0.77
7, May	1335.90	1335.90	1378	1381.40	0.38
8, May	1333.14	1333.14	1378	1383.39	1.99
9, May	1330.38	1330.38	1378	1385.36	1.97
10, May	1327.62	1327.62	1378	1387.10	1.74
11, May	1324.86	1324.86	1378	1388.05	0.95
12, May	1322.10	1322.10	1378	1388.40	0.35
13, May	1319.33	1319.33	1378	1388.06	-0.34
14, May	1316.57	1316.57	1378	1387.66	-0.40
15, May	1313.81	1313.81	1378	1387.32	-0.34
16, May	1311.05	1311.05	1378	1386.41	-0.91
17, May	1308.29	1308.29	1378	1385.42	-0.99
18, May	1305.52	1305.52	1378	1384.28	-1.14

3.3 Relationships Derivation

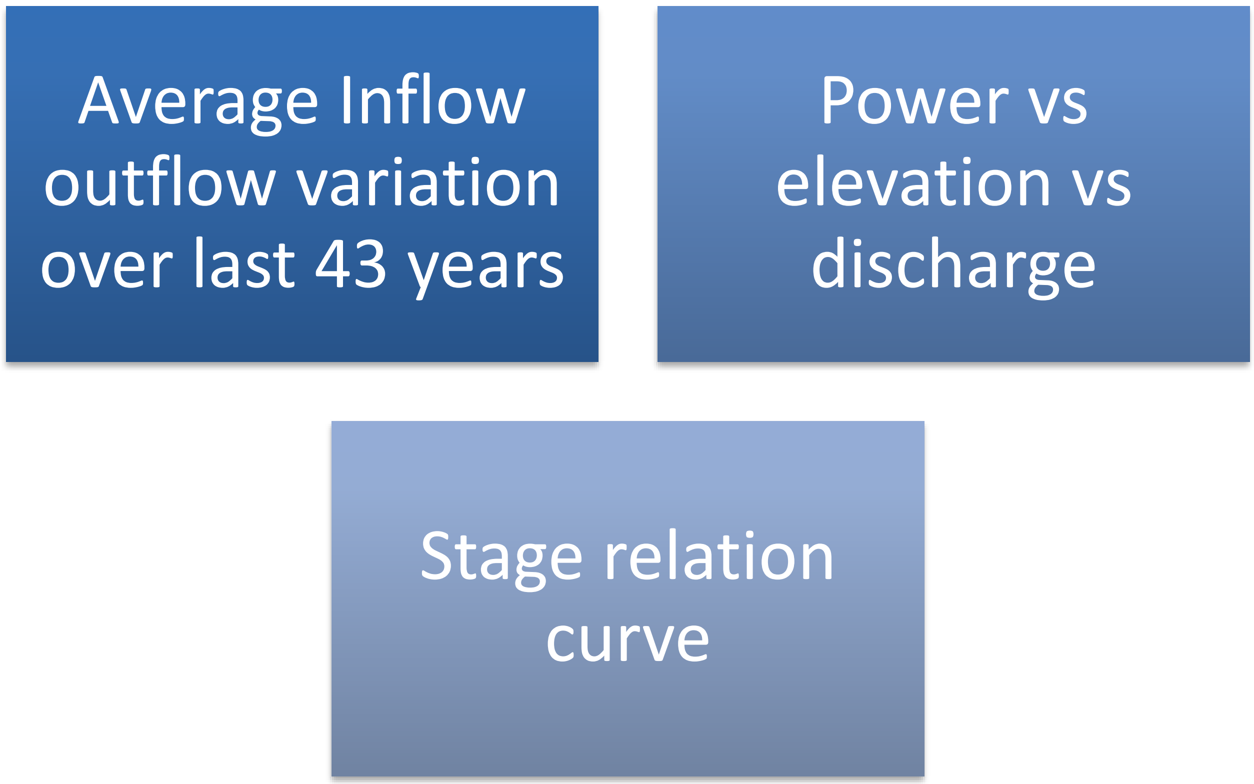


Figure 17 Relationships Derivation

3.3.1 Dam Filling Period

The inflow of the Tarbela reservoir is mainly due the rivers generated through melting of glaciers. The trend of the average monthly inflow data through the years does not show any appreciable change in the past 50 years. By taking the month-wise average of the historic data and by drawing a scattered plot of the data, a crest can be clearly seen. This crest shows the period in which the dam is filled. This period starts from May through September. The highest monthly average inflow is 240000 cubic feet per second which shows our upper limiting value of the inflow. Any inflow value that deviates from this upper limit can cause a flood.

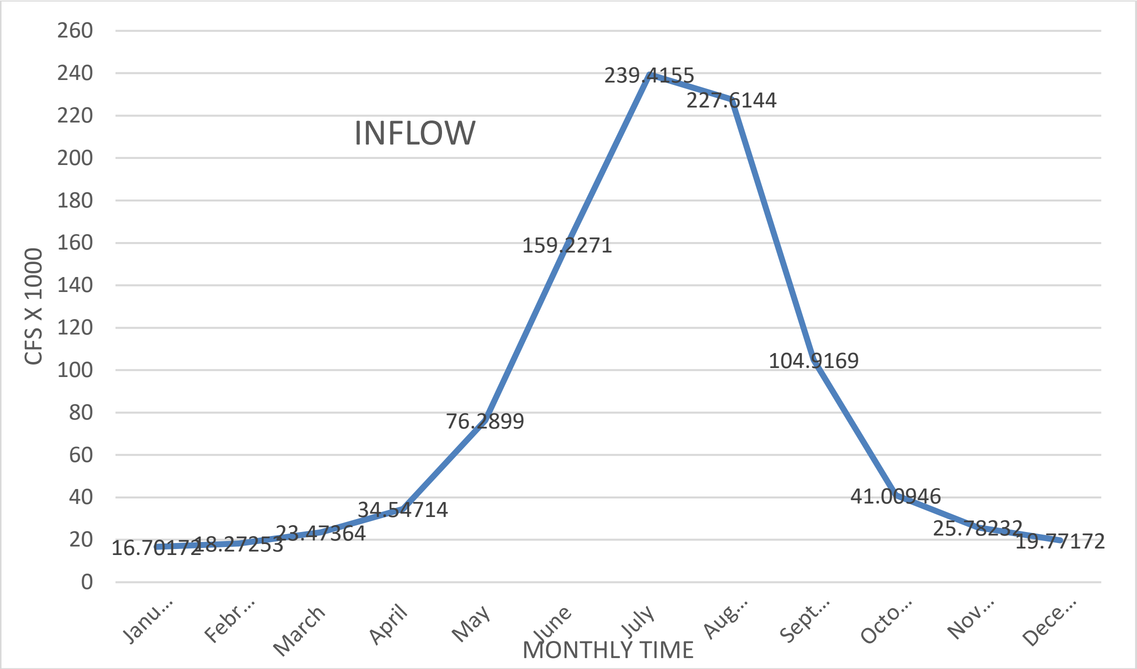


Figure 18 Days vs Inflow

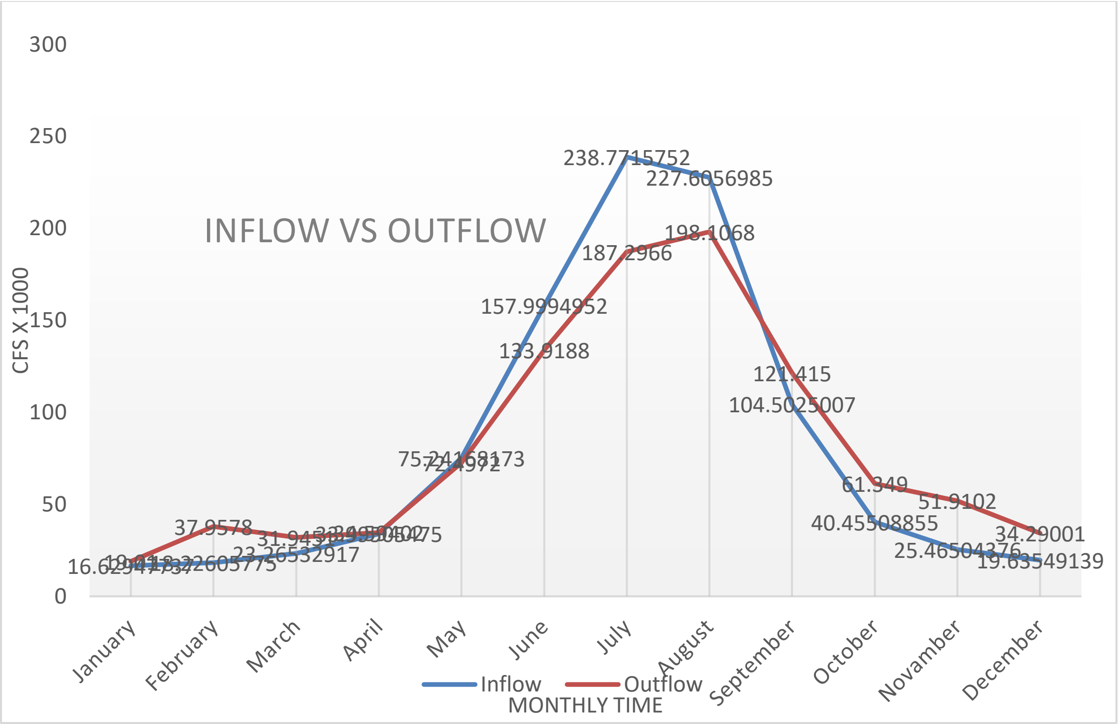


Figure 19 Average monthly Inflow vs Outflow

3.3.2 Stage Relation Curve

The side slopes of reservoir are not uniform, rather they are uneven crests and depressions throughout the gradient. The area or the volume of reservoir cannot be calculated through simple mathematical formulae rather a model is needed to calculate the storage of the reservoir at different elevations. For this purpose, we have derived the following equation to calculate the reservoir storage at a particular elevation.

$$\mathbf{y = 137.38x^2 - 363253x + 2E+08}$$

In above equation, dependent variable ‘y’ represents reservoir storage in MAF whereas, ‘x’ represents the elevation in feet from the mean sea level. The storage capacity of reservoir can be calculated for any value of elevation from the mean sea level using this equation. The maximum lake level is 1550 ft from MSL and dead level is 1378 from MSL.

