

POLITECNICO DI MILANO

Facolta di Ingegneria Civile, Ambientale e Territoriale



POLO REGIONALE DI COMO

Master of Science in

Environmental and Geomatic Engineering

**MODELING RESERVOIRS SYSTEM FOR
MULTIPLE OBJECTIVES IN THE RED RIVER
BASIN OF VIETNAM**

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Academic Year 2013 / 2014

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Anno Accademico 2013 / 2014

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ABSTRACT

In Vietnam, water resources management is essential for the economic development. It covers three important sectors that drive industrial productivity improvements and economic growth; those are hydropower energy, agricultural irrigation, and flood prevention. In the north of Vietnam, the reservoirs system of the Red river plays a central role in supplying water for the Red river delta and protecting the capital city of Hanoi from the threat of floods. This study focuses on these two main objectives of the Red River reservoirs system.

The thesis proposes a new way to improve the operation of the reservoirs system that includes Son La, Hoa Binh, Tuyen Quang, and Thac Ba reservoirs in the Red River basin of Vietnam based on a heuristic approach. Firstly, the historical operating data of the Hoa Binh reservoir is analyzed and then synthesized into a simple operating rule using the HEC-ResSim program. An improvement of the reservoir system's operation is achieved by implementing different rule curves. Rule curve is a simple and practical method for actual management; it defines desired reservoir storages, which can serve multiple purposes such as flood control, water supply or hydropower control.

SOMMARIO

In Vietnam, la gestione delle risorse idriche è essenziale per lo sviluppo economico. Essa comprende tre importanti aspetti che guidano il miglioramento della produttività industriale e la crescita economica: la produzione di energia idroelettrica, l'irrigazione delle colture agricole e la prevenzione degli straripamenti. Nel Nord del Vietnam, il sistema dei bacini artificiali del Fiume Rosso ha un ruolo centrale nella fornitura di acqua alla regione del delta, oltre a proteggere la capitale Hanoi dal rischio di inondazioni.

Scopo della presente tesi è illustrare una proposta per il miglioramento della gestione del sistema delle riserve idriche del bacino del Fiume Rosso – comprendente i laghi artificiali di Son La, Hoa Binh, Tuyen Quang e Thac Ba – attraverso un approccio euristico. In primo luogo, è stato analizzato lo storico delle operazioni sulla diga dell'Hoa Binh, al fine di ottenere un modello semplificato di gestione attraverso il programma HEC-ResSim. Il miglioramento della gestione del sistema di bacini è stato quindi ottenuto attraverso l'implementazione di diverse curve di regolazione. La curva di regolazione è un sistema pratico e semplice per l'effettiva gestione delle riserve idriche di bacini artificiali, che può essere impiegata efficacemente per il controllo delle inondazioni, della fornitura d'acqua e della produzione di energia idroelettrica.

CHAPTER 1

THE RED RIVER BASIN AND THE RESERVOIR SYSTEM

This chapter presents an ephemeral overview to the Red River Basin and reservoir system, deliberating main natural conditions, and specific operating scheme.

1.1. Territory

The Red River Basin (*Figure 1.0-1*) is the second largest basin of Vietnam. It is located between 20000N and 25030N, and 100000E and 107010E. The total area of the basin is approximately 169,000 km², of which 81,240 km² (48%) in China's territory, 86,600 km² (51.35%) in Vietnam, and the rest in Laos. Governmentally, the Red River basin covers 26 provinces and cities in the north of Vietnam, with the total population of about 30 million in 2009.

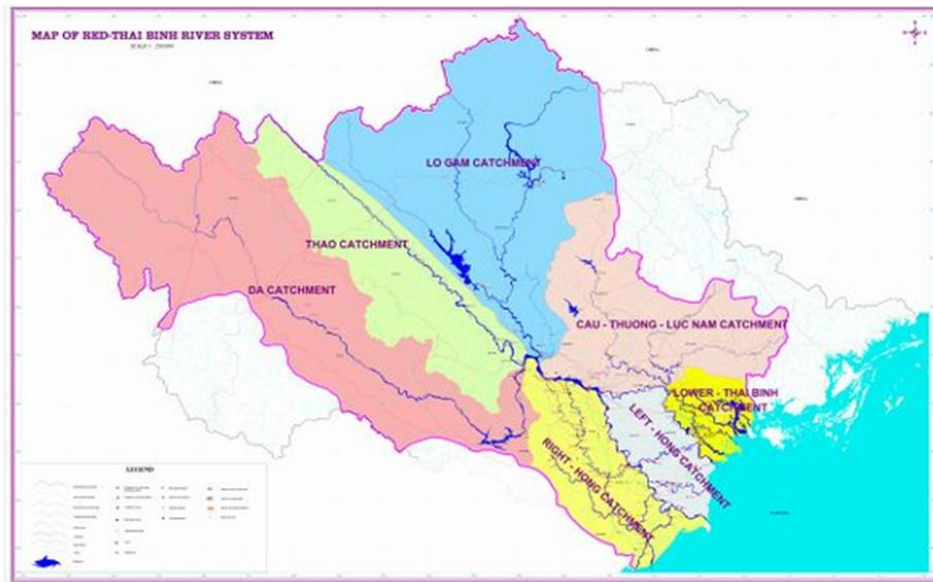


Figure 1.0-1. Area of the Red River delta in Vietnam¹

The whole basin is characterized by two distinguished seasons: the wet season from May to October and the dry season from November to April of the following year. Annual rainfall varies from 1,200 to 4,800 mm/year in Vietnam part, and about 80% of rainfall occurs in the rainy season. The flood (high flow) season is from June to October. Because of uneven rainfall, flows through the basin are unevenly

¹ Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>

distributed in time, causing flood and waterlogging in the rainy season and water shortages in the dry season (Quach, 2011).

The basin is formed by three large rivers, namely: Da River, Lo - Gam River and Thao River.

1.1.1. The Da River

The Da river is the largest subdivision of the Red river system. Its total area and total length are 52900 km² and 1010 km with 26800 km² and 570 km in Vietnam territory respectively. Da river flows in the North West – South East direction and joins the Red river at Trung Ha district, which is 15 km to the south of Viet Tri city (*Figure 1.0-2*).

More than 86.5% of the whole sub-basin area of Da River in Vietnam is forestry land and hilly land. Along the river, there are 557 small dams and 167 small reservoirs for irrigating 26500 ha of agricultural land.

There are three multi-objective reservoirs located in the Da river:

- Lai Chau reservoir with the designed Normal Water Level (NWL) at +295 m is under construction and expected to finish in 2016.
- Son La reservoir, which has been operated since 2010 with the NWL at +215.0m; and this has increased the total active volume of the Hoa Binh and Son La reservoirs to nearly 12.5 billion m³. The maximum capacity against floods of the Son La reservoir might reach 7 billion m³.
- Hoa Binh reservoir was set up in 1991.

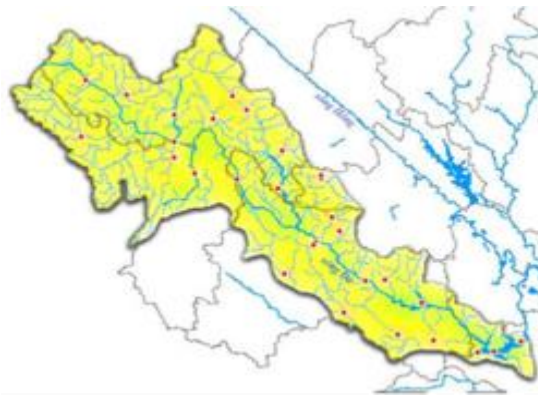


Figure 1.0-2. The Da River Basin²

² Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>

1.1.2. The Lo-Gam River

The Lo River originates from China, flows into Vietnam at Ha Giang province and then joins the Red river system at Viet Tri city. The Lo River has a total area of 38980 km², 22600 km² of which lies in Vietnam territory with the length of 217 km (*Figure 1.0-3*).

The Lo River sub-basin area is 2.26 million ha, including 1.52 million ha for forestry, 109 thousand ha for irrigation.

The Gam River is the largest branch of the Lo river system; it flows in the North East – South West direction. The river's area in Vietnam is 9700 km², which has a narrow river-bed, high river-bed inclination and many waterfalls.

Located on the main stream of the Gam River, the Tuyen Quang hydroelectric reservoir came into operation in 2010. Its NWL is +120 m, the total capacity is 2.26 billion m³, the capacity against flooding for the Red river delta is 1 billion m³ and the install capacity of the hydroelectric plant is 342 MW.



Figure 1.0-3. The Lo – Gam River Basin³

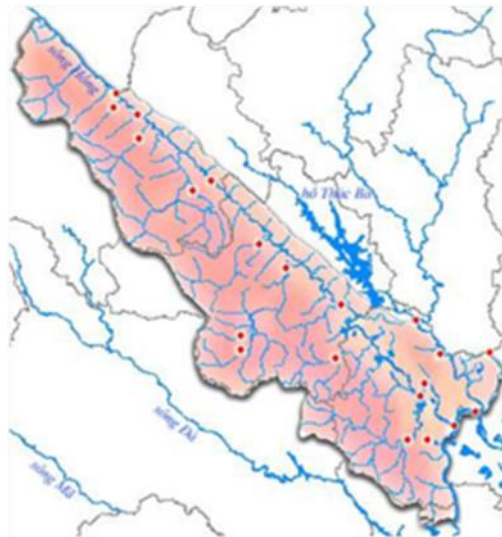
³Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>

1.1.3. The Thao River

The Thao River flows from the North West direction. Its total length is 902 km, which has 207 km in Vietnam. The Thao basin area in Vietnam is 11910 km² with many valleys extending to the lower land (*Figure 1.0-4*).

The Thao River is joined by the Lo river from the left bank at Viet Tri city. The height difference between the headwater and the end of this river is 68 m, and the average inclination IAV = 0.016‰.

There is no large hydroelectric power station on the main stream of the Thao River. The whole basin of the Thao River has 1089 irrigational projects, including 161 small reservoirs and 343 rolling weirs. The irrigational system assures enough water for 26.5 thousand ha rice in winter-spring season and 50% of the irrigational demand for 30 thousand ha rice in harvest season.



*Figure 1.0-4. The Thao River Basin*⁴

⁴ Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>

1.2. The reservoir system

1.2.1. Reservoirs on the Da River

1.2.1.1. Son La Reservoir

The Son La reservoir is the largest one in the Red River delta and the second step on the main stream of the Da River.

The NWL of Son La reservoir is + 215.0 m, the total capacity of the reservoir is 9.26 billion m³, and the active capacity is 6.5 billion m³ (According to the *Power Engineering Consulting Joint Stock Company 1-PECCI*).

These are three main objectives of Son La reservoir:

- Flood control: the total flood control capacity on the main stream of the Da River is 7 billion m³, comprising Son La reservoir (4.0 billion m³), and Hoa Binh reservoir (3.0 billion m³). In comparison with the period before the completion of Son La reservoir, the guaranteed flood control level at the same water level rise by 250 and 150 years. The maximum flood level in Hanoi is at +13.4 m in case the 500-year periodic flooding occurs; and at +13.1 m in case of the 300-year flood happens.
- Water supply: After the completion, Son La and Hoa Binh reservoirs enhance the average flow at 600 - 800 m³/s to the main stream of the Red River in dry season.
- Electricity generation: It is estimated that Son La hydroelectric station yearly output will reach 9.1 billion kWh and it will help the power of Hoa Binh hydroelectric station rise by 1.27 billion kWh/year.

1.2.1.2. Hoa Binh Reservoir

Hoa Binh reservoir (*Figure 1.0-5*) is the bottom step of the Da River. Hoa Binh reservoir has played an essential part in the Red River Delta development since 1991:

- Flood control: Hoa Binh reservoir attenuates the damage of floods to the Red River Delta. Specifically, no flood has been classified as the flood retarding and diversion since 1991. Moreover, during a severe flood in August 1996, the flood peak in Hanoi reached 12.47 m (that would have been 13.46 m without the flood control of Hoa Binh reservoir), exceeding the alert level 3 by 1.02 m, and staying above the alert level 3 for 7 days. The regulation of the reservoir made the flood level fall by 0.9m, which kept the main dike system intact.
- Water supply: Hoa Binh reservoir only discharges 1.5 – 2.4 billion m³ of water for submerging during the winter – spring crop, occupying over 60% of the total water discharge. Supplying water for submerging is important

since it decides the productivity of the Red River delta with 635 thousand hectare rice of the winter – spring crop to be irrigated.



Figure 1.0-5. Hoa Binh Reservoir⁵

- Referring to *PECCI*, operating data of Hoa Binh reservoir are:
 - + NWL: 115 m
 - + Flood control level: 117m
 - + Water level before flood: 85m
 - + Total capacity: 9.45 billion m³
 - + Capacity against flood: 5.6 billion m³

1.2.2. Reservoirs on the Lo River Basin

1.2.2.1. Thac Ba Reservoir

Thac Ba reservoir has the key dam in Yen Bai province. It has been operated since October 1971, which is the first reservoir in the Northern Vietnam.

Between 1971 and 1990, Thac Ba was the largest hydroelectric reservoir. The station usually operated all three set of engines constantly to the maximum capacity.

According to *PECCI*, the NWL of Thac Ba reservoir is +58.0m, its total capacity is 2.94 billion m³, and the active capacity is 2.16 billion m³.

⁵ Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>



Figure 1.0-6. The head dam of Thac Ba Reservoir⁶

1.2.2.2. Tuyen Quang Reservoir

Tuyen Quang reservoir was constructed on the Gam River at Na Hang district, Tuyen Quang. Tuyen Quang reservoir objectives are flood control, power generation, irrigation conditions improvement, and navigation. The basic characteristics of the reservoir are:

- Delta area near dam site 14,972 km²
- NWL + 120.0 m
- Total capacity 2.26 billion m³, effective capacity 1.699 billion m³
- Capacity against flood: 1 billion m³

1.3. Inter-reservoir regulation of Son La, Hoa Binh, Thac Ba and Tuyen Quang reservoirs during flooding season (*Decision No.198/QĐ-TTg*)

1.3.1. Operation during early flood (15th June to 19th July)

Elevation of the per-flood highest water levels during the early flood period is specified in *Table 1.0-1*

Reservoir water levels				
Reservoir	Son La	Hoa Binh	Tuyen Quang	Thac Ba
Water level (m)	200.0	105.0	105.2	56.0

Table 1.0-1. Normal water levels of the reservoirs in the period of early flood

⁶ Source: <http://xake.elet.polimi.it/mediawiki-1.19.1/index.php>

1.3.1.1. Operation before 25th June

a Rules for Hoa Binh Reservoir

- Discharge cannot exceed 4000 m³/s;
- When the inflow exceeds 4000 m³/s, the reservoir holds water up to 107 m for flood protection;
- When water level reaches 107m while the forecasted inflow is greater than 4000 m³/s, Son La reservoir will be used up to the water level at 205m to keep the elevation in Hoa Binh reservoir not exceeding 107m;
- If the forecasted elevation would not exceed 107m, Hoa Binh reservoir can discharge an amount equal to the inflow.

b Rules for Tuyen Quang Reservoir

- Discharge to downstream cannot exceed 1500 m³/s;
- When the inflow is greater than 1500 m³/s, the reservoir can store up to level 113m;
- When the water level is at 113m while the forecasted inflow is greater than 1500 m³/s, the reservoir can discharge an amount equal to the inflow.

c When the inflows to the reservoirs are reduced, reservoir operation is back to as stated in *Table 1.0-1*

1.3.1.2. Operation during flooding period from 26th June to 19th July

a The Da River cascade

- When the forecasted elevation of Hanoi exceeds 11.5 m in the next 24 hours, Son La reservoir will be used up to level of 205m to keep the Hanoi water level not exceeds 11.5 m. When the Hanoi water level is below 11m, water discharge operation is regulated toward as specified in *Table 1.0-1*;
- Hoa Binh reservoir will not be exploited for flood protection while the water level in Hanoi is not exceed 11.5 m;
- When Hanoi elevation is above 11.5m, Son La reservoir is used up to elevation +208 m, Hoa Binh reservoir is used up to elevation +108 m for flood control.

b Tuyen Quang Reservoir

- When the predicted water level in Lo River at Tuyen Quang city exceeds 26m in the next 24 hours and continuing to rise, Tuyen Quang reservoir is allowed to use up to elevation +113m for flood relief, keeping the water level at Tuyen Quang city below 27m;
- When the water level in Tuyen Quang is below 26m, the reservoir will be regulated towards as stated in *Table 1.0-1*.

1.3.1.3. From 10th July if there is no flood, the reservoir system is started to be regulated in order to reach the water level as stated in *Table 1.0-2* until 20th July

1.3.2. Operation during main flooding period (20th July to 21st August)

Elevation of the highest water level before flooding period in the reservoirs is stipulated as in *Table 1.0-2*.