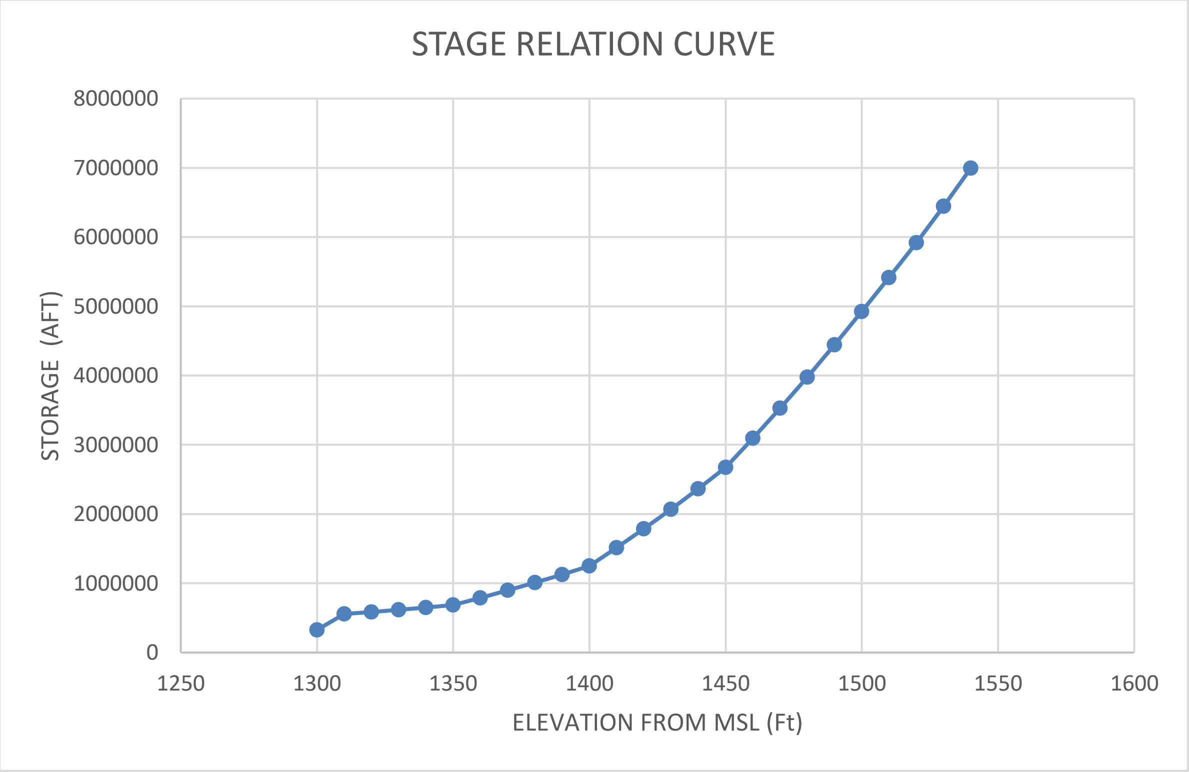


Figure 20 Stage Relation Curve

The plot shows the relation between the elevation from MSL and its corresponding lake storage is Acres ft.

3.3.3 Power vs. Elevation-Discharge Relation

We needed to generate an equation that could calculate the power generated for any given value of discharge and elevation of the reservoir so we carried out multiple linear regression modelling

To calculate the power generated keeping the elevation and discharge as inputs, we require a multiple linear regression model. Taking power output as a dependent variable ‘y’, discharge as an independent variable ‘x_1’ and elevation as ‘x_2’, we modeled an equation for calculation of power output. To calculate the power output for a particular value of discharge and elevation as inputs, we can use the following equation:

$$\mathbf{POWER= C + 0.02633*Discharge+7.066255*Elevation}$$

$$.\ \mathbf{POWER= -10411.41778 + 0.02633*x_1+7.066255*x_2}$$

Here, discharge is denoted as ‘x_1’, elevation as ‘x_2’ and ‘C’ is the regression coefficient. Power generated at a particular elevation and a certain discharge can be obtained by the above relation.

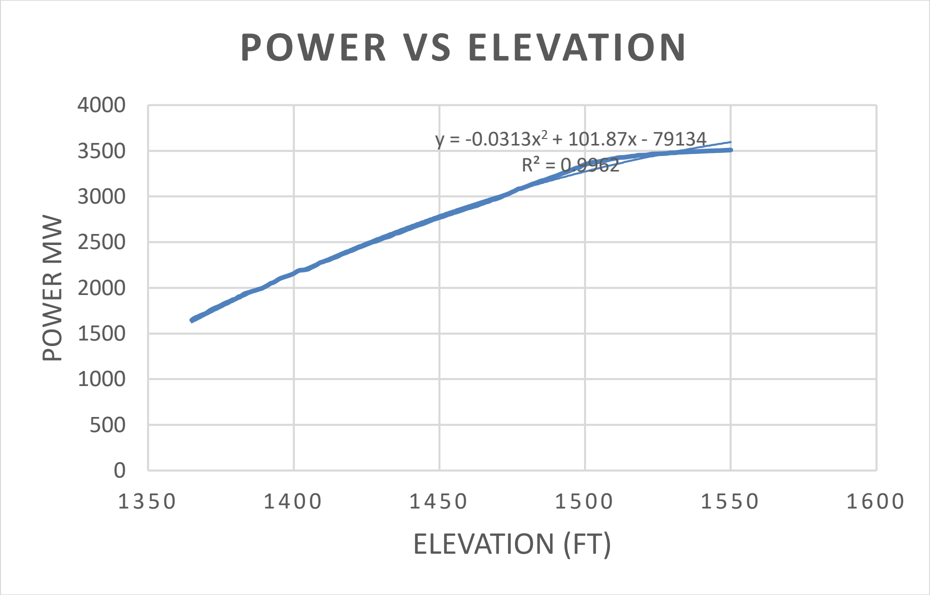


Figure 21 Modelled Power vs Elevation Plot

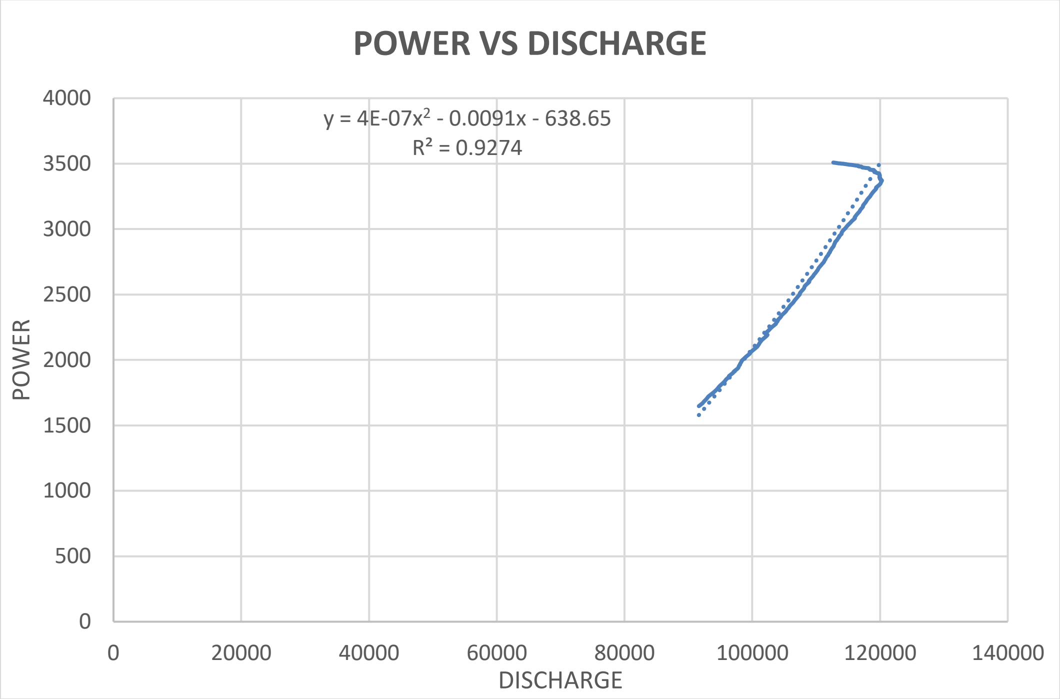


Figure 22 Modelled Power vs Discharge Plot

From the above plots, shown in power discharge and elevation data we gather that the data obtained from the Tarbela Dam Authorities had certain glitches and abrupt peaks.

We modeled the above equation but because of these glitches in the data the model gives us a deviation from the original data within a range of 30 MW. For a comparison, the maximum power generated at 1550 ft. from the reservoir according to the on-field data was 3478 MW, but our equation is giving an output of 3508 MW. This deviation is too much for a model to be authentic. So, in the next steps we will be minimizing this deviation as much as possible.

As the next step we sorted the original data and refined it by removing the data that was causing the model to deviate from trend line. The problem with the data was that the recursion of data from 1532 to 1550 gave the same amount of power with decrease in discharges due to increase in total head. This problem caused the model to deviate from on-ground results. After the removal of the abnormal data from the source data and by doing the regression again, the deviation of the modelled data from the field data was reduced and it came within a range of 15 MW. The removal of these ambiguities from the data made it a bit more certain and the chances of error were reduced, and the rule curve generated from this data can be better optimized as compared to the data originally obtained from the Tarbela Dam Authorities. The final modelled equation is:

$$\mathbf{Power = 0.01111 * Discharge + 9.992172 * Elevation - 12970.1}$$

$$\mathbf{Power = 0.01111 * x_1 + 9.992172 * x_2 - 12970.1}$$

Here, discharge is denoted as 'x_1', elevation as 'x_2' and 'C' is the regression coefficient. Power generated at a particular elevation and a certain discharge can be obtained by the above relation.

3.3.3.1 Residual Plots

Residual plots were generated to make a detailed analysis of how much bugs and glitches the data actually contains. It had unpredictable peaks at some places and the power output from the elevation 1550 ft till 1532 ft was same i.e. 3478 MW. This repetition of the data makes the model faulty. So, these glitches and repetitions must be removed and a quantitative analysis of the data for this purpose is required. This objective is fulfilled using Residual Plots.