Reservoir water levels				
Reservoir	Son La	Hoa Binh	Tuyen Quang	Thac Ba
Water level (m)	194.0	101.0	105.2	56.0

Table 1.0-2. Normal water level of the reservoirs in the main flooding period

1.3.2.1. The Da River cascade

a The estimated water level at Hanoi exceeds 11.5m in the next 24 hours

- Son La reservoir is used up to elevation of 196m for flood protection in advance of Hoa Binh reservoir;
- If the forecasted Da river flood continues to increase, Son La and Hoa Binh reservoirs are used up to water level 200m and 107m respectively to keep the elevation in Hanoi below 11.5m;
- When the water level in Hanoi is below 11m, reservoir operation will be gradually brought to the level as specified in *Table 1.0-2*.

b The water level in Hanoi exceeded 11.5m and is expected to rise in upcoming 24 hours

- Son La reservoir is used up to the water level 203m for flood protection in advance of Hoa Binh reservoir;
- If the Da river flood is forecasted to continue increasing, the further use of Son La capacity of 205m or higher elevation would be decided, Hoa Binh capacity of 109m or higher for flood relief to keep the water level in Hanoi under 13.1 m;
- When Hanoi water level is below 12.5 m, based on forecasts from the National Center for Meteorology and Hydrology (NCMH) for water discharge, water levels are gradually brought back to as specified in *Table 1.0-2*.

c When the water level in Hanoi is 13.1m and expected to exceed 13.4m in the next 24 hours

- Son La reservoir is used up to elevation of 215m, Hoa Binh is used to level of 117m to keep the flood water level in Hanoi under 13.4m;
- When Hanoi water level is below 13 m, based on forecasts from the NCMH for water discharge, water levels are gradually brought back to as specified in *Table 1.0-2*.

1.3.2.2. Tuyen Quang Reservoir

a The forecasted water level in the Da River and the Thao River is trivial and the elevation of Lo River at Tuyen Quang city exceeds 27m in the next 24 hours

- Tuyen Quang reservoir is allowed to use up to the water level at 115m for flood relief to keep the water level in the Lo River in Tuyen Quang city under 27m;
- When the elevation of Tuyen Quang city is below 26m, water discharge operation is brought back to as specified in *Table 1.0-2*.

b The predicted water level of the Red River in Hanoi is over 12.5m in upcoming 24 hours and Hoa Binh Reservoir elevation is above 109m or the elevation in Hanoi is above 12.8m

- Tuyen Quang reservoir joins regulating together with Hoa Binh and Son La reservoirs to keep the water level of the Red River in Hanoi under 13.4m (Reservoir water level does not exceed 120m);
- When the elevation of Hanoi is below 12.5m, water discharge operation is brought back to as specified in *Table 1.0-2*.

1.3.2.3. Thac Ba Reservoir

If the predicted water level in coming 24 hours of the Red River in Hanoi is greater than 12.5m

- Thac Ba reservoir joins regulating together with Hoa Binh, Son La and Tuyen Quang reservoirs to keep the water level of the Red River in Hanoi under 13.4m (Thac Ba water level does not exceed 58m);
- When the elevation of Hanoi is below 12.5m, water discharge operation is brought back to as specified in *Table 1.0-2*.

1.3.2.4. General operation

- When Son La, Hoa Binh, Thac Ba, and Tuyen Quang reservoirs have fully used their capacity, flood continues to rise in upcoming 24 hours, and Hanoi water level will be exceeding elevation of 13.4 m, the Prime Minister will announce alarm flood emergency. The reservoirs will prepare to switch into safety working mode. On the Red River Delta, preparation for flood protection against over-design flood will be initiated;
- In the absence of flooding, depending upon the weather, it is considered and allowed the reservoirs to raise the water level higher than as specified in *Table 1.0-2* to improve the efficiency of power generation. When forecasting shows there will be flooding occurs, water discharging will bring the reservoirs water levels to which as specified in *Table 1.0-2*;
- After 10th August, based on the weather forecast from NCMH, if flooding is likely to end soon, the water level of the reservoirs will be raised. Son La reservoir will be particularly considered to store water earlier.

1.3.3. Operation during the late flood period

- From 22nd August, Thac Ba reservoir is allowed to gradually store water to the normal level; Son La, Hoa Binh, and Tuyen Quang reservoirs based on the weather forecast from NCMH and if flooding is likely to end soon and is permitted by the Central Committee For Flood and Storm Control (CCFFS), will gradually store water to the normal level until 30th September;
- During the water storing period, Son La reservoir is allowed to use capacity from NWL to reinforced water level (217.83 m) for flood protection for downstream;
- When Hoa Binh and Tuyen Quang, and Thac Ba reservoir have stored water up to their normal levels and the inflows are increasing, the reservoirs are allowed to discharge the same amount to the inflows.

CHAPTER 2

MAIN ISSUES OF THE RED RIVER DELTA

In this chapter, we will analyse primary problems of the Red River Basin. After that is a literature review of previous studies which address methods to remediate these problems. Lastly, the HEC-ResSim program will be introduced as a new approach to model the basin as well as to find a better option for the regulation scheme.

2.1. The main issues of Red River Delta

2.1.1. Flood

In recent years, there has been a large number of big floods. These floods are combinations of floods from three upstream branches: the Da, Thao and Lo River (Quach, 2011). If they are formed by one of the three tributaries, their characteristics are similar to the mountainous area floods. They have several peaks, high fluctuation; they are fast rising and fast decreasing. If they are combined by more than one tributary, they will be fast rising, big and long duration.

Flood of the Da River is the main source causing big floods on the Red River. On average, it contributes 49% of eight flooding days (max is 69%) at Son Tay station. If only considered the flood peak, there are 69% of flood peaks of the Da River constituting the flood peaks of the Red River (*Table 2.0-1*).

Number	Station	River	Average flood	Peak flows	Date
			flows		
			m ³ /s	m ³ /s	
1	Sontay	Red	16,785	37,800	Aug-1971
2	Lai chau	Da	7,242	14,200	Aug-1932
3	Ta Bu	Da	9,919	22,700	Aug-1996
4	Hoa Binh	Da	9,618	22,700	Aug-1996
5	Yen Bai	Thao	5,143	10,350	Aug-1971
6	Ham Yen	Lo	2,897	5,700	Jul-1986
7	Chiem Hoa	Gam	3,188	6,220	Aug-1971
8	Tuyen Quang	Lo	5,156	11,700	Aug-1971
9	Vu Quang	Lo	5,467	14,000	Aug-1971

Table 2.0-1. Historical flood events at some stations in the Red River Basin

2.1.2. Water shortage

In the north of Vietnam, water shortage usually occurs in the dry season, from November to April of the following year. In recent years, water shortage has become more frequent and severe. The minimum water level in the Red River at Son Tay station has been getting lower and lower. It was 2m, 1.94m and 1.46m in 1999, 2004 and 2006, respectively. Especially, it was 0.66m in the end of March and 0.4m in the beginning of April in 2010, the latter is the historical event in the last 100 years. Minimum discharge at Son Tay station in March 2002 was at 380 m³/s while the total water demand in this time was about 500 m³/s, which led to a lack of more than 10 million m³/day. There are four main reasons for this problem.

The first reason is the unequal distribution of rainfall. The total rainfall in dry season constitutes only 24% of the annual rainfall.

The second reason is the climate change and abnormal weather phenomena such as La Nina or El Nino.

The third reason is the erosion of the Red River cause by the operation of Hoa Binh reservoir. Many forests were destroyed or overexploited that reduced the ground water table.

Finally yet importantly, it is due to low inflows from China. According to the NCMH, the inflows from China in all three tributaries are at the lowest level in history. Minimum flows in November 2009 and March 2010 on the Da River at Lai Chau were 23 m³/s and 56 m³/s, respectively, while the corresponding lowest in the past were 332 m³/s and 103 m³/s. These figures on the Thao River at Lao Cai province were 141 m³/s and 130 m³/s in comparison with the lowest ones of 161 m³/s and 97 m³/s in the past (Quach, 2011).

2.1.3. Electricity

Hydropower is one main energy source of Vietnam; it contributes from 35% to 40% of total energy consumed. Hoa Binh hydropower plant has been the biggest one that has supplied annually about 8 billion kWh since 1994, accounting for 35% energy of the northern part, and 15% of the country. After 20 years of operation, the yearly energy production has increased from 1.3 TWh in 1989 to 10.136 billion TWh in 2008 (*Figure 2.0-1*).

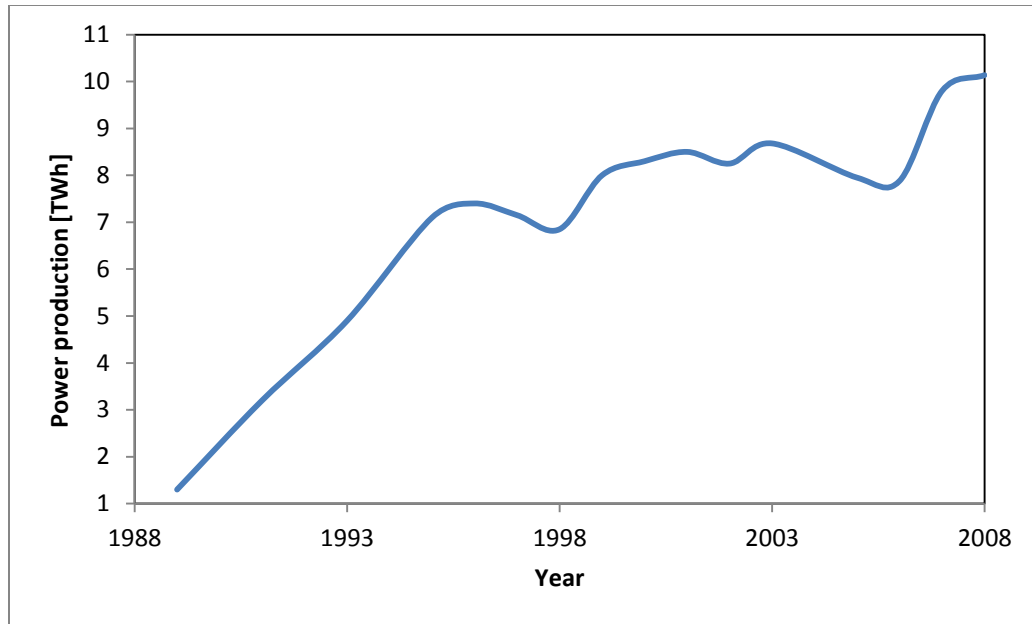


Figure 2.0-1. Energy production of Hoa Binh Reservoir from 1989 to 2008

(source: Vietnam Electricity-EVN)

The electric demand of Vietnam has been increased about 15 to 20% per year. Vietnam has started to import electricity from China from 2005. In 2011, the electricity deficit was approximately 4.76 TWh, and hydropower electricity contributed nearly 33% of the total energy production of Vietnam. Therefore, Hoa Binh hydropower plant will keep playing the most important role in improving hydropower to the electric system of the country. (Pham Khanh, Nguyen Minh, & Nguyen Ha, 2010).

2.2. Literature review

To the author's knowledge, there are three studies about Hoa Binh reservoir in the international literature:

- Simulation and optimization modeling approach for operation of Hoa Binh Reservoir in Vietnam (L.Ngo, H.Madsen, and D.Rosbjerg). *Journal of Hydrology*, 2007.
- Implementation and comparison of reservoir operation strategies for Hoa Binh reservoir, Vietnam using the MIKE-11 model (L.Ngo, H.Madsen, D.Rosbjerg, and Claus B.Pedersen). *Water Resource Management*, 2008.
- Assessing water reservoirs management and development in Northern Vietnam (Quach). *Politecnico di Milano*, 2011.

The first study optimizes the threshold water level values at which the release decision is changed by the Shuffled Complex Evolution optimization algorithm and the tradeoff between flood control and hydropower production.

The second study presents a what-if analysis comparing the impacts on flood control and hydropower production of three alternative regulation policies. MIKE-11 hydraulic model was used to simulate the different policies over the flood season in the period from 1963 to 1996.

The Quach's study investigates the operation of Hoa Binh reservoir and improves operation scheme by application of system analysis and optimal control techniques such as Stochastic Dynamic Programming and Policy Search.

This thesis plans to use HEC-ResSim as a tool to identify a desired storage curve for the reservoir system including Son La, Hoa Binh, Thac Ba and Tuyen Quang reservoirs. A storage curve is a simple method for reservoir managers since it does not need any complex evaluation to be followed. Moreover, modeling the reservoir system also supports room for its improvement in flood control, water supply management.

2.3. Modeling the Red River Basin – Heuristic solution of the Reservoir management problem

The main feature of this method is that the solution is strongly dependent upon the experience of the reservoir manager. Technically speaking, “the method should be viewed as a way of improving the physical operation by perturbing the operating rule used by managers in the past” (Guariso, Rinaldi, & Soncini Sessa, 1986).

The method is in four steps as follows

- 1 Conceptualization: to analyze the data related to the operation period of the reservoir, find out the technical and legal constraints, and on the basis of this information define a set P of operating rules $r(\cdot)$ which are candidates for describing the decision-making process followed by managers in the past.
- 2 Identification: to determine one particular operating rule $r^*(\cdot)$ within set P which approximates best historical releases. If the approximation is not satisfactory, go back to step 1 and fine-tune set P ; otherwise go to step 3.
- 3 Relaxation: to analyse the main features of the historical operating rule $r^*(\cdot)$ and relate these properties to the objectives of the management, thus finding some perturbations of the operating rule $r^*(\cdot)$ which might strongly affect the objectives. Then, check if these perturbations can be accepted by the manager. Based on this analysis, define a set R of acceptable operating

rules. This set contains the historical operating rule $r^*()$ and all the operating rules $r()$ obtained by relaxing $r^*()$ in an acceptable way.

- 4 Optimization: to determine within set R the operating rule $r_0()$ which best satisfies the manager objectives. Thus if $r_0() \neq r^*()$ an improvement has been obtained by modifying the operating rule of the manager in an acceptable way.

In the scope of this thesis, the reservoir system objectives are alleviating flood problem and supplying water demand in the Red river delta.

2.4. HEC-ResSim introduction

Hydrologic Engineering Center's Reservoir Simulation (HEC-ResSim) was developed with US Federal Government resource. It is comprised of a Graphical User Interface (GUI), a computational programming to simulate reservoir operation, data storage, and management capabilities, and graphics and reporting facilities (*HEC-ResSim Reservoir System Simulation User's Manual*).

2.4.1. HEC-ResSim program structure

HEC-ResSim offers three sets of functions called Modules that allow to access specific types of data within a watershed (Figure 2.0-2).

- Watershed setup Module: to provide general settings and definitions for the basins studied in different applications. A watershed includes river systems, irrigation works (reservoirs, dams, diversion), flood affected areas, and the hydrological, meteorological monitoring stations. In this module, the physical properties of the basin must be determined.
- Reservoir Network Module: to define the river network system; describe the physical components, operation of the reservoir and the alternatives to be analyzed in this module. The Data Storage System, HEC-DSS is used for storage and retrieval of input and output time-series data.
- Simulation Module: to isolate output analysis from the model development process (*HEC-ResSim Reservoir System Simulation User's Manual*). After performing a Simulation, the results can be viewed and printed in both tabular and graphical form.

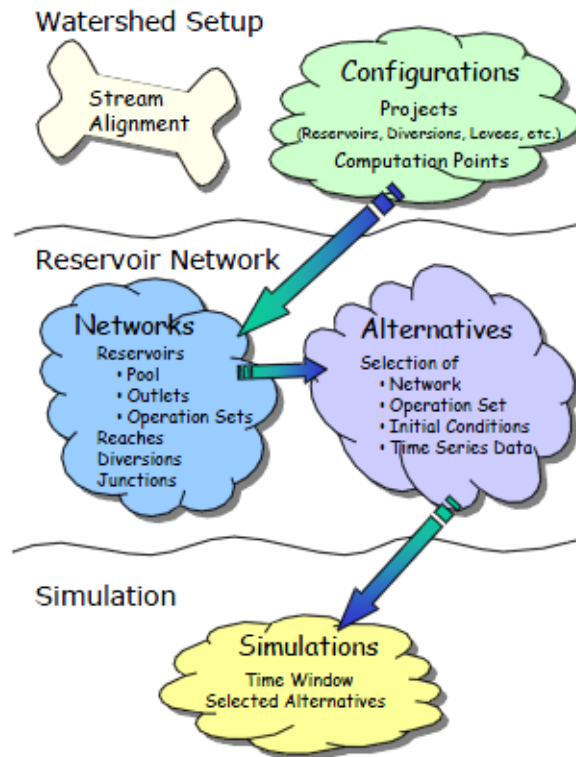


Figure 2.0-2. HEC-ResSim modules concept

2.4.2. Modeling the Red River Basin using HEC-ResSim

The basin is modeled in following four steps:

- Physical and hydrological characteristics of the rivers and reservoirs are defined in Watershed setup module (*Figure 2.0-3*).
- The physical and operational elements of Hoa Binh, Son La, Thac Ba, and Tuyen Quang reservoirs are described. We also develop different alternatives, which will be analyzed.
- The new defined model is validated against real data in one year. Evaluation of the results will be carried out to check the model performance.
- Different alternatives will then be implemented to find the optimal operation scheme for flood control and water supply.