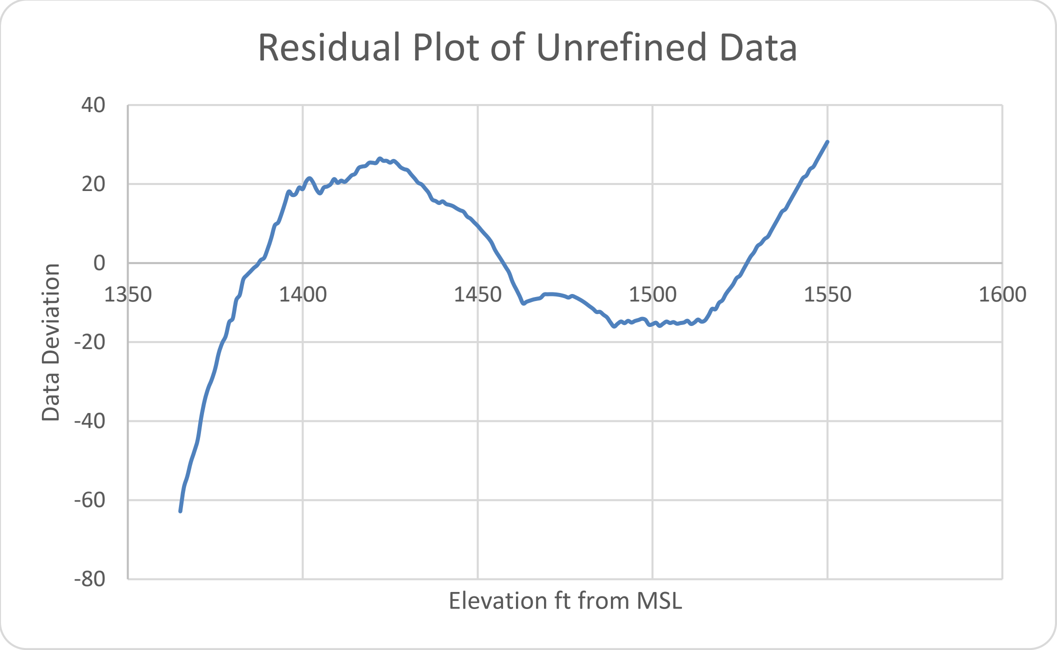


Figure 23 Residual Plot of the Original Data

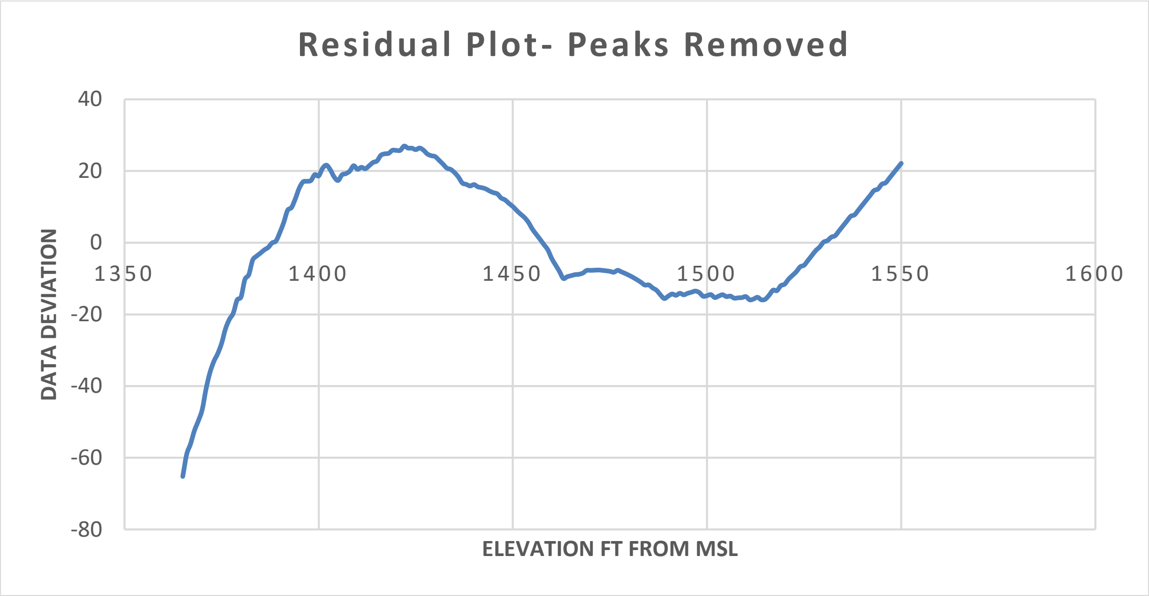


Figure 24 Residual Plot with the Peaks Removed from Original Data

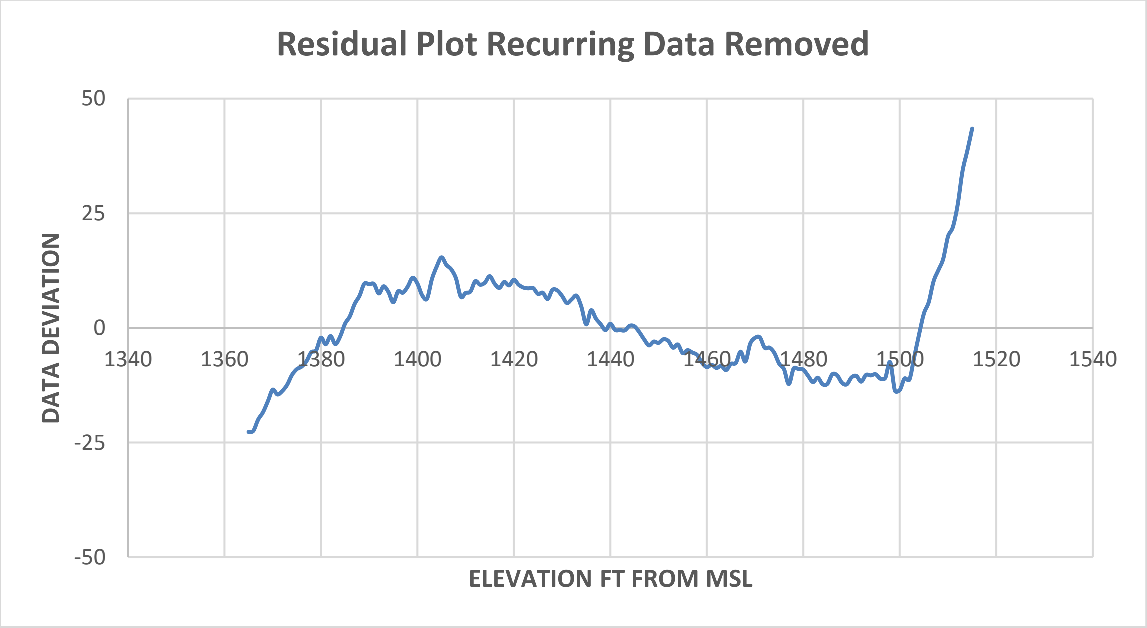


Figure 25 Residual Plot with the Recurring Data Removed

By closely observing the above plot, we can clearly see that the deviation of the data has been reduced and the curve has come closer to the neutral axis. Though, the extreme values show greater deviation from the neutral axis, but the major portion of the data has gained certainty.

Here, discharge is denoted as ‘x_1’, elevation as ‘x_2’ and ‘C’ is the regression coefficient. Power generated at a particular elevation and a certain discharge can be obtained by the above relation.

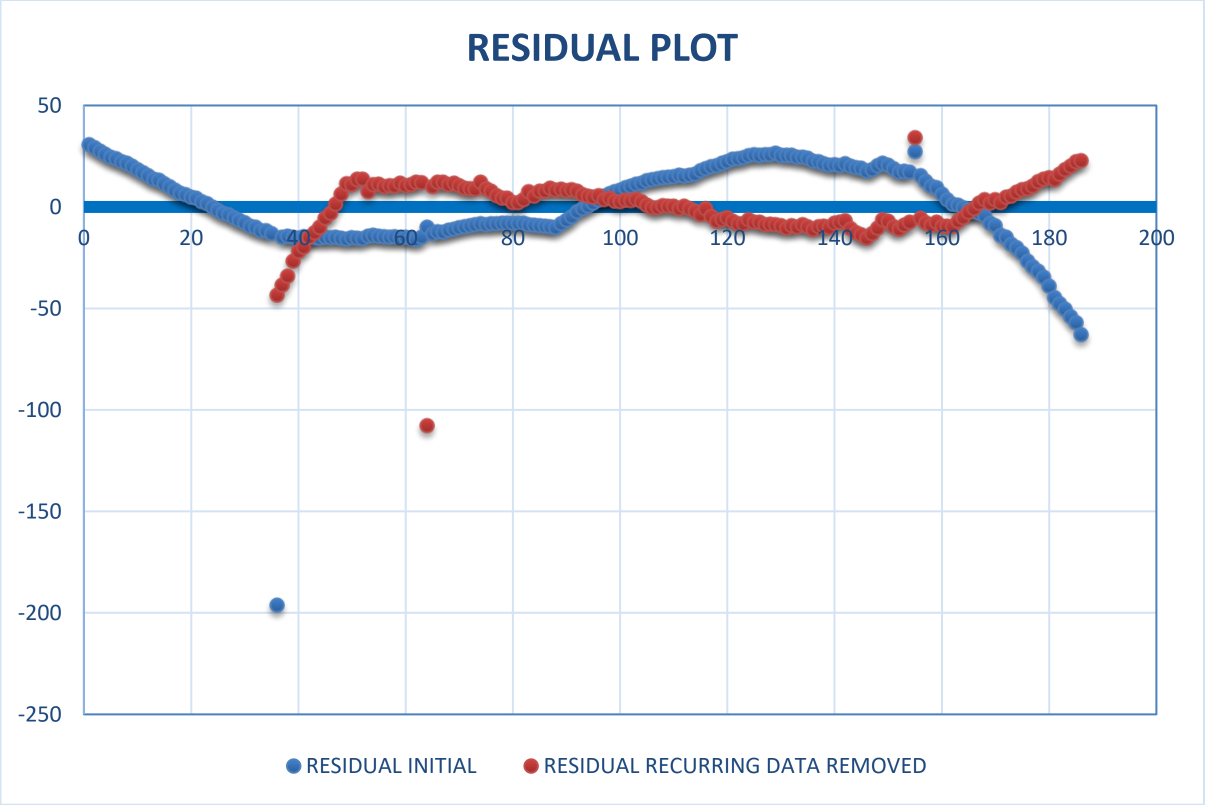


Figure 26 Comparison Residual Plot

This is the comparison of the original data with the final refined data. The difference in deviation from the neutral axis can be clearly seen in both the cases and finally we can conclude that the data is now refined to a usable form.

3.4 MATLAB Programming

3.4.1 Decision Variables

There are two decision variables

- Flood
- Power Generation

3.4.2 Objective Function

We have taken two objective functions in our dynamic programming

- To minimize flood
- To maximize power generation

3.4.3 Constraints

Optimization would be done keeping the following constraints

- Maximum lake conservation level is 1550 ft
- Minimum lake conservation level 1378 ft
- Maximum discharge through power tunnel 80,000 cusecs
- Maximum discharge through irrigation tunnel 80,000 cusecs
- Minimum operation level for spillway is 1473 ft
- Maximum power generation capacity of Tarbela is 3478 MWT
- The yearly cycle starts from August 21 of the present year till the August 20 of the next year.

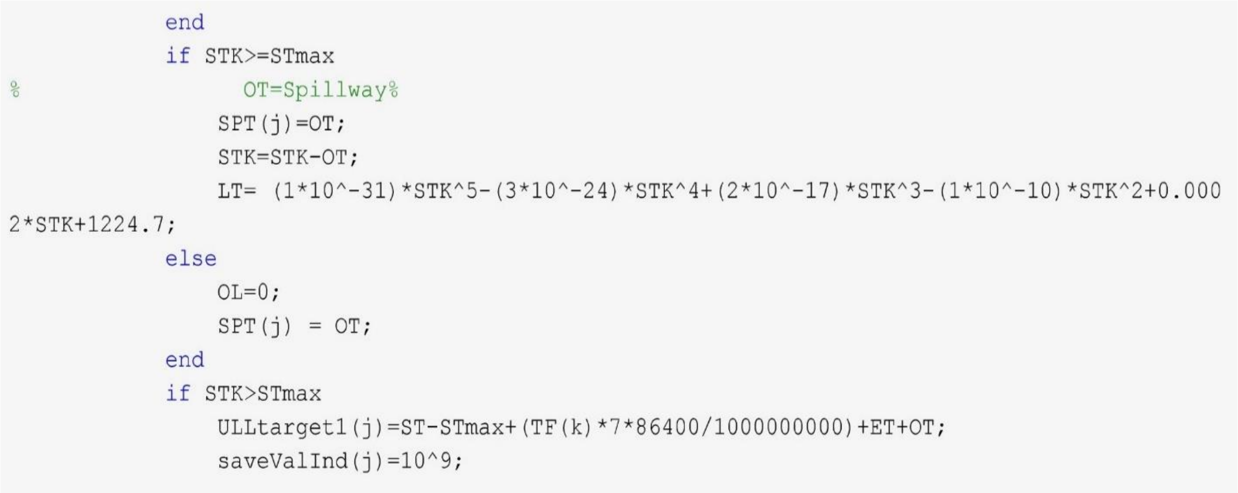
3.4.4 Program Coding

The MATLAB code was generated using these objective functions and constraints which is given below. This coding was done on the bases of various derived formulas for lake conservation level, pond area, outflows, power. These formulas can be clearly seen in the coding.

Table 14 Coding Variables

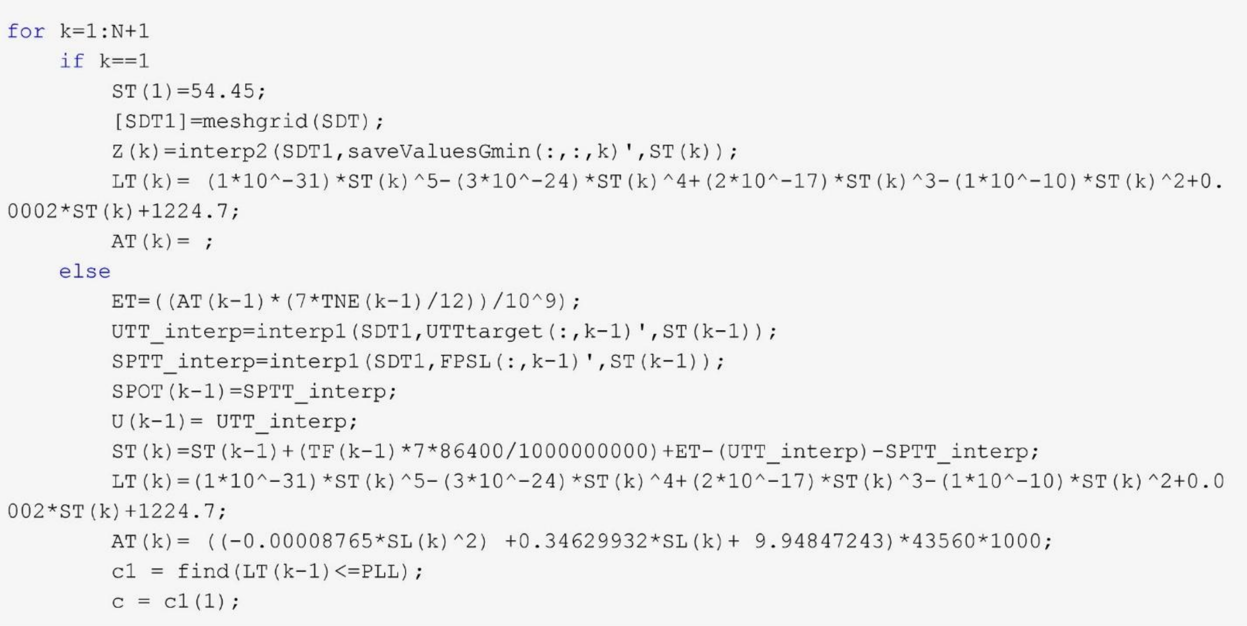
STORAGE	ST
OUTFLOW	UT
RANGE OF STORAGE OF TARBELA	STD
CONSERVATION LEVEL OF TARBELA	TCS
RANGE OF INFLOWS	UTT
EVAPORATION	ET
POND AREA	AT
SPILLWAY OPERATION	SPT

```
clc
clear all
% Import data files here for weekly model
N=(B-A)+1;%Horizon
kk=1:1:N+1;
size_ST=5; %STEP SIZE 'Storage'
size_UT=0.5; %STEP SIZE 'Out flow'
SDT=14.200  :size_ST:330;%Range of storage of Terbella
UTtarget=zeros(length(SDT),N+1);
saveValuesGmin=zeros(length(SDT),N+1);
STmax=330;
STmin=14;
%Recursive
for k=N+1:-1:1
    if k==N+1
        for i=length(SDT):-1:1
            ST=SDT(i);
            TCS1=54.45;
            saveValuesGmin(i,k)=((TCS1-ST)/TCS1)^2;
        end
        continue
    end
%     TCS(k)=(1*10^-31)*TCS(k)^5-(3*10^-24)*TCS(k)^4+(2*10^-17)*TCS(k)^3-(1*10^-10)*TCS(k)^2+
0.0002*TCS(k)+1224.7;
    for i=length(SDT):-1:1
        ST=SDT(i);
        UTT=(TMF(k)*7*86400)/1000000000:size_UT:(11000*7*86400)/1000000000;%Range of Inflows
        for j=length(UTT):-1:1
            UT=UTT(j);
            LT= (1*10^-31)*ST^5-(3*10^-24)*ST^4+(2*10^-17)*ST^3-(1*10^-10)*ST^2+0.0002*ST+122
4.7;
            AT= -2*10^-6*ST^5+0.0124*ST^4-26.337*ST^3+24787*ST^2-9*10^6*ST;
            ET=((AT*((7*TNE(k))/12))/10^9);
            STK=ST+(TF(k)*7*86400/1000000000)+ET-(UT);
            LT=(1*10^-31)*STK^5-(3*10^-24)*STK^4+(2*10^-17)*STK^3-(1*10^-10)*STK^2+0.0002*STK
+1224.7;
            if STK<STmin
                UTTtarget1(j)=ST-STmin+(TF(k)*7*86400/1000000000)+ET;
                SPT(j)=0;
                saveValInd(j)=10^9;
                continue
```

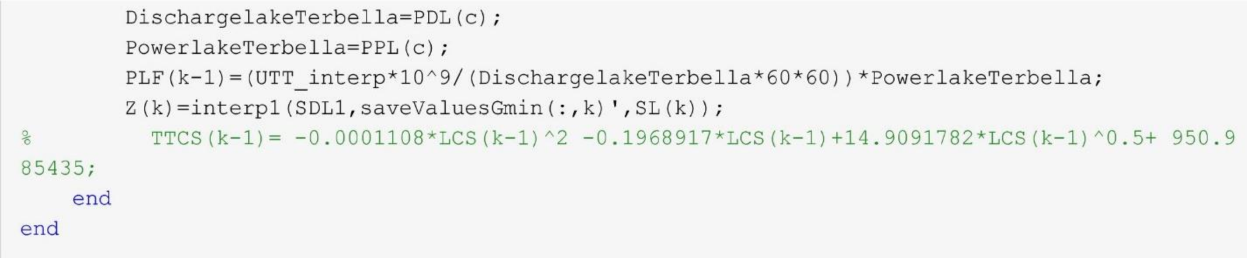


```
            end
            if STK>=STmax
%                 OT=Spillway%
                SPT(j)=OT;
                STK=STK-OT;
                LT= (1*10^-31)*STK^5-(3*10^-24)*STK^4+(2*10^-17)*STK^3-(1*10^-10)*STK^2+0.000
2*STK+1224.7;
            else
                OL=0;
                SPT(j) = OT;
            end
            if STK>STmax
                ULLtarget1(j)=ST-STmax+(TF(k)*7*86400/1000000000)+ET+OT;
                saveValInd(j)=10^9;
```

```
                continue
            end
            if  STK>TCS(k)
                TH=(((TCS(k)-STK)/0.01)^2);
            elseif  STK<TCS(k)
                TH=(((TCS(k)-STK)/0.1)^2);
            else
                TH=0;
            end
            a1 = find(LT<=PLL);
            a = a1(1);
            DischargelakeTerbella=PDL(a);
            PowerlakeTerbella=PPL(a);
            PL=(UL*10^9/(DischargelakeTerbella*60*60))*PowerlakeTerbella;
            g_interp = interp1(SDL1,saveValuesGmin(:,k)',SL(k));
            g=(((168*(116.5))-PL)/(168*(116.5)))^2+ +((OT/(1000000*7*8.64*10^-5))+LH;
            if k==N+1
                gk=g;
            else
                gk  = g + g_interp;%cost yo go function
            end
            saveValInd(j) = gk;
            ULLtarget1(j)=UL;
        end
    end
    [saveValuesGmin(i,k),Indexk] = min(saveValInd(:));
    ULLtarget(i,k)=ULLtarget1(Indexk);
    FPSL(i,k) =SPLL(Indexk);
end
```



```
for k=1:N+1
    if k==1
        ST(1)=54.45;
        [SDT1]=meshgrid(SDT);
        Z(k)=interp2(SDT1,saveValuesGmin(:,:,k)',ST(k));
        LT(k)= (1*10^-31)*ST(k)^5-(3*10^-24)*ST(k)^4+(2*10^-17)*ST(k)^3-(1*10^-10)*ST(k)^2+0.
0002*ST(k)+1224.7;
        AT(k)= ;
    else
        ET=((AT(k-1)*(7*TNE(k-1)/12))/10^9);
        UTT_interp=interp1(SDT1,UTTtarget(:,k-1)',ST(k-1));
        SPTT_interp=interp1(SDT1,FPSL(:,k-1)',ST(k-1));
        SPOT(k-1)=SPTT_interp;
        U(k-1)= UTT_interp;
        ST(k)=ST(k-1)+(TF(k-1)*7*86400/1000000000)+ET-(UTT_interp)-SPTT_interp;
        LT(k)=(1*10^-31)*ST(k)^5-(3*10^-24)*ST(k)^4+(2*10^-17)*ST(k)^3-(1*10^-10)*ST(k)^2+0.0
002*ST(k)+1224.7;
        AT(k)= ((-0.00008765*SL(k)^2) +0.34629932*SL(k)+ 9.94847243)*43560*1000;
        c1 = find(LT(k-1)<=PLL);
        c = c1(1);
```



```
         DischargelakeTerbella=PDL(c);
         PowerlakeTerbella=PPL(c);
         PLF(k-1)=(UTT_interp*10^9/(DischargelakeTerbella*60*60))*PowerlakeTerbella;
         Z(k)=interp1(SDL1,saveValuesGmin(:,k)',SL(k));
%          TTCS(k-1)= -0.0001108*LCS(k-1)^2 -0.1968917*LCS(k-1)+14.9091782*LCS(k-1)^0.5+ 950.9
85435;
    end
end
```

3.4.5 Limitations

This program has the following limitations

- We have not considered Irrigation Demand in it because we have done an opportunity Cost analysis in which we have taken two objective functions, and will measure their net economic benefit
- We have not taken the effect of rainfall and evaporation over Tarbela Reservoir because the size of Tarbela Reservoir is very small as compared to the overall size of Catchment area.

4 Chapter 4:Analysis and Results

4.1 Floods Analysis

With the aid of the program that we have developed, we have analyzed the 5 different intensity floods that have come in the last 30 years i.e.1988, 1992 , 2010, 2014 and 2018.