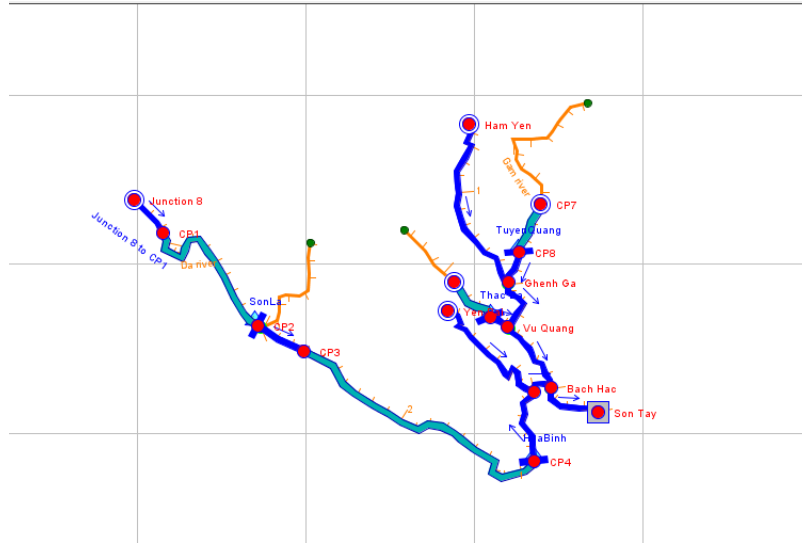


Figure 2.0-3. Red river system in HEC-ResSim

2.5. The available dataset

2.5.1. The dataset

The HEC-ResSim program uses the Data Storage System (HEC-DSS) to store the input data of flows in different stations, and in different years. Data in this thesis are sourced from the Water Resource Institute in Vietnam.

Most of the data are daily values measured at 12:00 AM. Moreover, in the period between 14th of August and 27th of August, flows were measured with a time step of six hours starting from 1:00 AM.

Hoa Binh reservoir flow conditions and water levels are collected consecutively from 1993 to 2009 in order to analyze a historical operating data of the reservoir.

These are the data, which have been collected:

- Flows in year 1971: Hoa Binh, Ham Yen, Ta Bu, Tuyen Quang, Yen Bai, and Thac Ba stations;
- Flows in year 2002: Hoa Binh, Son La, Yen Bai, Ham Yen, Son Tay, and Thac Ba stations;
- Flows in year 2010: Hoa Binh, Ham Yen, Son La, Son Tay, Thac Ba, Tuyen Quang, and Yen Bai stations;
- Flows in period from 14th of August to 27th of August: Hoa Binh, Na Hang, Ham Yen, Tuyen Quang, and Yen Bai stations;
- Inflows, releases, and water level of Hoa Binh reservoir from year 1993 to 2009.

2.5.1. Some feedbacks of the dataset

- Data obtained are time-series data, which has trends, periodically cycles, and residuals. Data processing is necessary to remove outliers and trend. Basic steps are done for this process.
- In reality, most of the variables (levels, disturbances, and flows) are continuous through time. Only the management decision, i.e. the control, is taken in discrete instants of time (Soncini-Sessa, Castelletti, & Weber, 2007).
- There are some limitation in collecting data, which leads to an absent of data in the year 2012. If flows data in this year were collected, the calibration and validation progresses for the Red River reservoir system (*Chapter 3.2.3*) would be more completed.

CHAPTER 3

METHODOLOGY

The scope of this Chapter is twofold. Firstly, we analyze historical operating data of the Hoa Binh reservoir based on available data from 1993 to 2009 (Quach, 2011). Base on that we will model the reservoir system operating through HEC-ResSim software.

3.1. Analysis of historical operating data of the Hoa Binh reservoir

The analysis emphasizes the Hoa Binh operating scheme is based on a seasonal strategy. In dry season from January to June, the water level gradually decreases by average of 35m. It is due to the outflows are larger than the inflows, Hoa Binh reservoir uses its storage which is hold up from early September to supply the Red River Delta water demand. This decrease in reservoir elevation reaches a favorable water level before the flood season occurring in June, July and August. The flood storage capacitates from 77.5m to 105m in order to hold up the inflow if there is a large deluge. Between the end of August and the 1st of November (so called the wet-to-dry transition), the reservoir is managed to reach its full capacity.

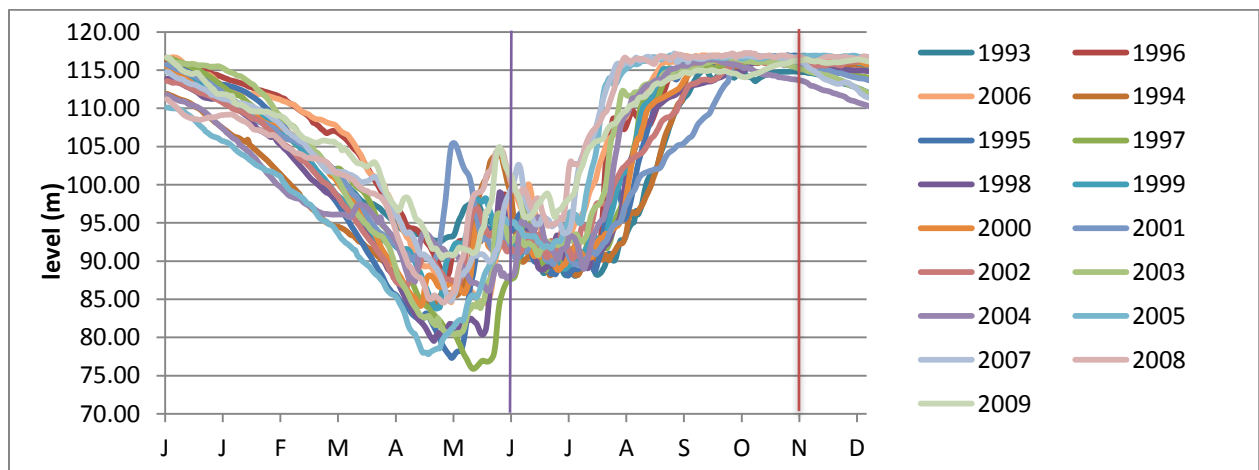


Figure 3.0-1. Yearly pattern of the Hoa Binh water level over the horizon 1993-2009.

Figure 3.0-2 shows the historical inflow and release of the Hoa Binh reservoir from 1993 to 2009. It is seen that at the flood event of 1996 the inflow peak is at 18680 m³/s (recorded on 19th of August), while the release at the same time is at 7892 m³/s and the peak release around this period is 12405 m³/s. This reduction of 10788 m³/s decreases the water level at Hanoi.

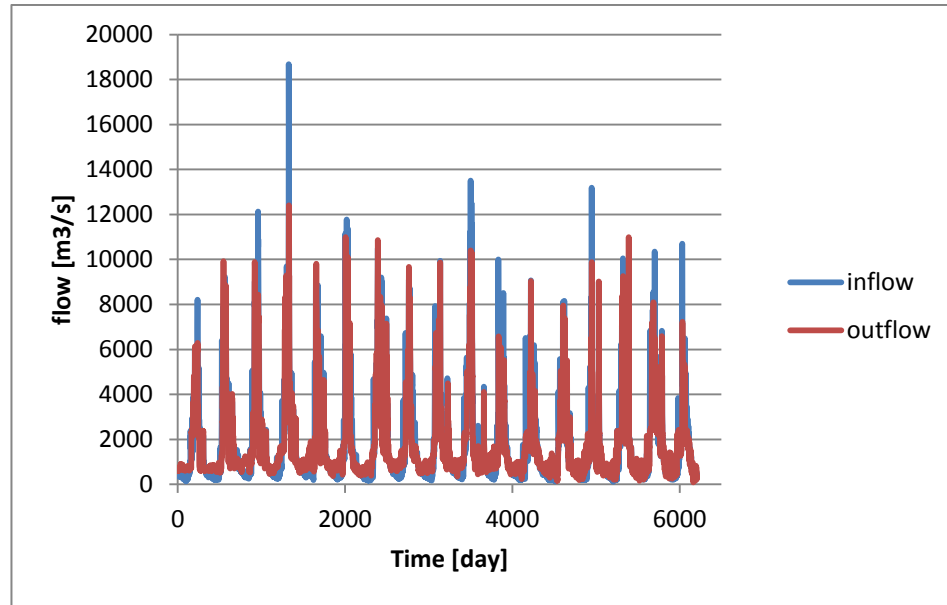


Figure 3.0-2. Inflow and release of Hoa Binh reservoir over the period 1993 – 2009.

The release operations are analyzed by year. It shows that there were 8 years (1993, 1997, 1998, 2000, 2002, 2003, 2004, 2009) the reservoir was not filled up to the NWL of 117 m (According to PECC1), i.e. the reservoir was not completely full before the dry season. Particularly, in the year 1993, 1998 and 2004, the level at the beginning of the dry season was very low (compared with other years at the same time) with severe consequences on the system operating in the following year. In the year 1994, 1999, 2005, the reservoir was not at its full capacity, which led to water demand shortage in the Northern Vietnam, especially water for the spring cultivation of the Red River Delta.

3.2. Modeling the reservoir system using the HEC-ResSim program

After analyzing the historical operating data of the Hoa Binh reservoir particularly and the Red River system generally, the subsequent step in our study is to model the operating of the reservoir system into the HEC-ResSim program. This is a basic step to implement new HEC-ResSim alternatives (*HEC-ResSim Reservoir System Simulation User's Manual*) using the software in order to determine the ideal

model operating policy of the reservoir system, i.e. finding the release decisions both mitigates flooding problems and improves water supply.

The module Reservoir Network (2.4.1) will isolate the development of the reservoir model from the output analysis. Network schematic will be developed includes physical and operational elements of the reservoir models.

3.2.1. Formulas

We base the operating plan on two formulas; those are the water balance equation and the water storage equation.

- Water balance equation:

$$\frac{dV}{dt} = Q(t) - q_r(t) \quad Eq- 1$$

$$q_r(t) = q_x(t) + q_c(t) \quad Eq- 2$$

$Q(t)$: Inflow to the reservoir (m³/s).

$q_r(t)$: Outflow of the reservoir (m³/s) includes controlled release $q_x(t)$ and water evaporation $q_c(t)$.

- Water storage for flood control:

$$V_{fc} = \int_{t_1}^{t_2} [Q(t) - q_x(t)] dt \quad Eq- 3$$

Figure 3.0-3 illustrates the relationship between the outflow and the inflow of Son La reservoir.

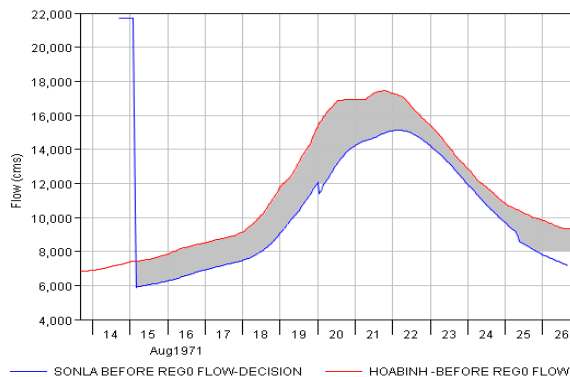


Figure 3.0-3. The flood control storage of Son La reservoir.

3.2.2. Zones and Operating rules

In order to model the reservoir system, in HEC-ResSim, each reservoir has 4 to 5 zones in the operating plan. These zones represent reservoir objectives and working condition.

- a 1st zone - Maximum water level: to define the highest water level of the reservoir.
- b 2nd zone – Flood control level: the reservoir’s maximum water level for flood control so called the normal water level in HEC-ResSim.

This zone includes three following operating rules:

- Downstream Control Function Rules: to describe the minimum or maximum flow (e.g., flow requirement or channel capacity) or stage at a control point rather than an explicit limit on the release. The final release limit will be determined based on the influence of routing and cumulative local flows at the downstream control point.

In this study, Downstream Control Function rules take a reference on the required flood control flow and the water demand of Son Tay control point.

- Tandem Operation Rule: to establish a tandem system operating where an upstream reservoir operates for a downstream reservoir to achieve a storage balance. The Tandem Operation rule identifies the downstream reservoir that is the object of Tandem Operation.

For the model, Tandem Operation rule applied to Son La reservoir, which has Hoa Binh reservoir as a downstream reservoir. An implicit storage balance scheme is invoke by the Tandem Operation rule.

- Flow Rate of Change Limit Rule: to specify the allowable change when increasing or decreasing release values. To describe both increasing and decreasing limits, two rules must be defined and the type of one is set to increasing and the other to decreasing.

We used Excel to calculate the ramping rates for each prior release to avoid fast variation in release flow.

- c 3rd zone – Water supply (*Figure 3.0-4*): the corresponding water level for supplying water to agriculture annually. During the dry season, it is kept at the normal water level and started to fall to the lowest elevation in May in order to prepare for the wet season.

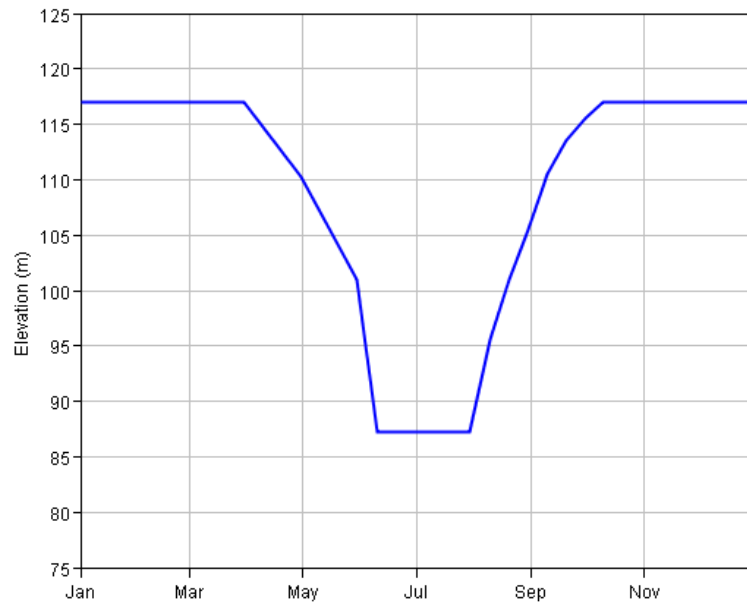


Figure 3.0-4. Hoa Binh reservoir water supply curve

The Water supply zone has a Release Function Rule: with this rule, you can define a wide array of “function of” rules, meaning release is a function of date or pool elevation. This rule can be assigned to any of the release elements (pool, dam, or outlet) and it allows you to specify the maximum, minimum, or specified flow to be released through the release element.

- d 4th zone – Upper normal (*Figure 3.0-5*): The actual operating plan of the reservoir. The water level is kept at the normal one during the dry season and at the lowest level when the wet season comes. It has a similar shape with the Water supply curve, however, the variations are much steeper since they can go up or down by 15 m within 15 days.

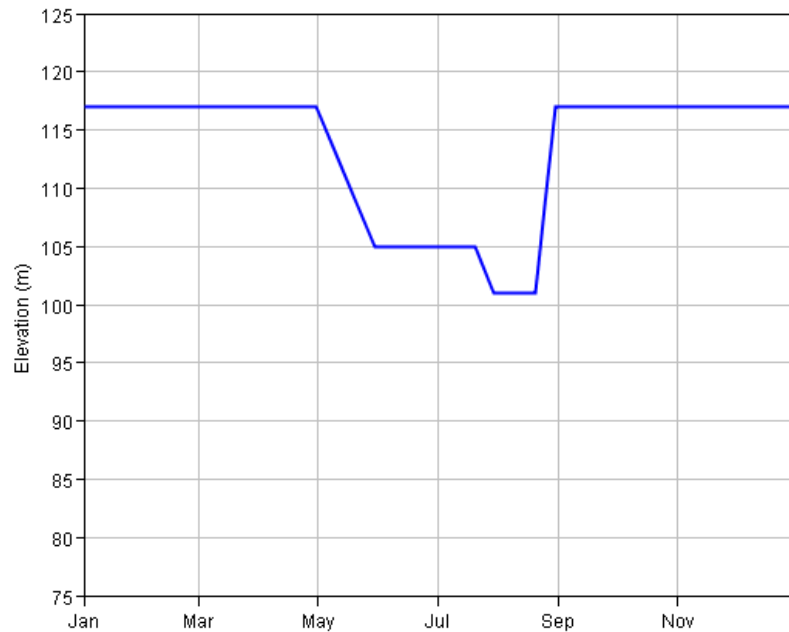


Figure 3.0-5. Hoa Binh reservoir upper normal curve

- e 5th zone – Inactive: The dead level of the pool. Once you delete this zone, you cannot restore it.

3.2.3. Model validation

Before testing new alternative, it is important to check that the model set up by HEC-ResSim (The ‘4Res’ model) represents well the real situation. The ‘4Res’ model is calibrated using data from 5 control stations Hoa Binh, Yen Bai, Thac Ba, Ham Yen, Tuyen Quang in 2010. The Son La reservoir has been fully operated since 2011; however, data in that year cannot be obtained, we decide to put Son La reservoir into an inactive operating in the model so it only acts like an unregulated reservoir. Son La reservoir operating only affects Hoa Binh operating scheme, therefore if we use data measured in the Hoa Binh station, the rest of the model could still be calibrated and validated with good precision. For the Son La reservoir, if updated data could be found, its operating modeled by HEC-ResSim would be validated.

The calibration is carried out by setting the relevant values.

Data of the real flow in the Son Tay station in 2010 is used to validate the calibration one. In addition, the outcome operating plan of the Hoa Binh and Tuyen Quang reservoirs will be compared with the real operating schemes.