4.1.1 1988 Flood

Intensity	**medium**
Maximum Discharge	394000 cusecs
Flood Losses	1407 million $

4.1.2 1992 Flood

Intensity	**Low**
Maximum Discharge	332000 cusecs
Flood Losses	4926 million $

4.1.3 2010 Flood

Intensity	**High**
Maximum Discharge	527000 cusecs
Flood Losses	16400 million $

4.1.4 2014 Flood

Intensity	**Low**
Maximum Discharge	219000 cusecs
Flood Losses	614.27 million $

4.1.5 2018 Flood

Intensity	**Low**
Maximum Discharge	234000 cusecs
Flood Losses	11.5 million $

4.2 Optimization Results

The program was designed is such a way that by importing the input data it gives us the optimization Results. These optimization results were used to develop the graphs. Following are the optimization results for selected flood Years

FLOOD 1987-1988

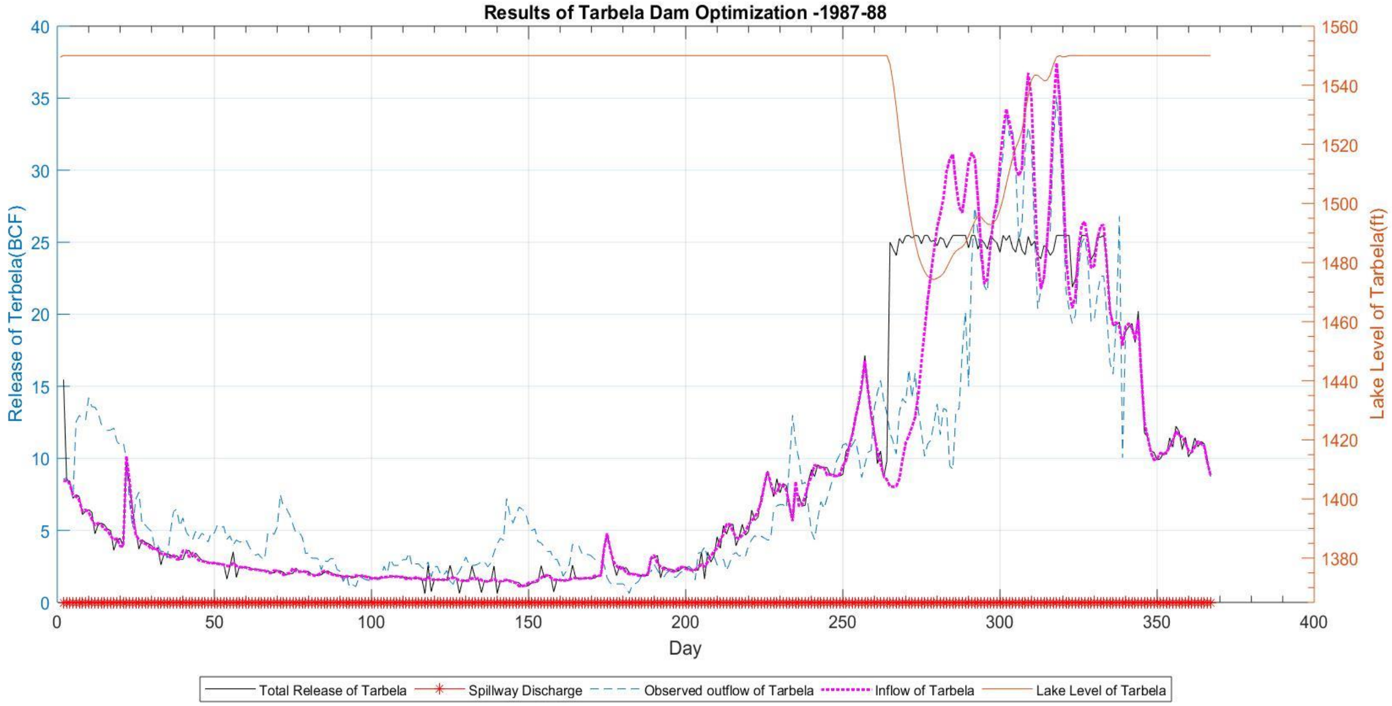


Figure 27 Flood 1987-1988 optimization Results

FLOOD 1991-1992

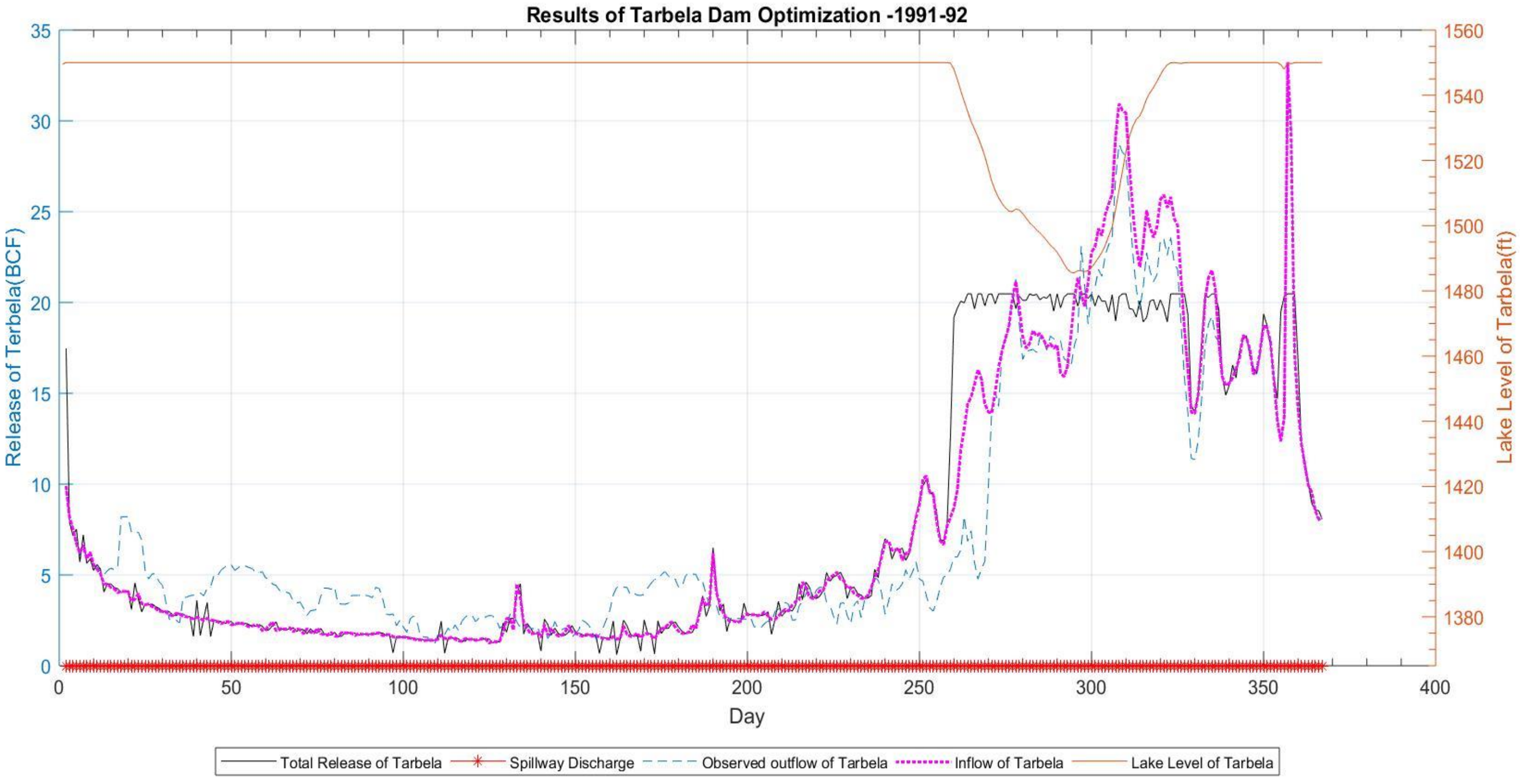


Figure 28 Flood 1991-1992 optimization Results

FLOOD 2009-2010

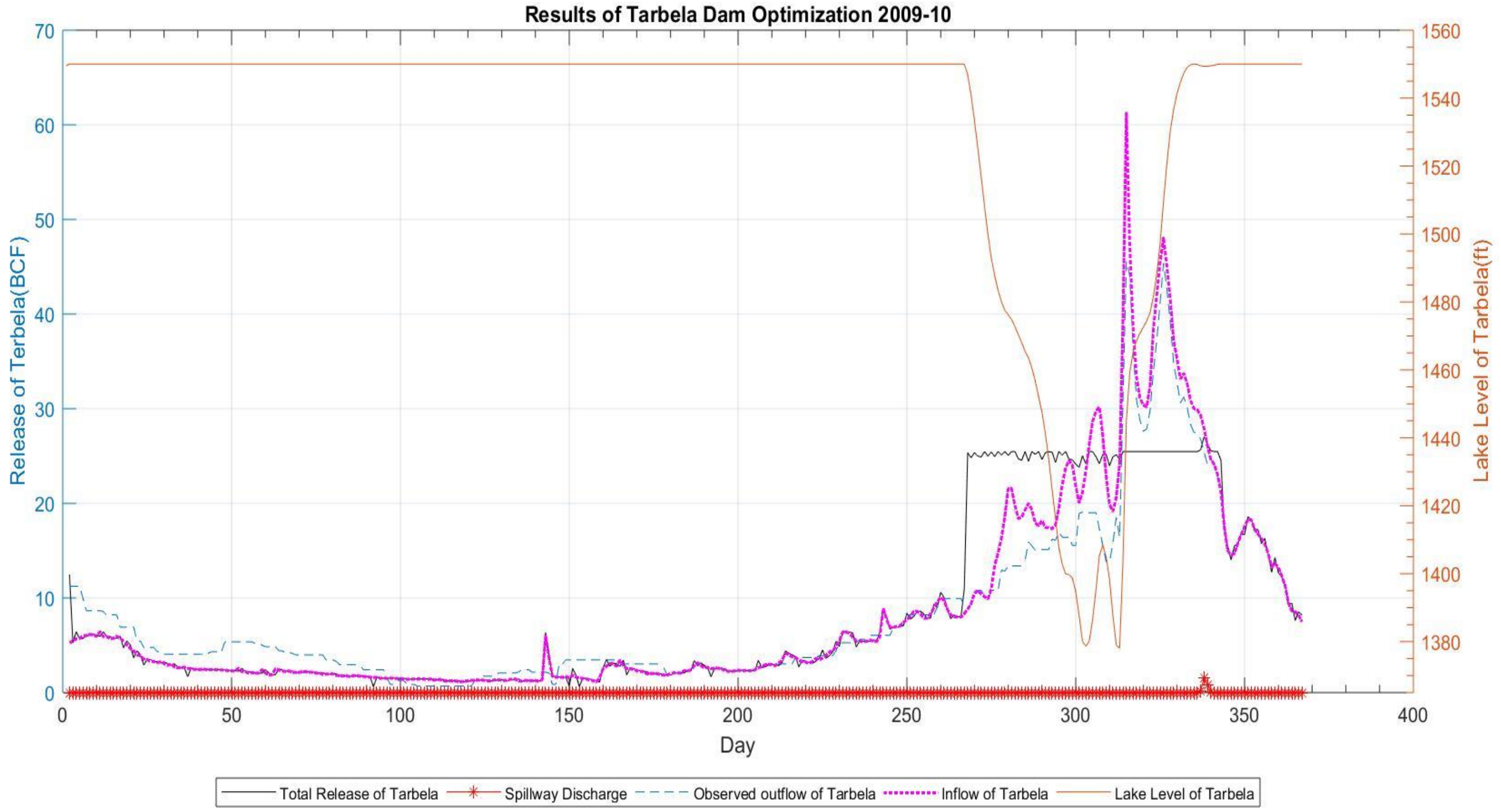


Figure 29 Flood 2009-2010 optimization Results

FLOOD 2013-2014

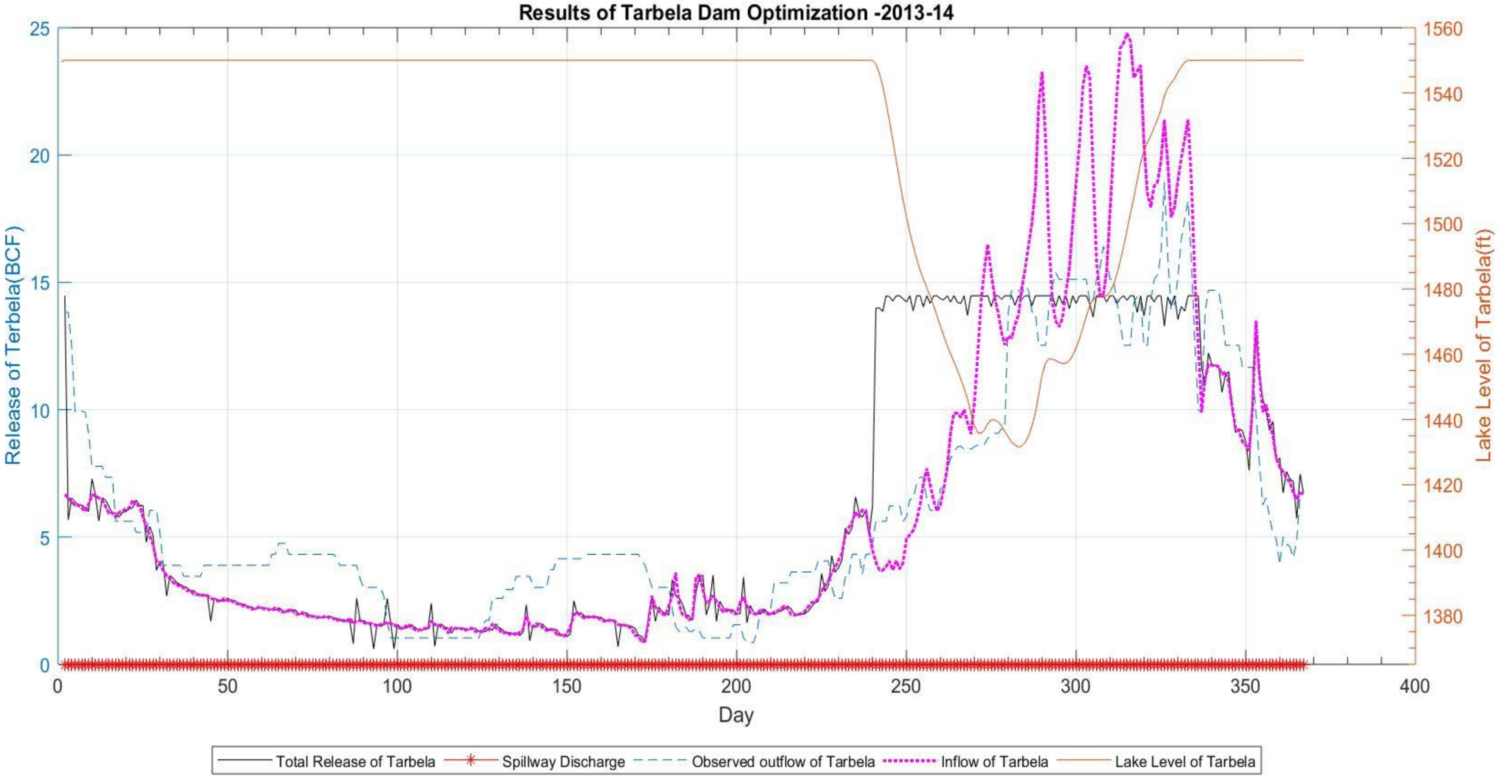


Figure 30 Flood 2013-2014 optimization results

FLOOD 2017-2018

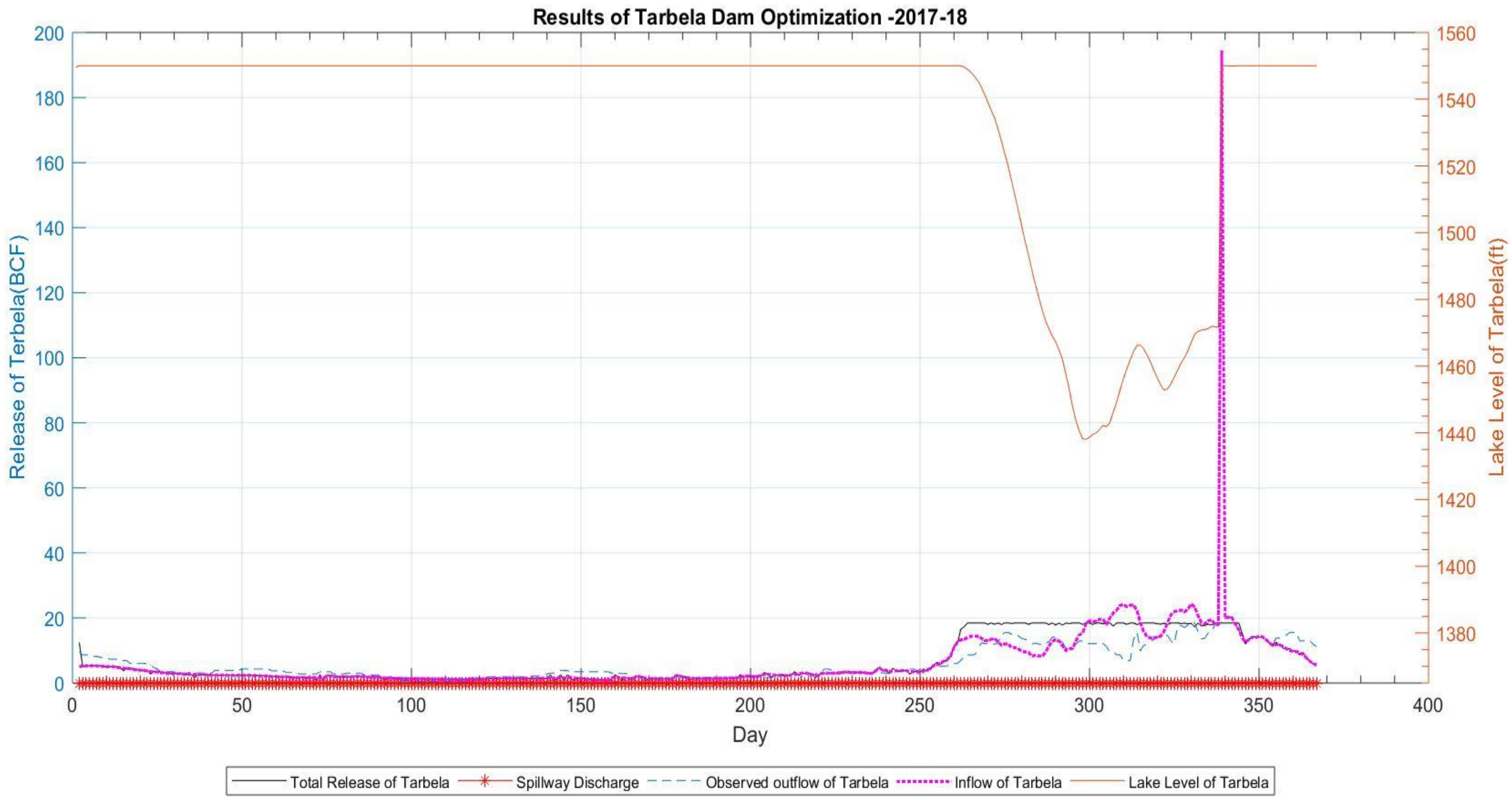


Figure 31 Flood 2017-2018 optimization Results

4.2.1 Discussions on Results obtained through graphs

4.2.1.1 Lake conservation level

The lake conservation levels obtained from optimization remains at 1550 ft. from MSL throughout the dam operation cycle except for the duration of 3 months that starts from 15th May and ends on 15 August. This maximum available head makes the power generation convenient with low discharges and highest efficiency. The drawdown of the lake level to 1470 ft. for 3 months accounts for flood mitigation in emergency situations for greater inflows in monsoon season.

4.2.1.2 Total Release Tarbela

To maintain the lake level at 1550 ft. so as to produce maximum total head for daily inflow to produce maximum power possible, we flush the same amount of water through power production tunnels we receive as an inflow throughout the year except for the three months of monsoon for which we have high inflow values. So during these 3 months the optimized outflow increases to a constant uniform value which do not cause any flood downstream. This mechanism maintains the available head to the maximum achievable level for most of the time of the year and a zero-net change in the elevation of reservoir.