Nash formula is used for the validation process:

$$NASH = \frac{\sum_{i=1}^n (Q_{cali} - \bar{Q}_{cal})^2 - \sum_{i=1}^n (Q_{cali} - Q_{vali})^2}{\sum_{i=1}^n (Q_{cali} - \bar{Q}_{cal})^2} \quad Eq- 4$$

3.2.3.1. The default operating of the reservoirs

The current operating of Hoa Binh, Thac Ba and Tuyen Quang reservoirs are modeled in HEC-ResSim using the ‘normal’ as a guide curve (*Figure 3.0-6*).

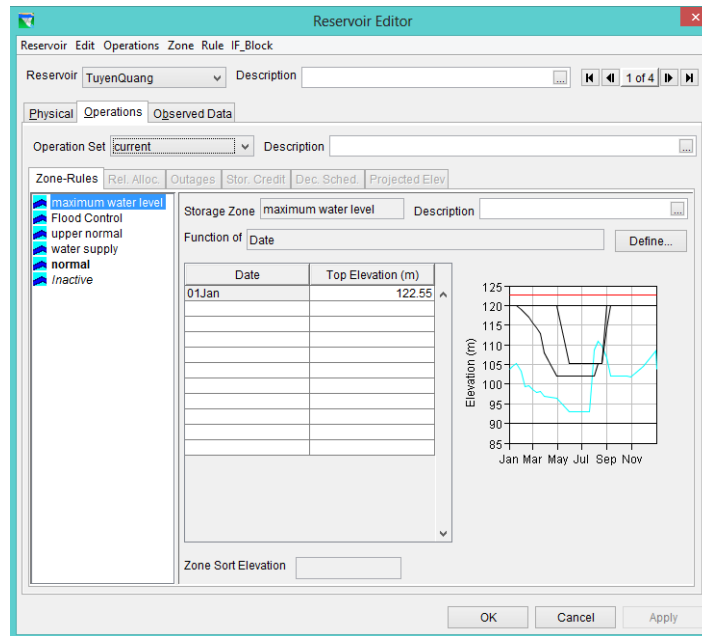


Figure 3.0-6. The operating scheme of Tuyen Quang reservoir.

The proper time step must be chosen. Decision time step is the time between one decision and the next. Since the decision time step is equal to one day, the modeling step will be $1/k$ with k is an integer. To choose the value of k , one must consider:

- The sampling time of the hydrological measurements used for model calibration and validation;
- That the computing time needed to solve the control problems and to evaluate the alternative operating policies increase linearly with k ;

- That the discrete-time description of the system should not produce an excessive loss of information (the system is continuous).

Most of the time series in our possession have a daily time step, so it is reasonable to assume $k=1$. This assumption also has the advantage of reducing the computing time to a minimum.

-Time step: 1 day

-Operating: All the reservoirs have been assigned to the operating set.

Reservoir	Operating Set
HoaBinh	Current
Son La	Inactive
Thac Ba	Current
Tuyen Quang	Current

Table 3.0-1. Operating set of the reservoir system.

-The initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics, which are elevation, storage, and initial release, are set. In this case, the initial elevation and the initial release are the actual data at the beginning of year 2010.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	103.85
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	0.0
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	51.0
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	116.0
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	163. 6

Location	Variable	Type	Default Value
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	0.0
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	0.0

Table 3.0-2. The initial conditions of the reservoirs in year 2010.

3.2.3.2. Comparison and Validation

-The results:

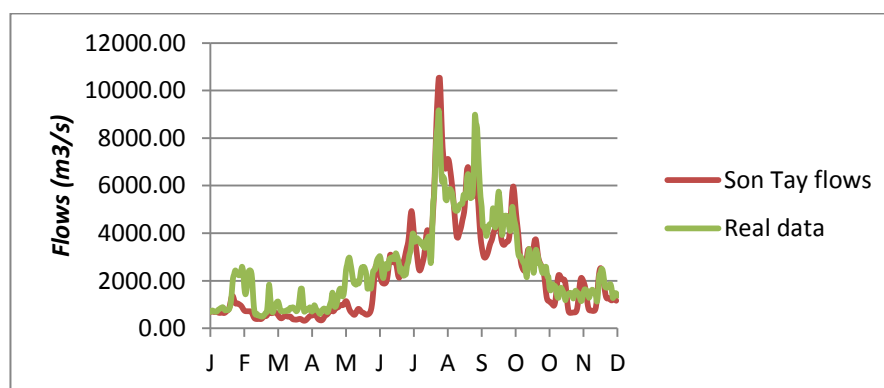


Figure 3.0-7. Son Tay flows (red line) vs. the historical data (green line)

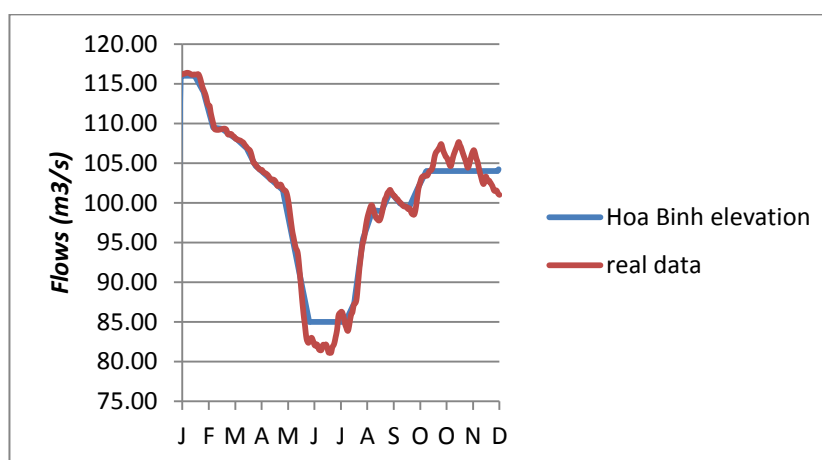


Figure 3.0-8. Hoa Binh reservoir: computed elevation vs. the historical water level

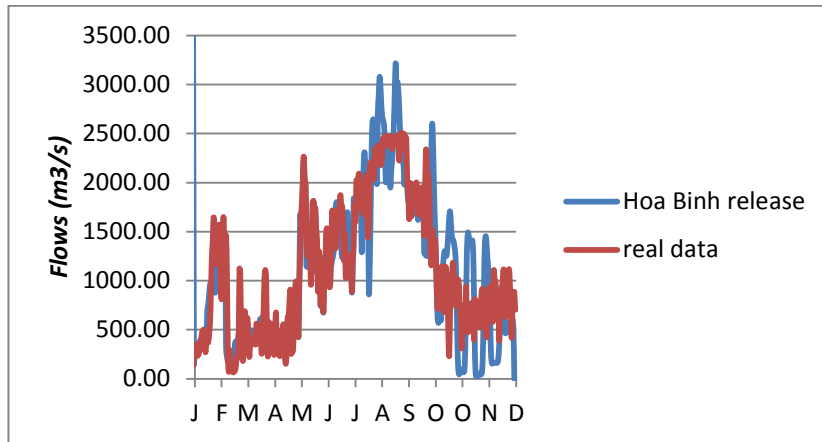


Figure 3.0-9. Hoa Binh reservoir: computed release vs. the historical release

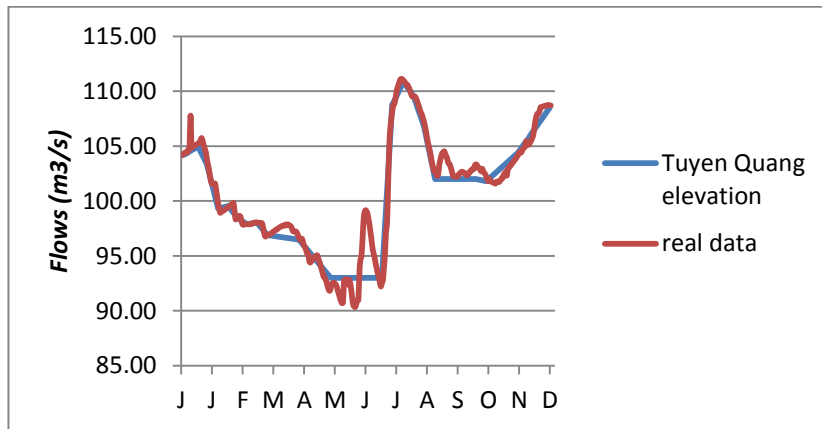


Figure 3.0-10. Tuyen Quang reservoir: computed elevation vs. the historical water level

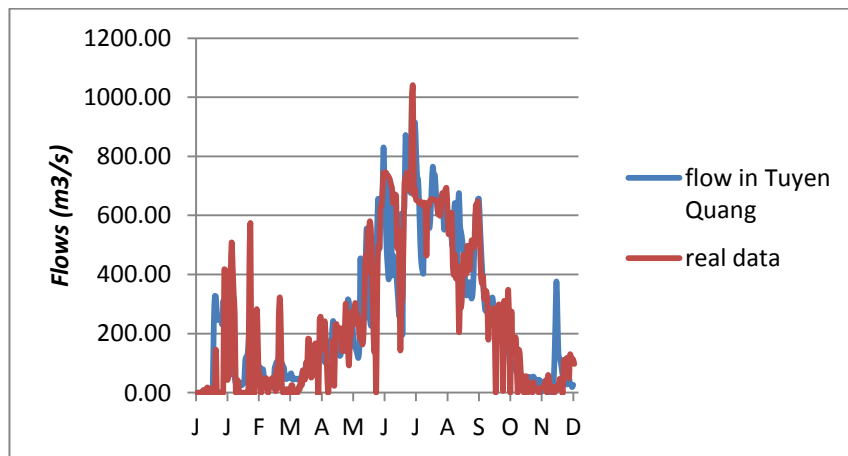


Figure 3.0-11. Tuyen Quang reservoir: computed release vs. the historical release

Nash coefficient is used to validate operating scheme of Tuyen Quang, Hoa Binh reservoir as well as flows in Son Tay station. All the results are more than 71% accuracy. Especially, the reservoir elevations are modeled specifically with the accuracy of 94% and 97% for Tuyen Quang and Hoa Binh reservoirs respectively. For Son Tay station, the model represents approximately two flood peaks in July and August with the accuracy of 83%.

	Nash coefficient
Son Tay station	83%
Hoa Binh reservoir	
Elevation	97%
Release	71%
Tuyen Quang reservoir	
Elevation	94%
Release	72%

Table 3.0-3. Results of the validation

CHAPTER 4

ANALYSIS AND RESULTS

Given the validated model, reservoir operation optimization can be achieved by applying different alternatives. In this chapter, we discuss the results of application to the reservoir system under several alternatives of the operation scheme.

4.1. Simulation and validation of different alternatives

With the validated model, different alternatives are implemented in order to determine a potential improvement of the reservoir system. A recorded flood with $P=0.5\%$ in 1971 is used for model simulation due to its dreadful damage.

The flood in 1971 was the combination of the biggest flood of the Lo River, the second biggest flood of the Thao River, and the fourth biggest flood of the Da River. These caused the historical flood in the Red River Basin, the biggest one since 1902, with the maximum flow at Son Tay of $37,800 \text{ m}^3/\text{s}$. The flood peak in Hanoi was 14.13 m, 1.63m and 2.63m above the third and the second alarming levels, respectively. The water level above the third alarming lasted in eight consecutive days. As a result, dike spilling and dike breaking happened in several places. According to the price in 1971, total property damage to the State sectors under management of the Central Government was more than VND 44 billion (approximately 1.5 million Euros). In addition, 100000 dead, other losses to local people, and flood effects such as epidemics and interrupted production could not be counted out (Quach, 2011).

New alternatives with downstream control rules are expected to satisfy not only flood control, in this case, one of the biggest flood but also water supply for irrigation of the Red River Delta. Therefore, the scope of this simulation will be twofold, first for the whole year of 1971 with the time step 1 day and secondly for the period of the flood between August 15th and 26th with the time step of 1 hour.

Moreover, besides regarding at the proposed alternatives in terms of flood level, it is important to demonstrate that they do not generate useless deficits. Thus, the simulation of one entire year would be useful.

4.1.1. The first alternative

4.1.1.1. Operational rules

As the objectives of the reservoirs are flood control and water supply, operational rules for maximum flood control flow, water demand in Son Tay and the MEF (Minimum Environmental Flow) have been implemented (*Figure 4.0-1*).

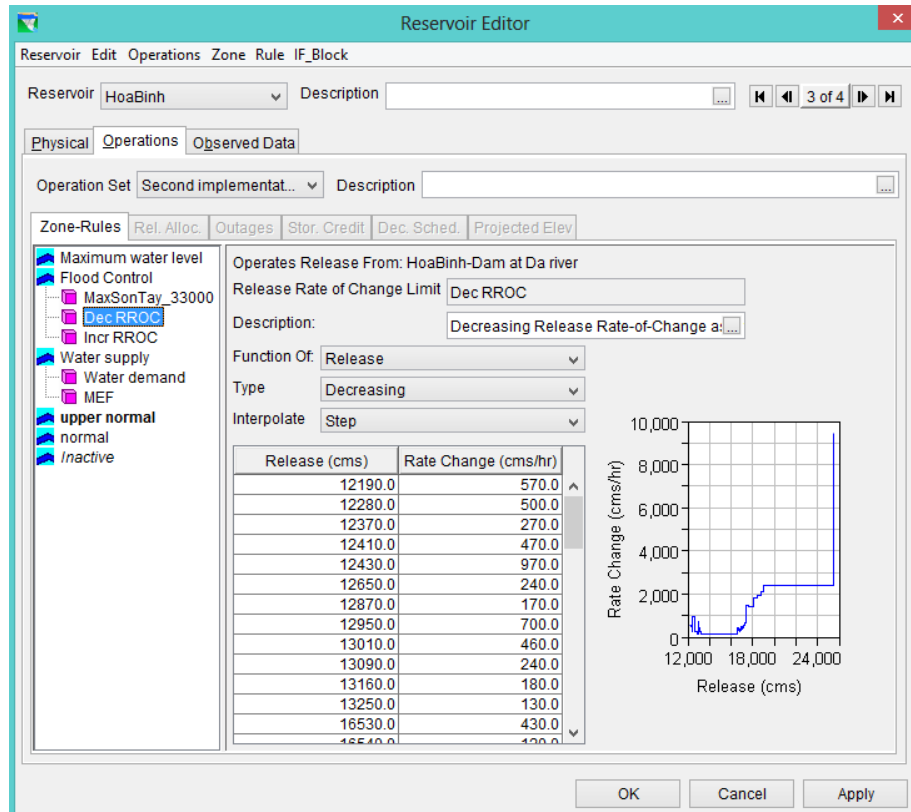


Figure 4.0-1. Hoa Binh operation plan in the first alternative.

- For the first rule, according to the ‘Regulation Rule 62/1999/ND-CP of flood protection for Hanoi’: *The water level in Hanoi must not exceed 13.40 m that means a safety threshold for flow rate in Son Tay station is 33000 cubic meter per second (cms).*

Therefore, a Downstream Control Function Rule has been applied; the maximum flow in Son Tay station does not exceed 33000 m³/s.

- For the second rule, as *the minimum flow in historical time series is 20 cms* (Quach, 2011), so in the thesis we will consider $q_{mef} = 20$ (m³/s).

- The third rule is the water demand for irrigation in the Red River Delta (RRD) that is composed of 31 irrigation schemes serving around 850000 ha of irrigated agriculture (Chien, 2002). *Figure 4.0-2* describes the highest demand of water for agriculture in the end of February, which is the spring cultivation of the Northern Vietnam.

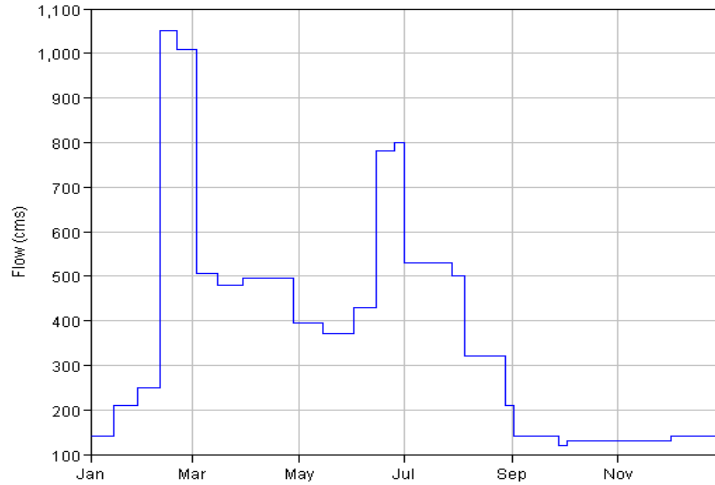


Figure 4.0-2. Yearly pattern of water demand at Son Tay.

4.1.1.2. Alternative

The first alternative we set the water supply zone (Figure 4.0-3) as the guide curve. Along with the implemented operation rules, it is important to set a priority of the reservoir objectives. Firstly, we will try with the main concern of distributing water for irrigation.