4.2.1.3 Spillway Discharge

As the lake is set to the maximum level and power generation is to be done to a highest amount so no water is flushed through spillways and all of the water is utilized for electricity production.

4.2.1.4 Actual Discharge

Form the above plots we observe that the actual discharges during these floods had no controlled values that caused destruction all along. But the optimization has enabled us to release the same amount of total flood water in a systematic gradation, which made the reduction in losses as an outcome.

4.2.1.5 Inflow

In dams operation we come across various high inflow conditions. But releasing all the flood water to downstream in a flash or without controlling it, is the worst possible solution. This is the dilemma we have observed in the past in an exactly identical way. With this proposed optimized solution for these predetermined flood scenarios we have created a room for flood water, so that a controlled outflow becomes possible.

4.2.2 Power Comparison

As per the comparison of power generation in 1988, 1992, 2010, 2014 and 2018 and the power generation predicted from optimized rule curve, we can clearly observe that there is a large difference in the amount of the power generated. For a quantitative comparison, the least power generated in the year 1988 was 781 MW whereas the power predicted from the optimized rule curve was 2672 MW. The power generation in the past had no definite trend and the conservation levels as well as the discharges had a very large deviation from each other which made power generation very uncertain. Whereas by analyzing the data of power generation obtained from the optimized rule curve, we can see that the power remains almost within the same higher range (3000 MW-3478 MW) throughout the year as the conservation levels of the lake are set to 1550 ft from MSL for most time of the year. As a result, we get maximum power throughout the year and maximum lake storage available for any urgency and emergency.

Following are the comparison plots for actual power and Optimized power using the equation we derived earlier using discharge and elevation relation with power.