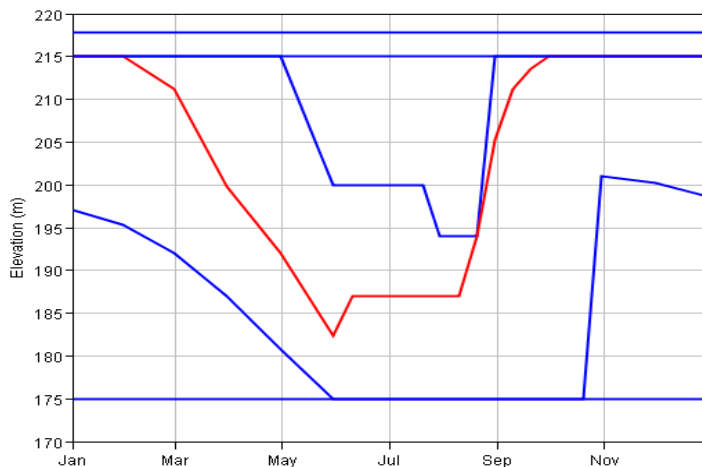


Figure 4.0-3. Son La reservoir: Water supply curve (red); Maximum water level, flood control, upper normal, normal and inactive curves (blue)

a The time frame for the whole year 1971

-We choose the time step for 1 day.

-Operations: four reservoirs have been assigned to the operation set with main concern to water supply.

Reservoir	Operation Set
Hoa Binh	First implementation
Son La	First implementation
Thac Ba	First implementation
Tuyen Quang	First implementation

Table 4.0-1. Operation set of the reservoir system - the first alternative.

-The initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics, which are elevation, storage, and initial release, are set. In this case, the initial elevation and the initial release of the reservoirs were taken from the calibrated data of the model in the last day of year 1971. The initial data is constant for every alternative of this year.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	119.7
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	256.3
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	57.0
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	142.8
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	117.0
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	586.9

Location	Variable	Type	Default Value
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	214.4
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	571.8

Table 4.0-2. The initial conditions of the reservoirs in year 1971 - the first alternative.

-Result:

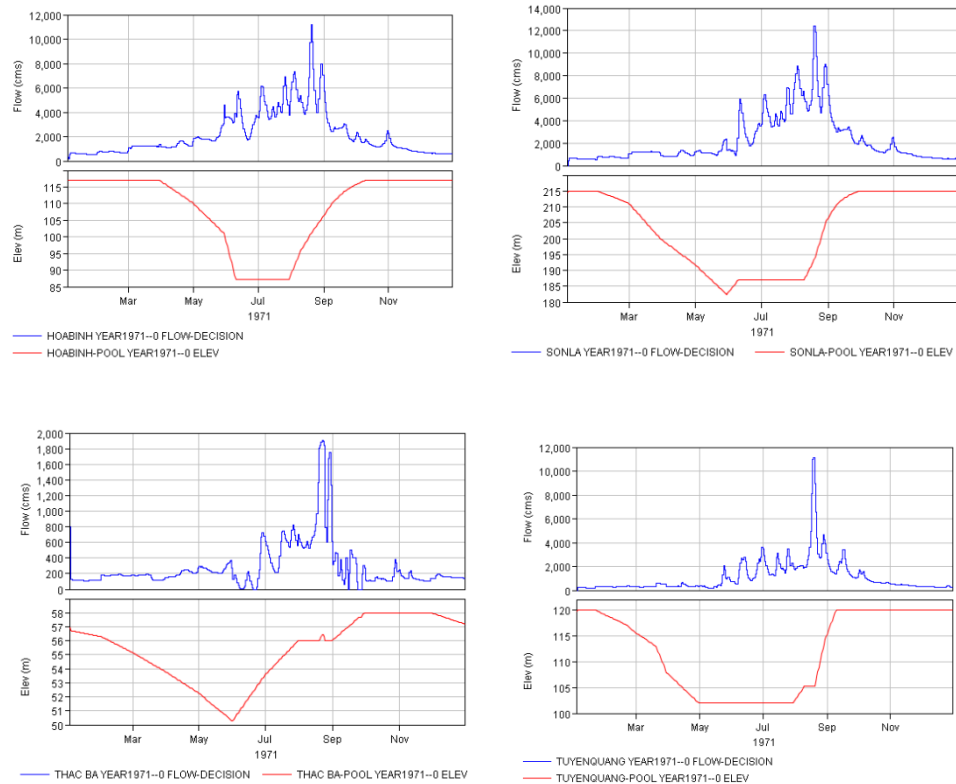


Figure 4.0-4. Release flow and water level of Hoa Binh, Son La, Thac Ba and Tuyen Quang reservoirs in year 1971

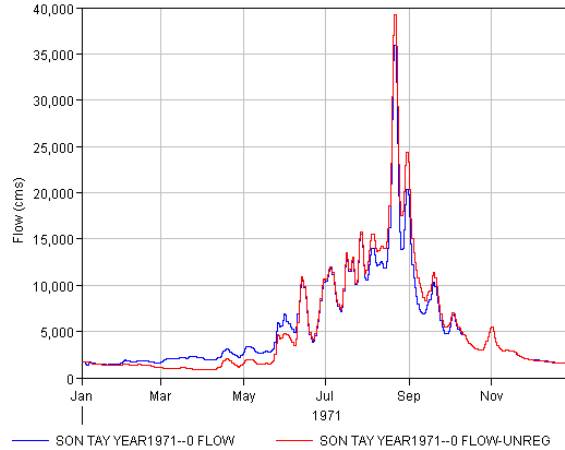


Figure 4.0-5. Flows in Son Tay station

Unregulated plan (red) versus the first alternative (blue)

-Comparison between the regulated flows and the water demand in Son Tay (Figure 4.0-2)

The parameter used to evaluate the first alternative is *mean daily volume of water deficit* (V_N)

$$V_N = \frac{1}{365} \sum_{t \in H} \left[\frac{(\bar{q} - q_t)^-}{\bar{q}} \right]^7 \quad \text{Eq- 5}$$

- $(.)^-$ an operator that returns the value of the argument, when it is negative, or zero in the opposite case
- \bar{q} the flowrate demand
- q_t the average real flowrate in day t
- H number of day

$$V_N = 0 \text{ m}^3$$

⁷ Source: INTEGRATED AND PARTICIPATORY WATER RESOURCES MANAGEMENT: THEORY

-Conclusion: the first alternative ensures the reservoirs are completely full before the dry season and vice versus reach the dead water level before the wet season. It helps to distribute more water to Son Tay region during April and May and to reduce the flood peak during the flood season.

b The time frame from August 15th to 26th

-Time step: 1 hour

-Initial (Lookback): the initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics, which are elevation, storage, and initial release, are set. In this case, the initial elevation and the initial release are taken from the data of the previous calibrated model for year 1971.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	105.0
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	2564.85
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	55.85
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	663.0
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	97.5
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	3955.0
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	190
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	4797.7

Table 3.0-3. The initial conditions of the reservoirs in 15th August - the first alternative.

-Results:

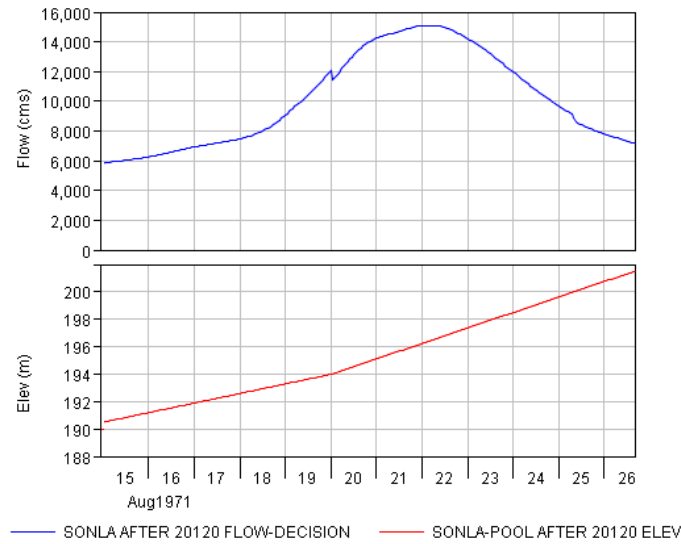


Figure 4.0-6. Son La reservoir flow decision and pool elevation.

The water supply guide curve allows the water level to increase steadily. In *Figure 4.0-7* we can see that the acceptable top elevation between August 10th to 20th is 187 m (preparing storage for flood control) and then it increases to 194m in the next five days. Therefore, the initial elevation of the pool was already 190m (*Figure 4.0-6*) so the release of 6000 m³/s is calculated in order for the water level to increase gradually.

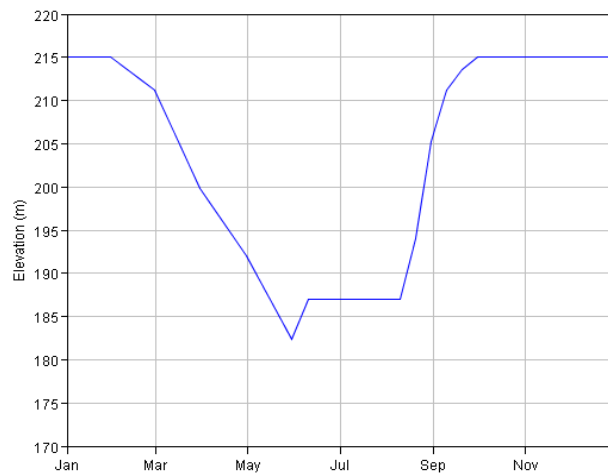


Figure 4.0-7. Water supply guide curve of Son La reservoir.

The same situation happens to Hoa Binh reservoir (*Figure 4.0-8*) since it works accordingly to Son La reservoir in the Da river system.

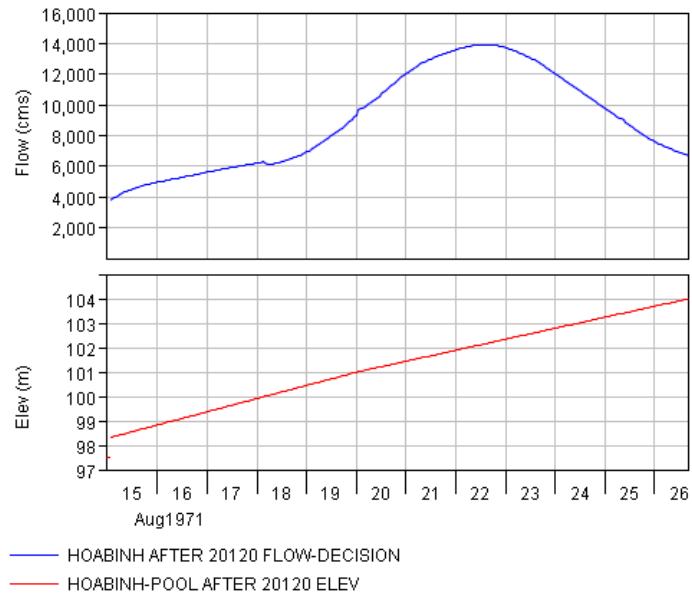


Figure 4.0-8. Hoa Binh reservoir flow decision and pool elevation.

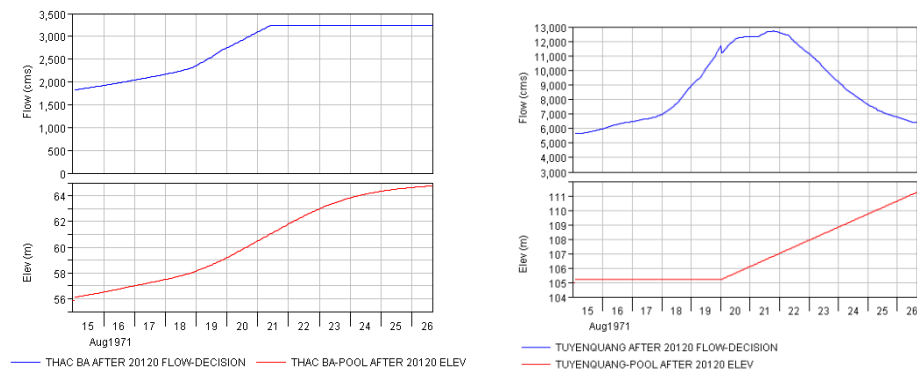


Figure 4.0-9. Thac Ba and Tuyen Quang reservoir flow decisions and pool elevations.

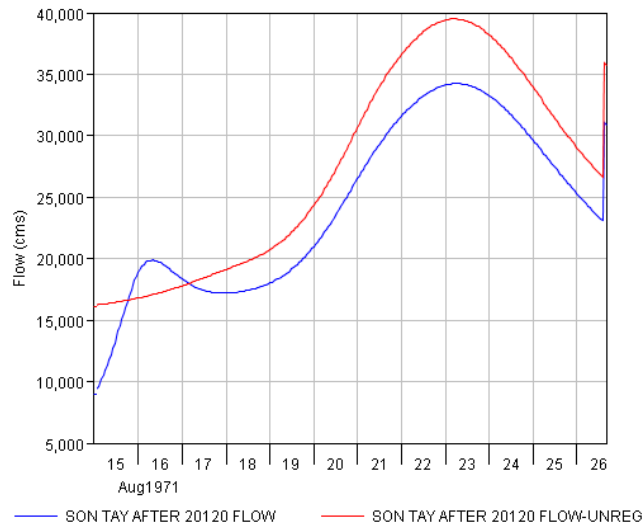


Figure 4.0-10. Flows in Son Tay station unregulated plan (red) versus first alternative (blue)

The regulated flows in Son Tay station using the water supply curve is lower than the unregulated one since it is during August and a water demand for irrigation is low. Moreover, it also helps to reduce the flood level in Son Tay station however the flow still surpasses the critical one ($33000 \text{ m}^3/\text{s}$).

4.1.2. The second alternative

4.1.2.1. Alternative

The second alternative we set the upper normal (Figure 4.0-11) as the guide curve. Flood control is one of two main objectives should be optimized. Generally, this curve focuses on the storage for flood control by plummeting to the minimum water level in June and refilling the reservoir after the late flood period (in the end of August).

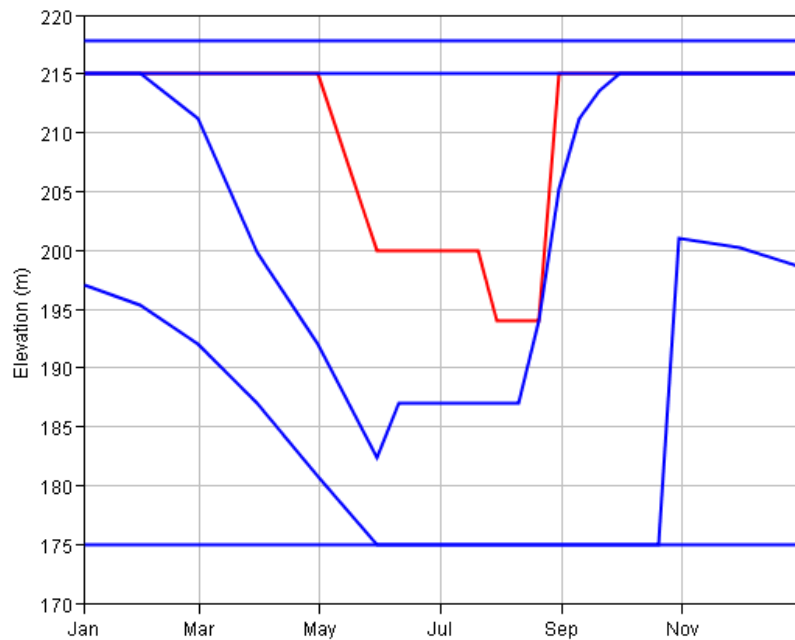


Figure 4.0-11. Son La reservoir: Upper normal curve (red); Maximum water level, flood control, water supply, normal and inactive curves (blue)

a The time frame for the whole year 1971

-We choose the time step for 1 day.

-Operations: four reservoirs have been assigned to the operation set with main concern to water supply.

Reservoir	Operation Set
HoaBinh	Second implementation
Son La	Second implementation
Thac Ba	2nd implementation
Tuyen Quang	Second implementation

Table 4.0-4. Operation set of the reservoir system - the second alternative.

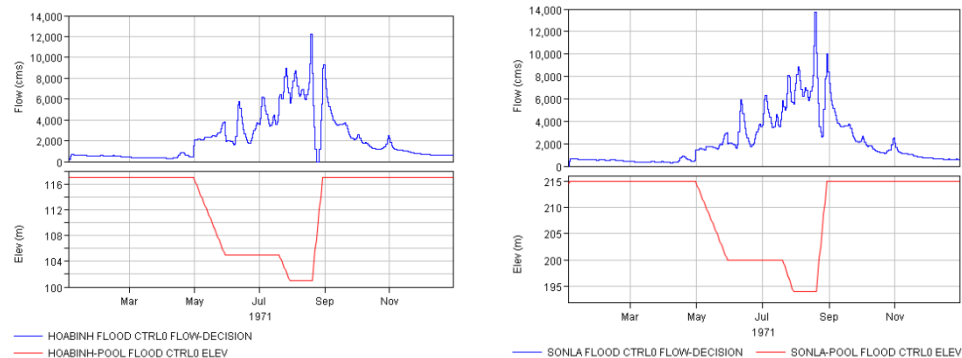
-The initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics, which are elevation, storage, and initial release, are set. In this case, the initial elevation and the initial release of the reservoirs were

taken from the calibrated data of the model in the last day of year 1971. The initial data is constant for every alternative of this year.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	119.7
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	256.3
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	57.0
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	142.8
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	117.0
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	586.9
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	214.4
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	571.8

Table 4.0-5. The initial conditions of the reservoirs in year 1971 - the second alternative.

-Result:



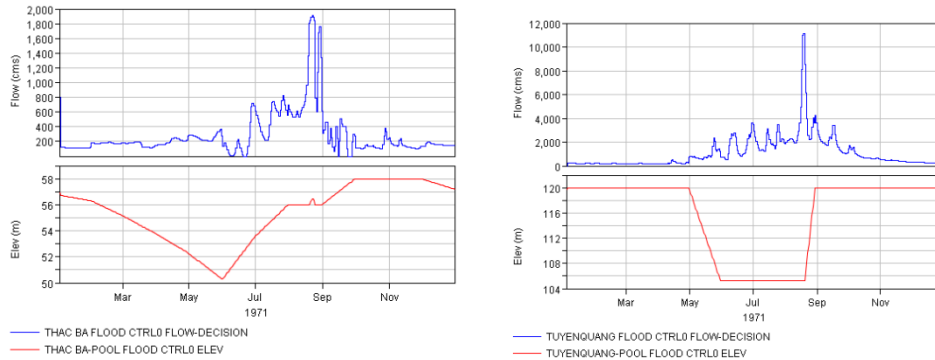


Figure 4.0-12. Release flow and water level of Hoa Binh, Son La, Thac Ba and Tuyen Quang reservoirs in year 1971

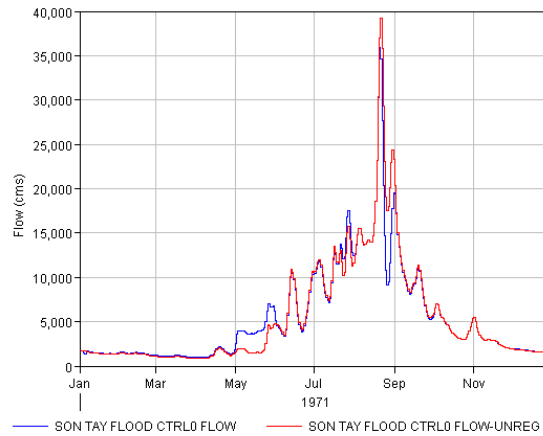


Figure 4.0-13. Flows in Son Tay station: unregulated plan (red) versus the first alternative (blue)

-Comparison between the regulated flows and the water demand in Son Tay (Figure 4.0-2)

The parameter used to evaluate the first alternative is *mean volume of water deficit* (V_N)

$$V_N = \frac{1}{365} \sum_{t \in H} \left[\frac{(\bar{q} - q_t)^-}{\bar{q}} \right] \text{Eq- 6}$$

$$V_N = 0 \text{ m}^3$$

-Conclusion: the second alternative ensures the reservoirs are completely full before the dry season and vice versus reach the dead water level before the wet season. It reduces the flood peak during the flood season.

b The time frame from August 15th to 26th

-Time step: 1 hour

-Initial (Lookback): the initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics which are elevation, storage and initial release are set. In this case, the initial elevation and the initial release are taken from the data of the previous calibrated model for year 1971.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	105.0
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	2564.85
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	55.85
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	663.0
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	97.5
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	3955.0
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	0.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	190
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	4797.7

Table 4.0-6. The initial conditions of the reservoirs in 15th August - the second alternative.

-Results:

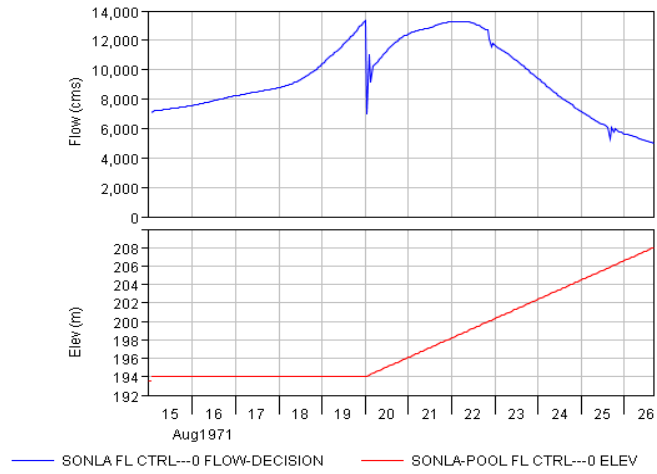


Figure 4.0-14. Son La reservoir flow decision and pool elevation.

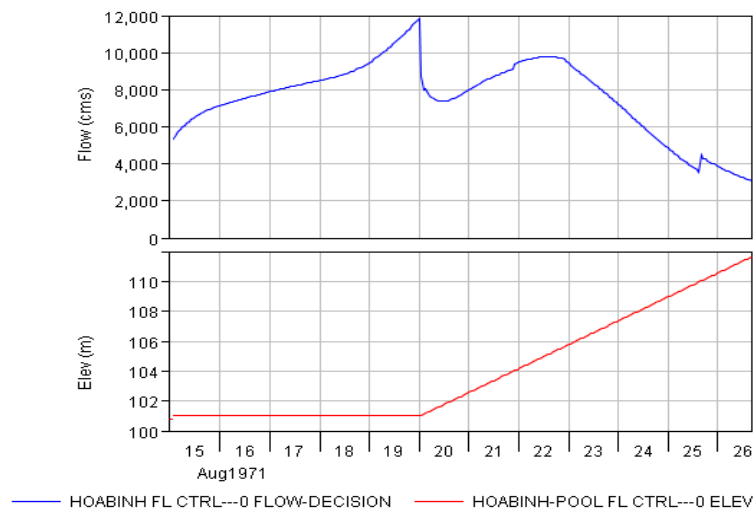


Figure 4.0-15. Hoa Binh reservoir flow decision and pool elevation.

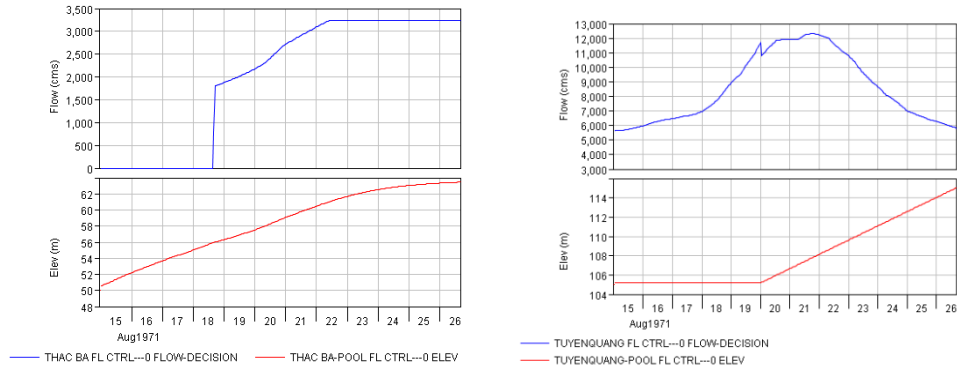


Figure 4.0-16. Thac Ba and Tuyen Quang reservoir flow decisions and pool elevations.

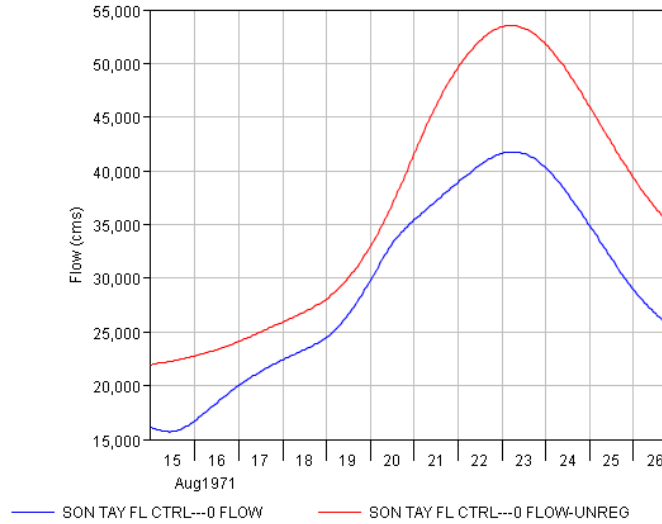


Figure 4.0-17. Flows in Son Tay station: unregulated plan (red) versus first alternative (blue)

The regulated flows in Son Tay station satisfy the critical ones (33000 m³/s) which demonstrates the effectiveness of flood control guide curve.

4.1.3. The third alternative

4.1.3.1. Alternative

The third alternative we merge the ‘water supply’ curve with the ‘upper normal’ curve into a new curve named ‘new regime’ (Figure 4.0-18) as a trial. The flood occurred in 1971 is one of the most severe natural disasters in Vietnam, with the flood control as the priority, the result is expected to have a better flow status in Son Tay, i.e. lower flood peak and shorter consecutive days of flood as well as a better water distribution plan.

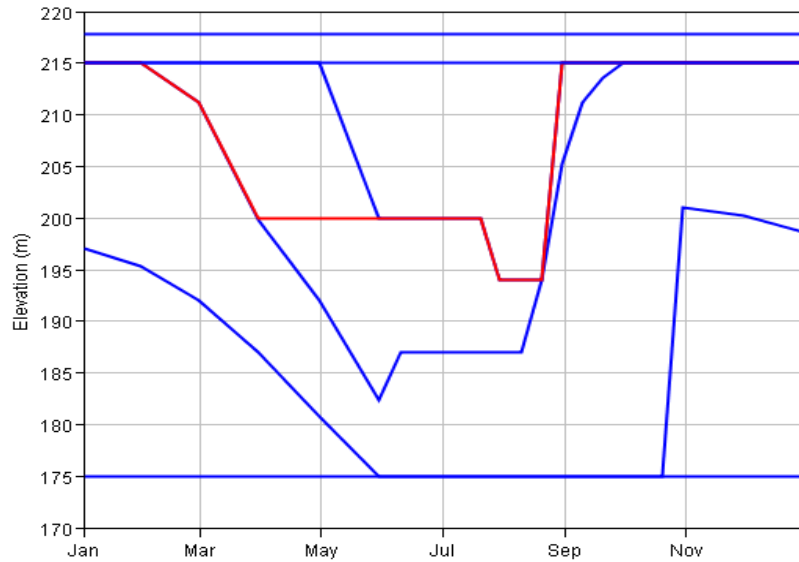


Figure 4.0-18. Son La reservoir: new regime curve (red); Maximum water level, flood control, water supply, normal, upper normal and inactive curves (blue)

a The time frame for the whole year 1971

-We choose the time step for 1 day.

-Operations: four reservoirs have been assigned to the operation set.

Reservoir	Operation Set
HoaBinh	Day-to-Day operations
Son La	Day-to-Day operations
Thac Ba	Day-to-Day operations
Tuyen Quang	Day-to-Day operations

Table 4.0-7. Operation set of the reservoir system - the third alternative.

-Result:

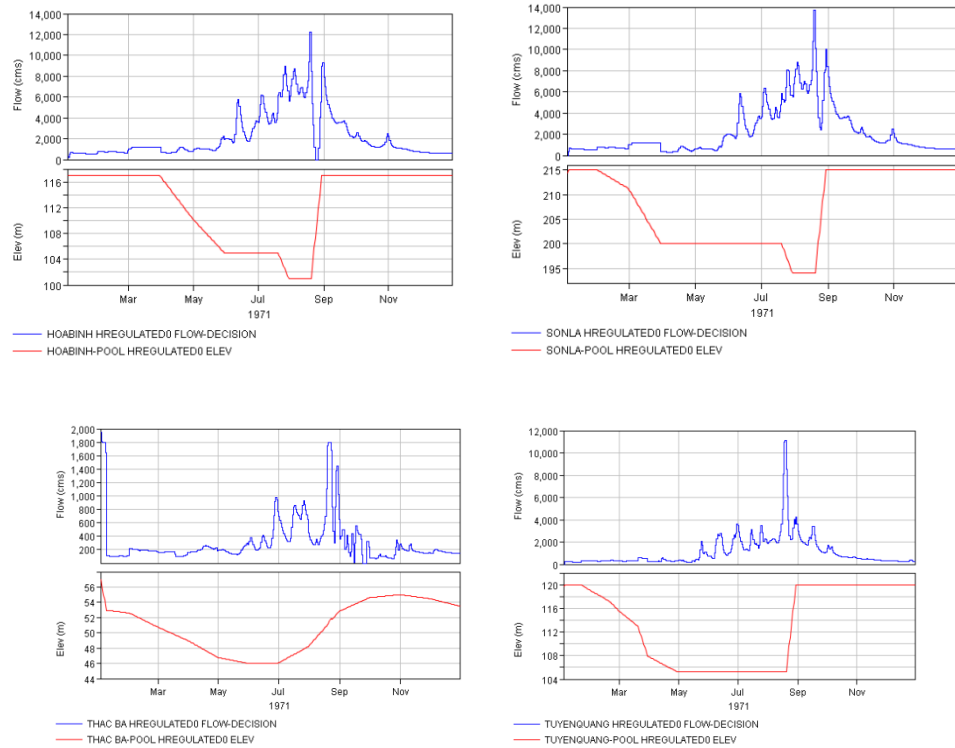


Figure 4.0-19. Release flow and water level of Hoa Binh, Son La, Thac Ba and Tuyen Quang reservoirs in year 1971

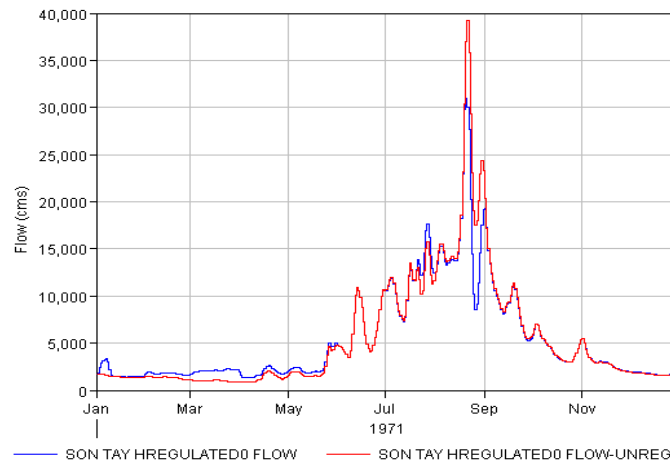


Figure 4.0-20. Flows in Son Tay station: unregulated plan (red) versus the first alternative (blue)

-Comparison between the regulated flows and the water demand in Son Tay (Figure 4.0-2)

The parameter used to evaluate the first alternative is *mean volume of water deficit* (V_N)

$$V_N = \frac{1}{365.N} \sum_{t \in H} \left[\frac{(\bar{k} - k_t)^+}{\bar{k}} \right] \text{Eq- 7}$$

$$V_N = 0 \text{ m}^3$$

-Conclusion: the third alternative distributes water for irrigation better than the ‘*water supply*’ curve. Moreover, the flood peak in Son Tay is reduced to lower than the critical condition of 33000 m³/s.

b The time frame from August 15th to August 26th

In this period, we expect a result as good as the one obtained from the second alternative.

-Time step: 1 hour

-Lookback: the initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics, which are elevation, storage, and initial release, are set. In this case, the lookback elevation and the lookback release are taken from the data of the previous calibrated model for year 1971.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Lookback Elevation	Constant	105.0
Tuyen Quang – Pool	Lookback Storage	Computed	
Tuyen Quang – hydropower plan	Lookback Release	Constant	0.0
Tuyen Quang – spillways	Lookback Release	Constant	0.0
Tuyen Quang – bottom gates	Lookback Release	Constant	2564.85
Thac Ba – Pool	Lookback Elevation	Constant	50.0
Thac Ba – Pool	Lookback Storage	Computed	
Thac Ba – bottom gates	Lookback Release	Constant	402.95
Hoa Binh – Pool	Lookback Elevation	Constant	100.75

Hoa Binh – Pool	Lookback Storage	Computed	
Hoa Binh – hydropower plan	Lookback Release	Constant	0.0
Hoa Binh – bottom gates	Lookback Release	Constant	5990.7
Hoa Binh – spill ways	Lookback Release	Constant	0.0
Son La – Pool	Lookback Elevation	Constant	193.5
Son La – Pool	Lookback Storage	Computed	
Son La – bottom gates	Lookback Release	Constant	5860.4

Table 4.0-8. The initial conditions of the reservoirs in 15th August year 1971 - the third alternative.

-Results:

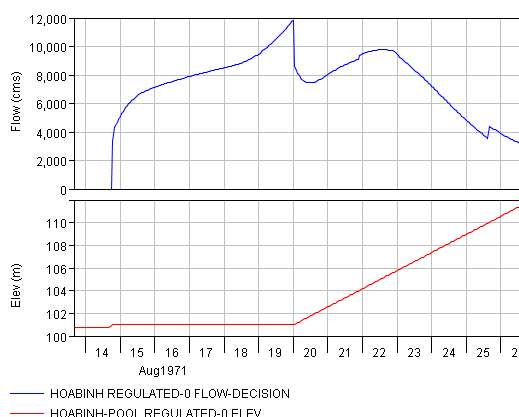


Figure 4.0-21. Hoa Binh reservoir flow decision and pool elevation.

Hoa Binh reservoir adjusts the release outflow for one week until in order to keep the water level at 101m since the ultimate objective is to reduce the flood peak as well as the number of consecutive flood days. According to the inflow to Hoa Binh reservoir (Figure 4.0-22.) it releases only 9000 m³/s when the inflow gets its highest of 17200 m³/s in the afternoon of August 21st. After that, the release goes down gradually.