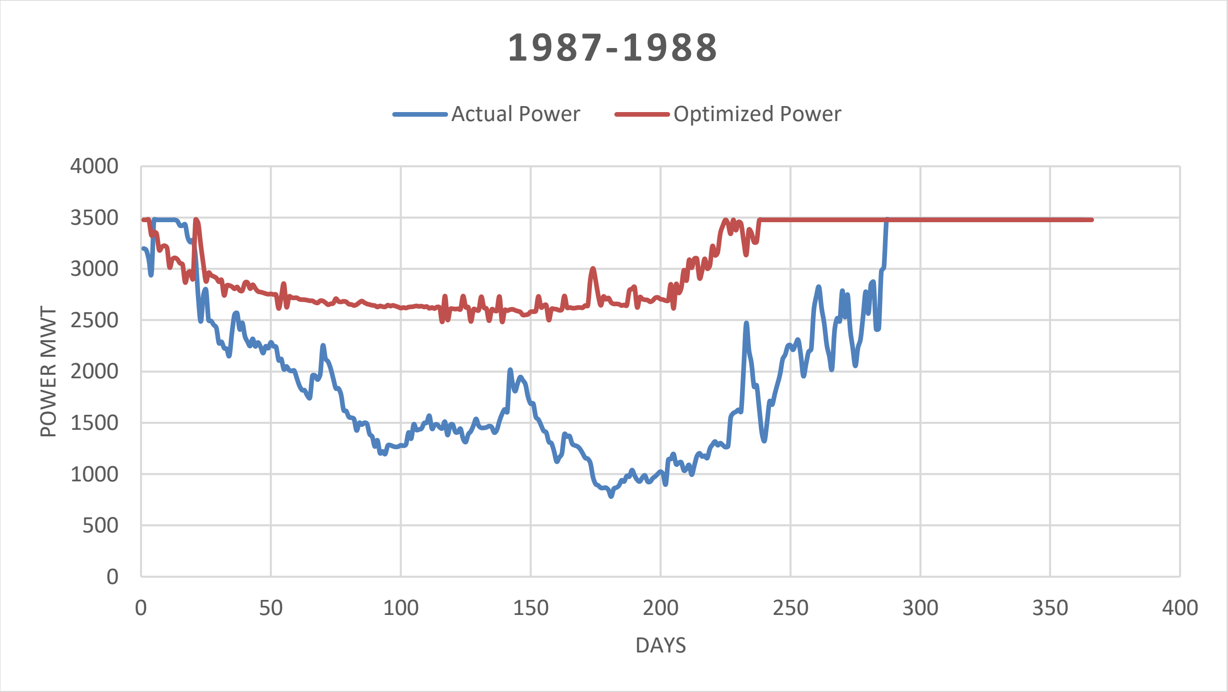


Figure 32 Flood 1987-1988 Power Comparison

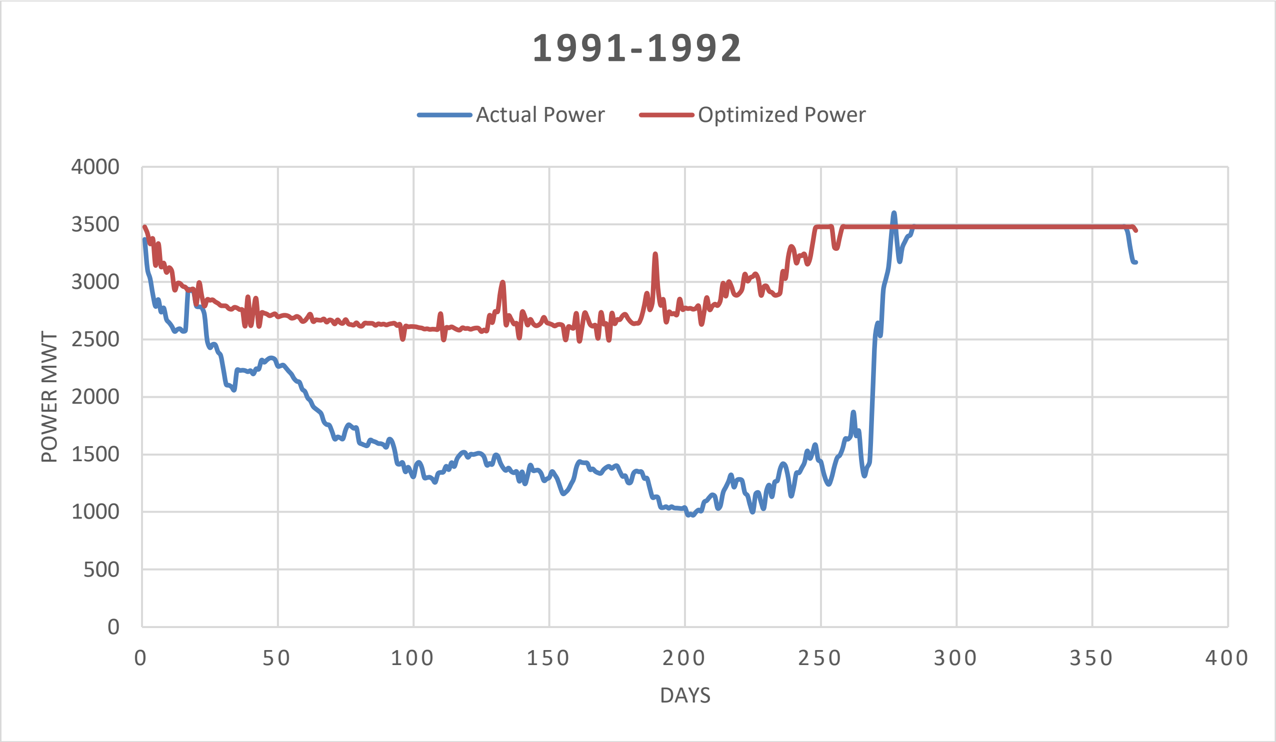


Figure 33 Flood 1991-1992 Power Comparison

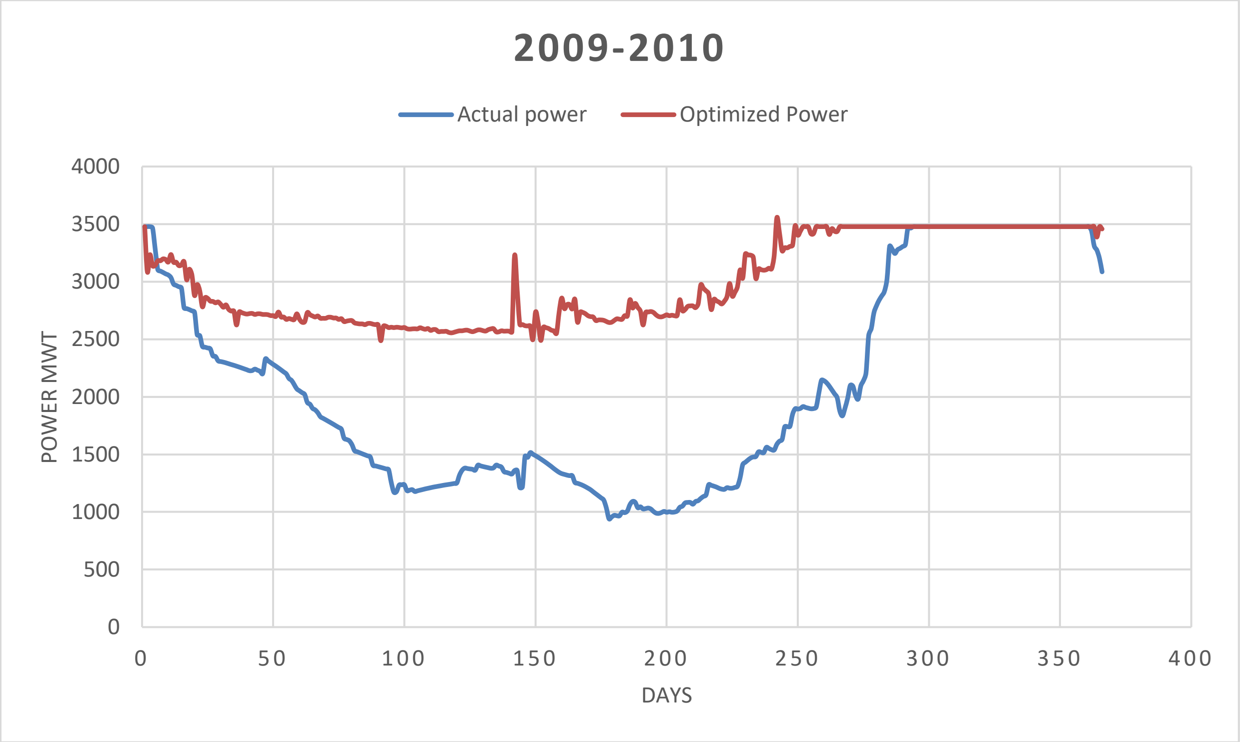


Figure 34 Flood 2009-2010 Power Comparison

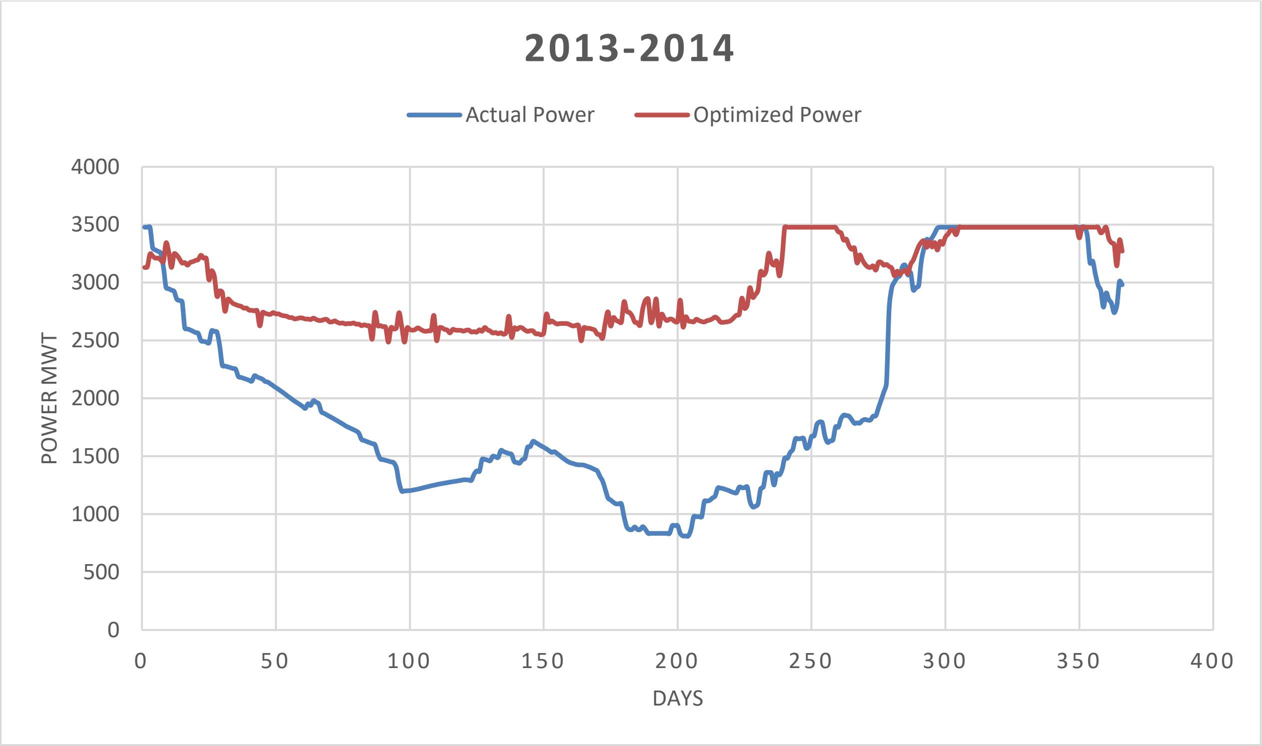


Figure 35 Flood 2013-2014 Power Comparison

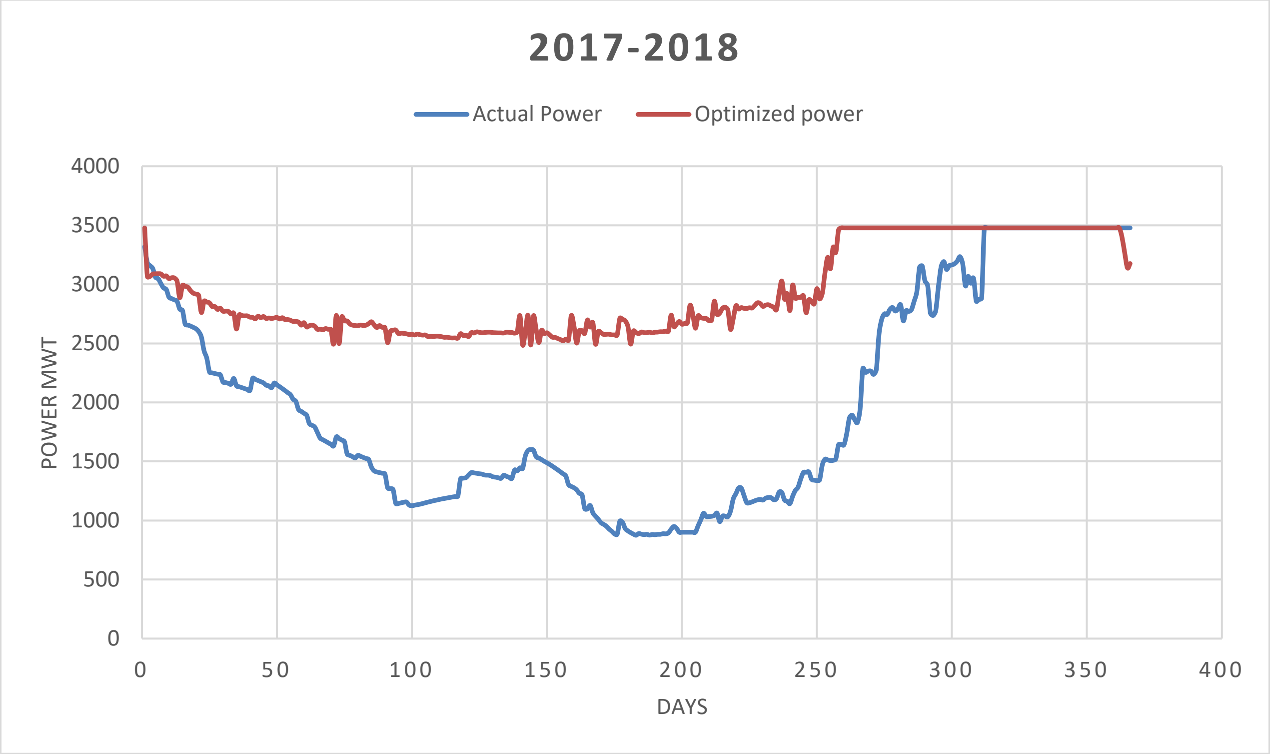


Figure 36 Flood 2017-2018 Power Comparison

4.2.3 Floods Comparison

4.2.3.1 Intensity Comparison

By analyzing these statistical comparisons, we can infer that the floods in the past had proved devastating and disastrous for Pakistan. But the optimization process has made us able to minimize these floods and reduce their peak discharges. A flood can be categorized on the basis of discharge level it possesses. The flood ranges start from a minimum or lower category of 250000 cusecs to a super high category range of more than 800000 cusecs. With the aim of lowering the flood intensities, we applied our optimized rule curve on the actual scenarios of most damaging floods of the past. In all of the cases we have been successful to mitigate these floods to a minimum level and the flood intensities are either lowered or nullified. 2010 flood, being the most devastating flood of the past was of high intensity for a discharge value of 530000 cusecs but after applying our optimization we could have reduced its intensity to “low” with a reduction of 44% in intensity similarly we achieved intensity reduction of 26% in 1988, 29 % in 1992, 30 % in 2014 and 9 % in 2018.

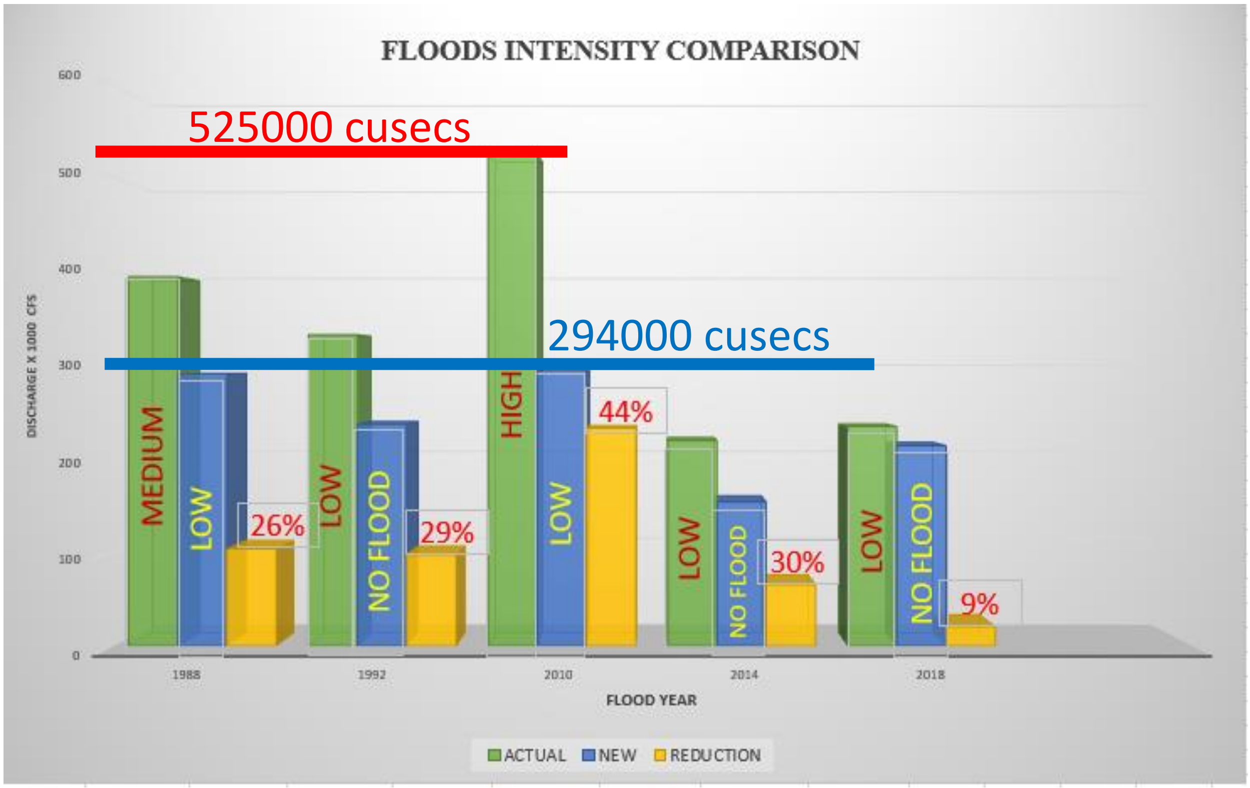


Figure 37 Floods Intensity Comparison

4.2.3.2 Losses Comparison

While comparing the floods, only discharges are not important rather the damages caused by floods in terms of lives, livestock, installed facilities, houses, buildings are also important. Considering the past floods, the 2010 flood not only had the greatest discharge but also caused a record-breaking damage to the economy. Calculating the damages of 2010 flood according to the 2019 foreign currency rate, the damages amount to humongous value of **16.4 Billion US$**. But with the optimized rule curve, we could have reduced these losses to **9.7 Billion US$** with a total reduction of losses by a hefty amount of **7.5 Billion US$.** Similarly the reduction in losses for the rest of the years is shown in the BAR Chart.

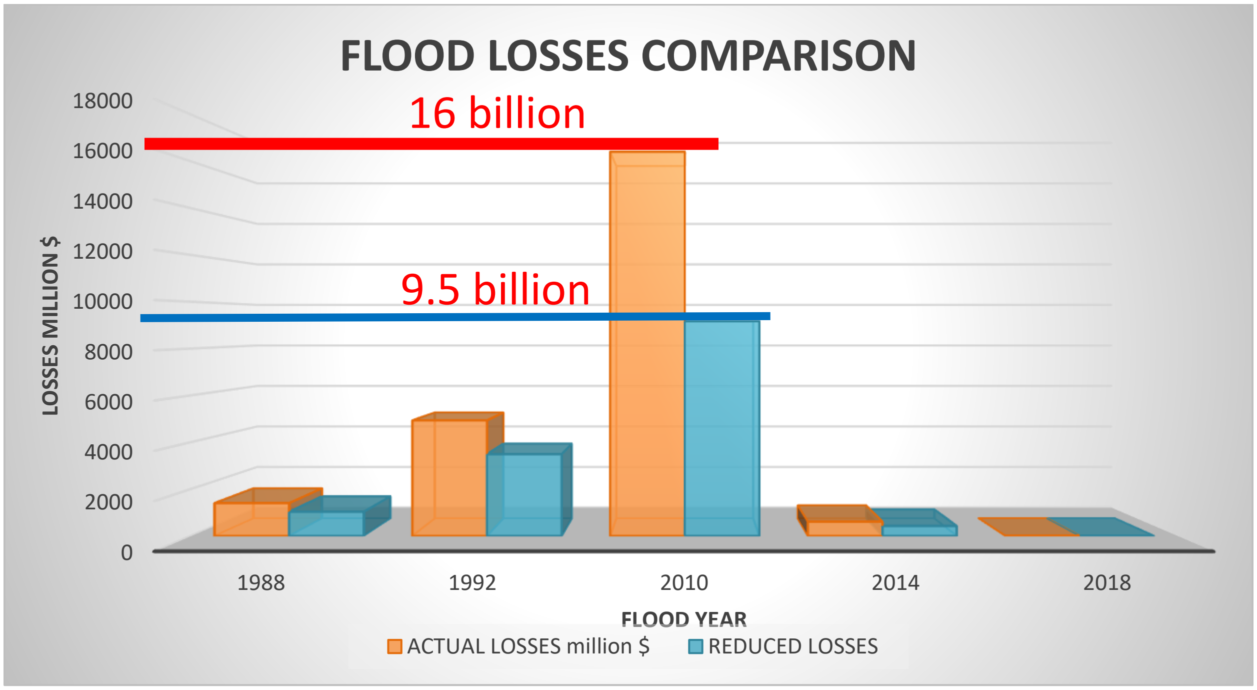


Figure 38 Floods Losses Comparison

4.3 Comparison Results Summary

Table 15 Floods Comparison Summary

	Actual	**Optimized**
1988 Flood		
Intensity	medium	low
Maximum Discharge	394000 cusecs	290818 cusecs
Flood Losses	1407 million $	1037 million $
1992 Flood		
Intensity	Low	No Flood
Maximum Discharge	332000 cusecs	236981 cusecs
Flood Losses	4926 million $	3490million $
2010 Flood		
Intensity	High	Low
Maximum Discharge	527000 cusecs	294851 cusecs
Flood Losses	16400 million $	9172million $
2010 Flood		
Intensity	Low	No Flood
Maximum Discharge	219000 cusecs	153711 cusecs
Flood Losses	614.27 million $	431 million $
2018 Flood		
Intensity	Low	No Flood
Maximum Discharge	234000 cusecs	213833 cusecs
Flood Losses	11.5 million $	10.5 million $

5 Chapter 5 : Conclusion and Recommendations

5.1 Conclusions

After the analysis of the results obtained from optimization of Tarbela dam rule curve we can conclude that:

- Floods of 1988,1992,2010,2014 and 2018 could be better managed if we had optimized reservoir operations
- Orthodox Flood Management practices should be minimized as far as possible.
- Integrated Flood Management should be preferred.
- Apart from building structures for flood control, which is a costlier solution for flood management, we can minimize its destruction by managing the flood water in mechanized and organized way, that is by the Optimization of Rule Curve.
- Due to shortcomings of electricity generation in the power sector, rule curve optimization can possibly be a cheap solution to the problem with water available for power generation throughout the year.
- The reduction in losses will help our country to save money which in turn will be utilized in development projects and prospering the country.
- Power shortfall in the country is due to lack of water resource management.

5.2 Recommendations

- Our first step should be optimizing the present reservoir operations of dams that is easy besides building new dams for the cost of billions of rupees.
- Government of Pakistan should take serious note on the water management of Tarbela dam by suitable optimization of the rule curves which will help to limit the flood affects thereby producing maximum power generation
- Tarbela Dam can produce more power when it operates on optimized rule curve. So, there should be initiation of new projects for the installation of new units
- Opportunity Cost Analysis should be run for various objective functions to obtain the optimized final rule curve.
- Irrigation, Power generation and Flood control should be given priority weightages based on their net economic results.

- We as a nation should prevent the wastage of water.
- We should not discharge water in the sea and makeup a setup to utilize that water.
- Sedimentation of Tarbela Dam should be evacuated timely, so that it doesn't further harm the capacity of the dam.

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