The same schemes are also occurred to Son La, Thac Ba and Tuyen Quang reservoirs.

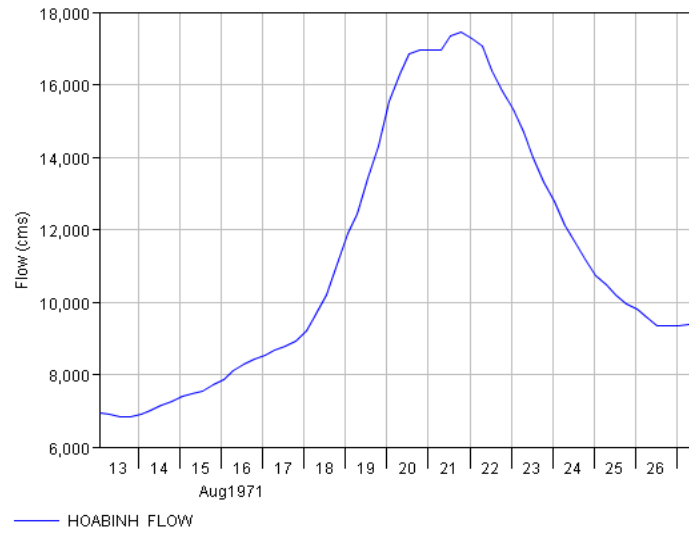


Figure 4.0-22. Inflow to Hoa Binh reservoir.

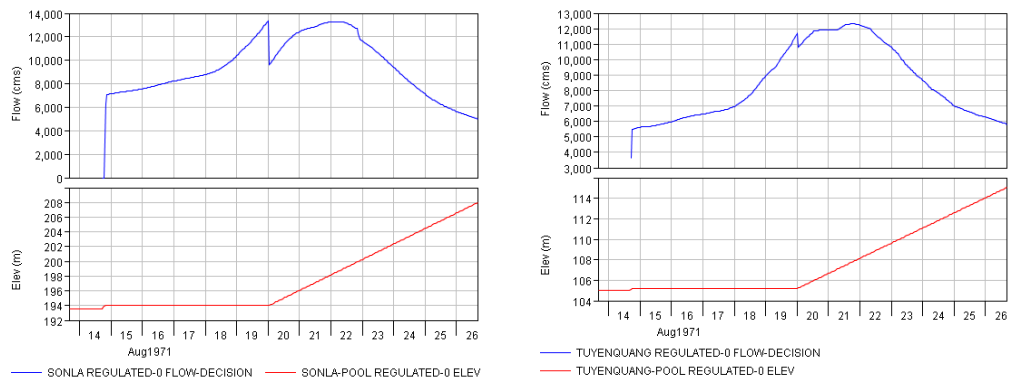


Figure 4.0-23. Son La and Tuyen Quang reservoirs: flow decision and pool elevation.

The flow in Son Tay station during the flood period is reduced significantly. The flood peak of unregulated flow is 39495 m³/s in 5am 23rd of August while the flood peak of a regulated one is only 30953.37 m³/s in 5am 23rd of August. The regulated flow has satisfied the critical condition of 33000 m³/s.

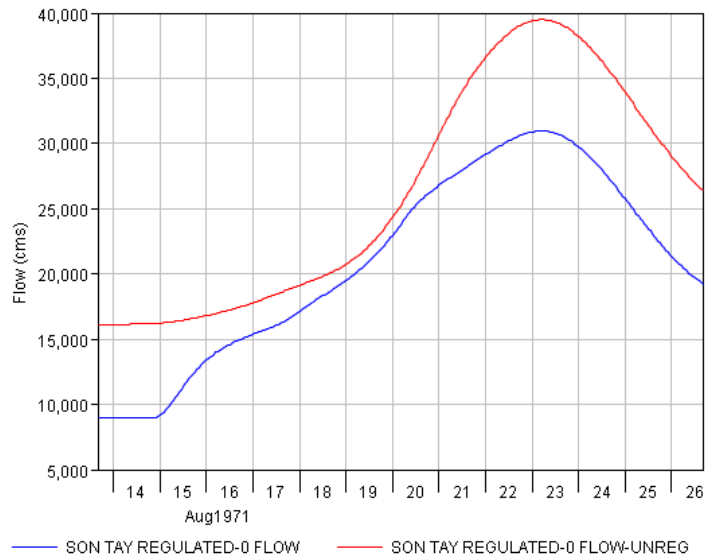


Figure 4.0-24. Flows in Son Tay station: unregulated plan (red) versus second alternative (blue)

4.2. Simulation the ‘new regime’ alternative with data in year 2002

4.2.1. Alternative

The new alternative appears to be able to balance between flood control and water supply. In this part, we will test the new alternative to manage the flows in Son Tay and Viet Tri stations in year 2002.

-We choose the time step for 1 day.

-Operations: four reservoirs have been assigned to the operation set.

Reservoir	Operation Set
HoaBinh	Day-to-Day operations
Son La	Day-to-Day operations
Thac Ba	Day-to-Day operations
Tuyen Quang	Day-to-Day operations

Table 4.0-9. Operation set of the reservoir system – the new regime alternative.

-Initial (Lookback): the initial conditions of the alternative have been defined. In this function, all the starting reservoir characteristics which are elevation, storage and initial release are set. In this case, the initial elevation and the initial release of Tuyen

Quang, Thac Ba and Hoa Binh reservoir are the actual data at the beginning of year 2002. For Son La reservoir, since it had not been built at that time, the initial values were taken from the calibrated data of the model in the last day of year 2002.

Location	Variable	Type	Default Value
Tuyen Quang – Pool	Initial (Lookback) Elevation	Constant	119.7
Tuyen Quang – Pool	Initial (Lookback) Storage	Computed	
Tuyen Quang – hydropower plan	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – spillways	Initial (Lookback) Release	Constant	0.0
Tuyen Quang – bottom gates	Initial (Lookback) Release	Constant	181.2
Thac Ba – Pool	Initial (Lookback) Elevation	Constant	53.35
Thac Ba – Pool	Initial (Lookback) Storage	Computed	
Thac Ba – bottom gates	Initial (Lookback) Release	Constant	157.4
Hoa Binh – Pool	Initial (Lookback) Elevation	Constant	114.1
Hoa Binh – Pool	Initial (Lookback) Storage	Computed	
Hoa Binh – hydropower plan	Initial (Lookback) Release	Constant	698
Hoa Binh – bottom gates	Initial (Lookback) Release	Constant	20.0
Hoa Binh – spill ways	Initial (Lookback) Release	Constant	0.0
Son La – Pool	Initial (Lookback) Elevation	Constant	214.4
Son La – Pool	Initial (Lookback) Storage	Computed	
Son La – bottom gates	Initial (Lookback) Release	Constant	1202.9

Table 4.0-10. The initial conditions of the reservoirs in year 2002 – the new regime alternative.

-Results:

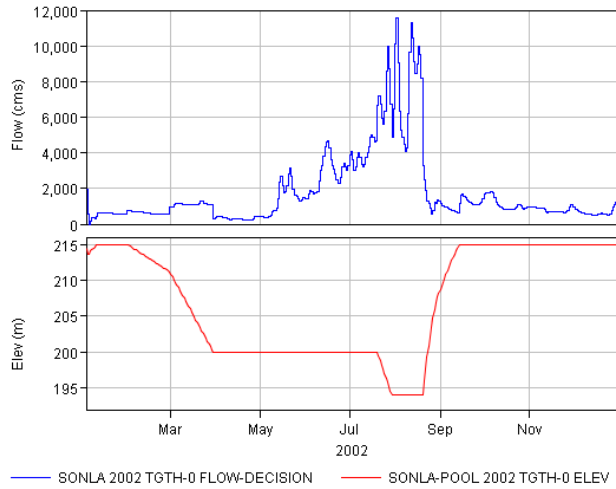


Figure 4.0-25. Son La reservoir flow decision and pool elevation.

The new regime guide curve controls the water level sensibly through the out flow. In Figure 4.0-25 we can see that the elevation is always kept at high level during the dry season for agriculture. The flood in 2002 came late and was not so significant so after remaining the lowest water level in August, Son La reservoir hold up the release for 6 days to raise the water level to the normal one before the dry season.

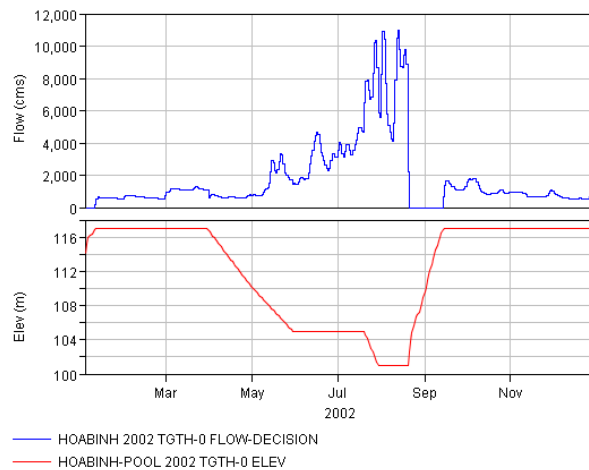


Figure 4.0-26. Hoa Binh reservoir flow decision and pool elevation.

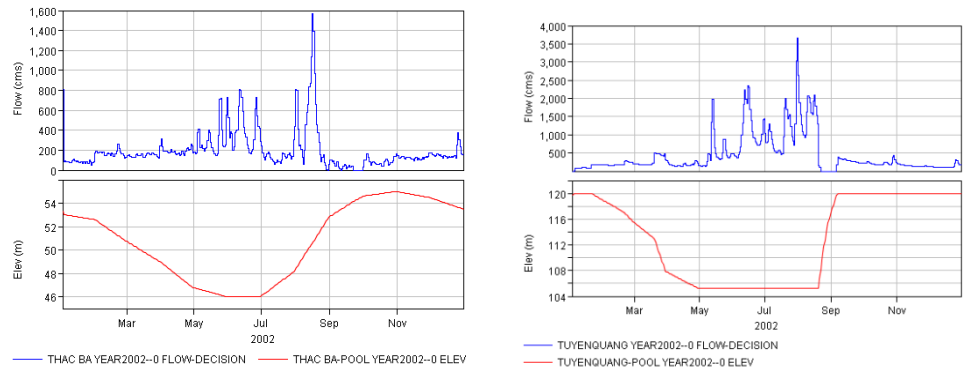


Figure 4.0-27. Thac Ba and Tuyen Quang reservoir flow decisions and pool elevations.

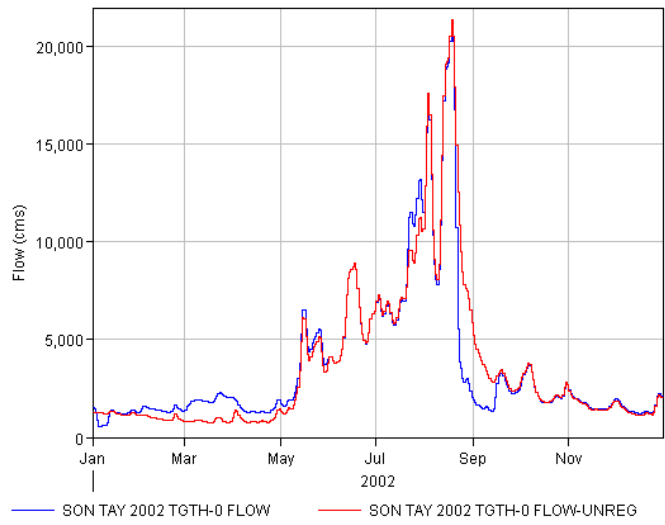


Figure 4.0-28. Flows in Son Tay station: unregulated plan (red) versus regulated one (blue)

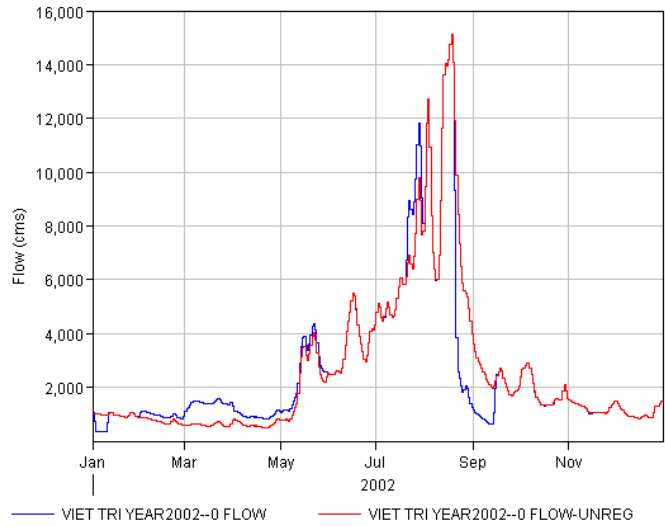


Figure 4.0-29. Flows in Viet Tri station: unregulated plan (red) versus regulated one (blue)

The regulated flows in Son Tay and Viet Tri stations demonstrate that both the objectives are fulfilled.

4.2.2. Tandem reservoirs analysis

Consider a two-reservoir tandem system, as shown in Figure 4.0-30. Son La reservoir is the upstream reservoir where a **Tandem Operation** rule has been applied in its operation set. This establishes an implicit system operation with the downstream reservoir, Hoa Binh reservoir.

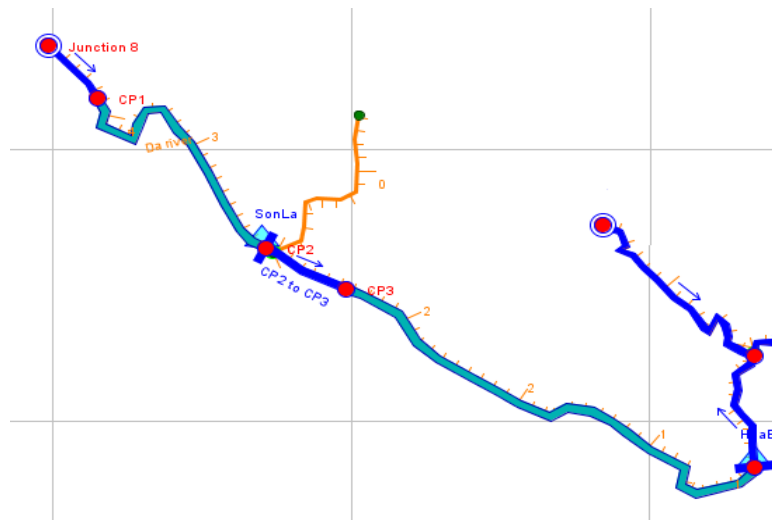


Figure 4.0-30. Da River Reservoir System

The implicit system storage balance scheme (illustrated in *Figure 4.0-31*) takes into account the **System Storage** (the total storage from the reservoirs in the system). In this case, the system storage ranges from empty to full (20,770,949,721 m³). Besides, this default scheme considers only one **System Zone**, the System Guide Curve storage, which amounts to the sum of both reservoirs storages.

The **desired storage** for each reservoir is determined through an implicit “balance line”. The balance line is simply a linear relationship between storage at each reservoir and the system storage (*HEC-ResSim Reservoir System Simulation User's Manual*).

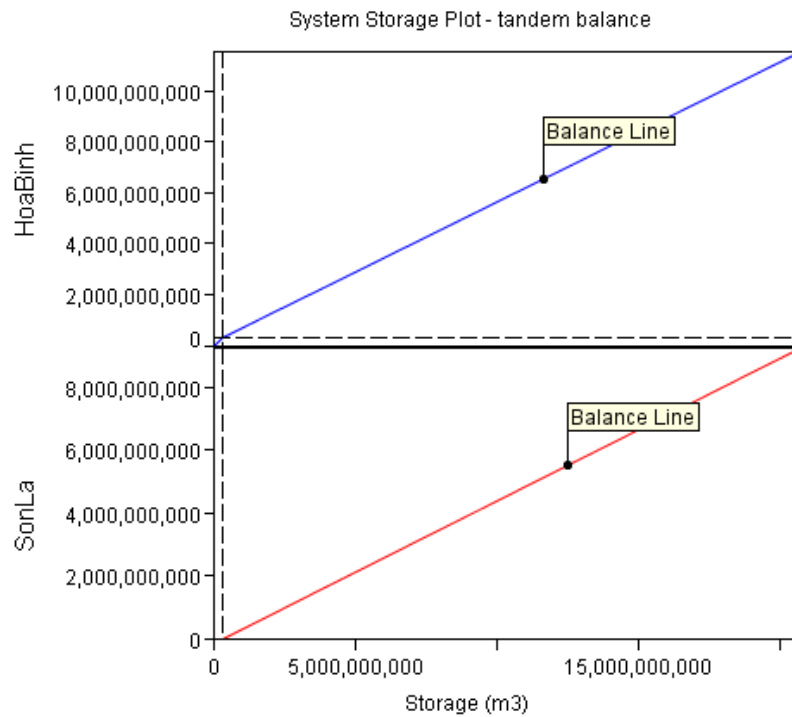


Figure 4.0-31. Implicit System Storage Balance

At the end of each decision interval, the **desired storage** for a reservoir corresponds to a point on the balance line that coincides with the sum of the estimated storages for both reservoirs. When the total estimated storage from both reservoirs is *less than* the System Guide Curve storage, the corresponding desired storages represent an equal percentage of the storage *below* the Guide Curve at each reservoir. When the total estimated storage from both reservoirs is *greater than* the System Guide Curve storage, the corresponding desired storages represent an equal percentage of the storage *above* the Guide Curve at each reservoir (*HEC-ResSim Reservoir System Simulation-User's Manual*).

For instance, assume that preliminary end-of-period storage estimates are 150,000,000 m³ for Son La reservoir and 200,000,000 m³ for Hoa Binh reservoir (Figure 4.0-32). The resultant total system storage of 350,000,000 m³ coincides with each reservoir-desired storage (about 320,000,000 m³ for Hoa Binh reservoir and 30,000,000 m³ for Son La reservoir). With 200,000,000 m³ estimated as its end-of-period storage, Hoa Binh reservoir would be below its desired storage of 120,000,000 m³. On the other hand, at an estimated storage of 150,000,000 m³, Son La reservoir would be above its desired storage of 120,000,000 m³.

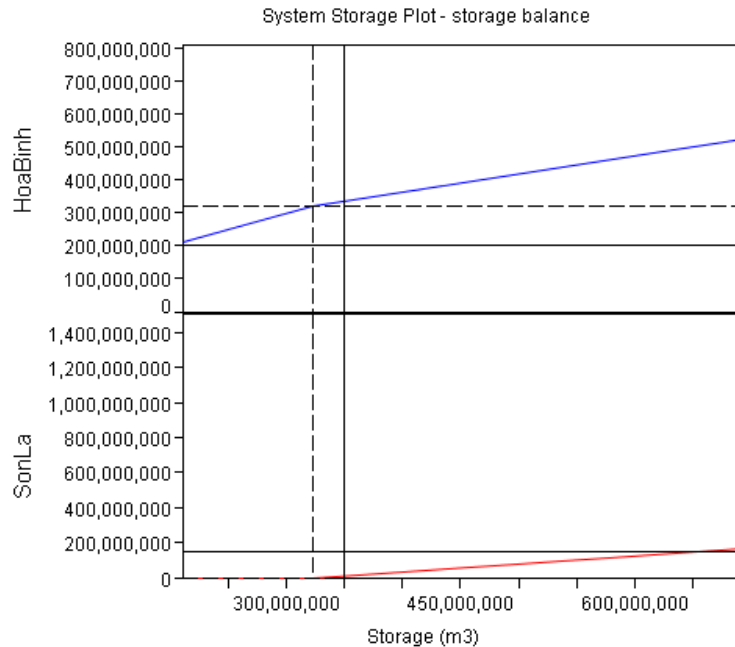


Figure 4.0-32. Example of Desired Storage using the Implicit System Storage Balance Method

Since Son La reservoir is above its desired storage, it receives the priority to release for this period in order to drop its storage down, as close as possible, to the desired storage. As for Hoa Binh reservoir, it is forced to cut back its release so that its storage can rise, as close as possible, to its desired storage of 320,000,000 m³.

4.2.3. Comparison between reservoir system with tandem reservoir operation and reservoirs managed separately

As defined above, the main difference of tandem reservoir system and the system manages each reservoir separately is that the former has a desired storage and an implicit system storage balance line. They support two connected reservoirs in redeeming reservoir storage. Figure 4.0-33 and Figure 4.0-34 can illustrate the difference in Hoa Binh and Son La operation scheme in two periods, the first one is at the beginning of January and the second one is from August to September.

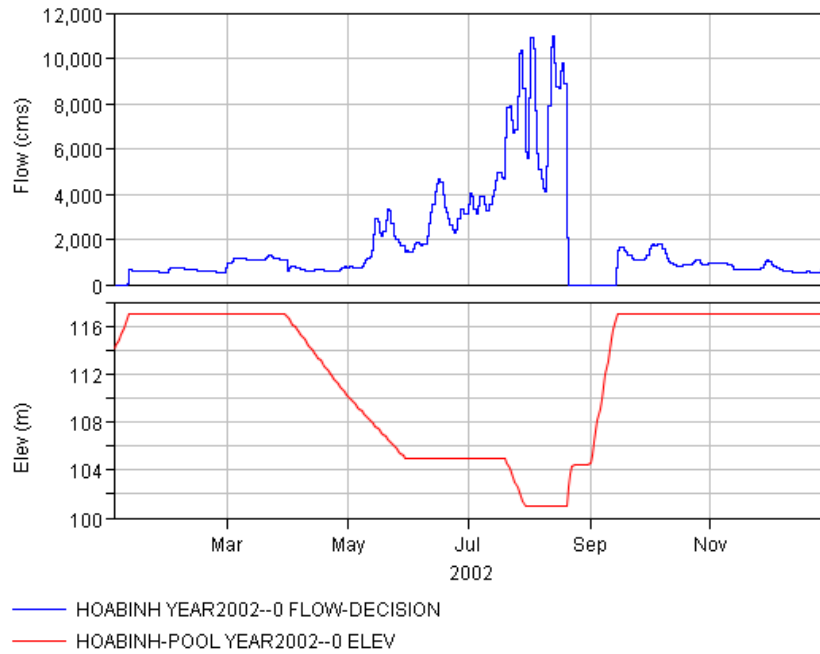
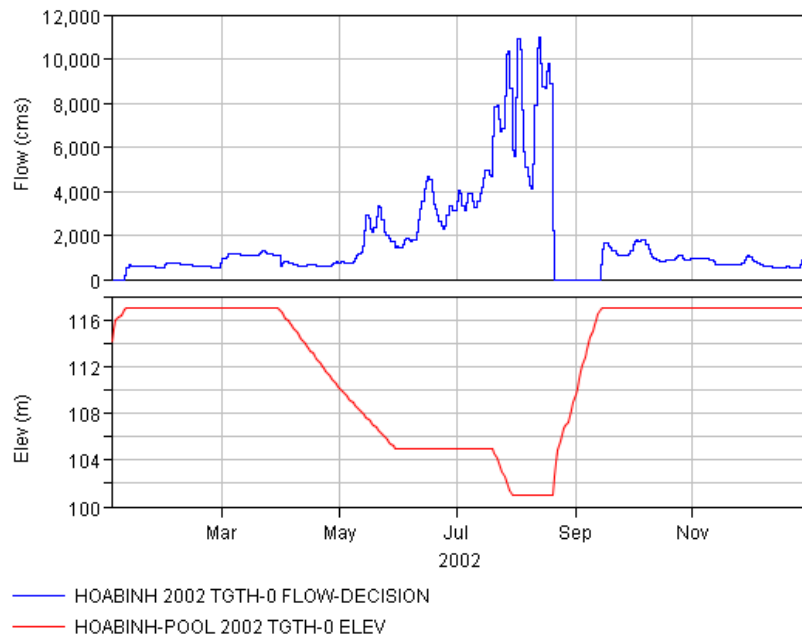


Figure 4.0-33. Hoa Binh reservoir operation system with 'tandem reservoir' (above) and individual management (below)

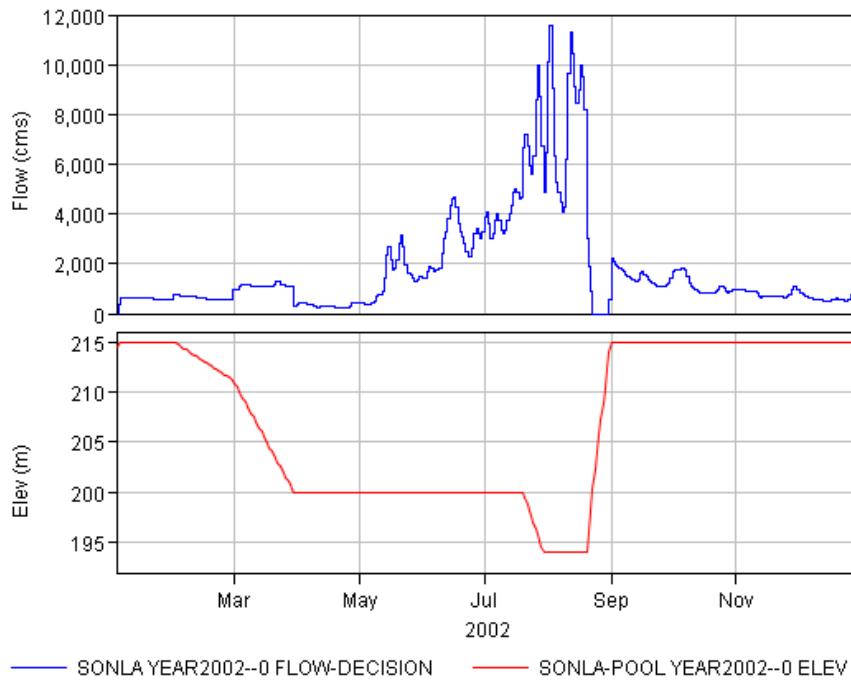
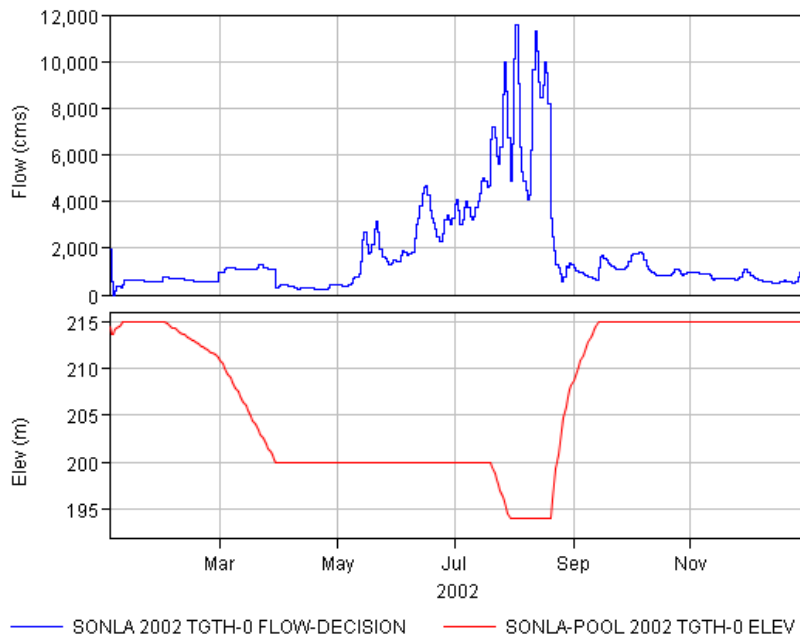


Figure 4.0-34. Son La reservoir operation system with 'tandem reservoir' (above) and individual management (below)

In the first period, both the reservoir experienced a slight increase in water elevation by 1m and 1.5m to reach to the NWL 215m and 117m in Son La and Hoa Binh respectively. On the other hand, there was only a growth of 2.5m to the NWL in Hoa Binh reservoir if they were managed separately. This results in the decrease in Son Tay flows since Hoa Binh reservoir is more important to affect Son Tay flow (*Figure 4.0-35*). Moreover, during the late flood period from 27th of August to the beginning of September, the tandem reservoir has proven its advantage. Hoa Binh reservoir increased the storage earlier in order to make the rise of Son La reservoir less steeper.

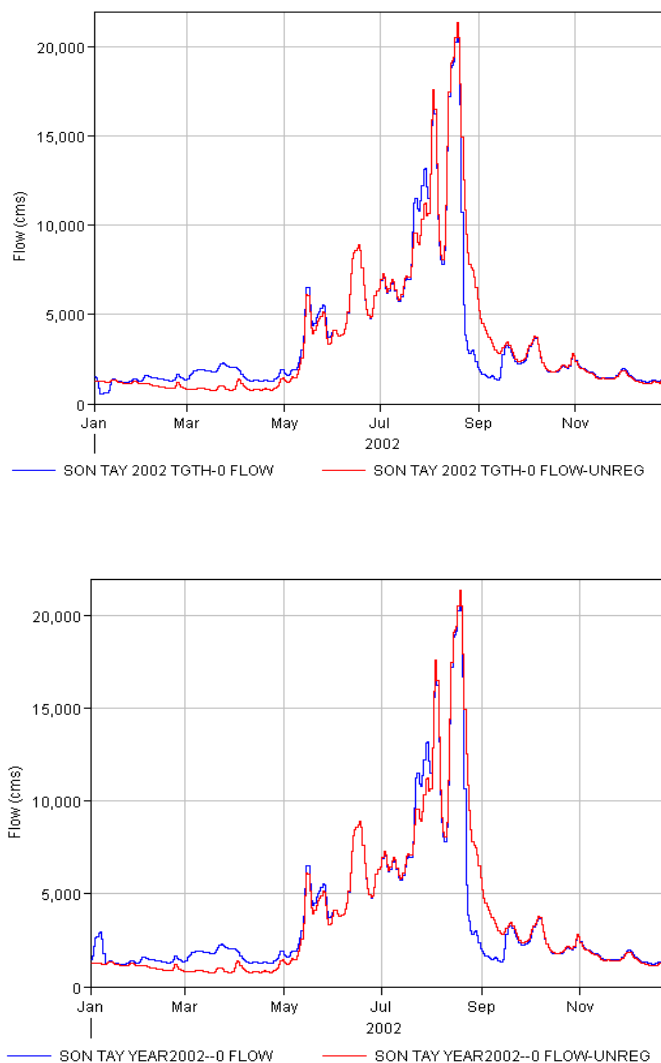
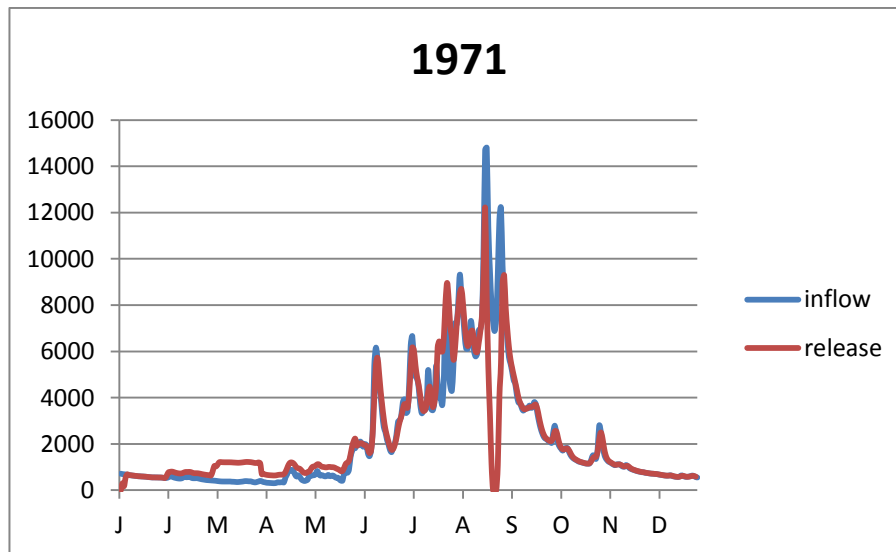


Figure 4.0-35. Son Tay flows with ‘tandem reservoir’ (above) and individual management (below)

4.3. Comparison of model simulations in year 1971, 2002 and 2010 using the ‘new regime’ alternative

The calibrated data by the model in 1971, 2002 and 2010 respectively will be compared in order to provide a general understanding of how the ‘new regime’ works in different conditions. Afterwards, the most critical year in which the flow in Son Tay is highest will be concentrated and analyzed.

These figures below demonstrate the operation schemes of four reservoirs in year 1971, 2002 and 2010. It is quite tranquil to notice that the release decisions in 1971 are more significant. The chosen alternative has controlled the reservoir system effectively to lessen one of the biggest floods in Northern Vietnam. By determining a **lower pool water elevation** before flooding season, the reservoirs have more storage for holding up the flood. Therefore, the release is considerable lower than the inflow (*Figure 4.0-36*). The results are shown in Fig 4.38 in which the flows in Son Tay do not exceed the critical flow of 33,000 m³/s even in the most serious condition. During normal years like year 2002 and 2010, the operation fulfilled both flooding control and water supply for irrigation.



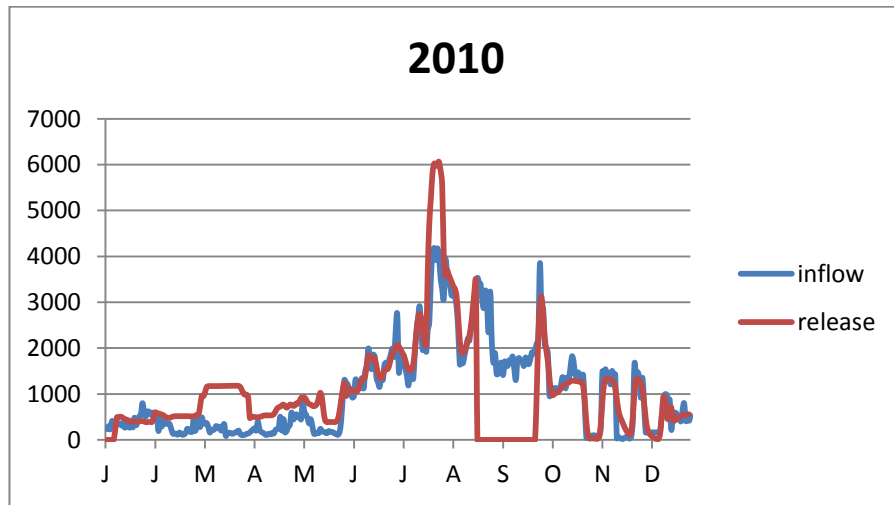
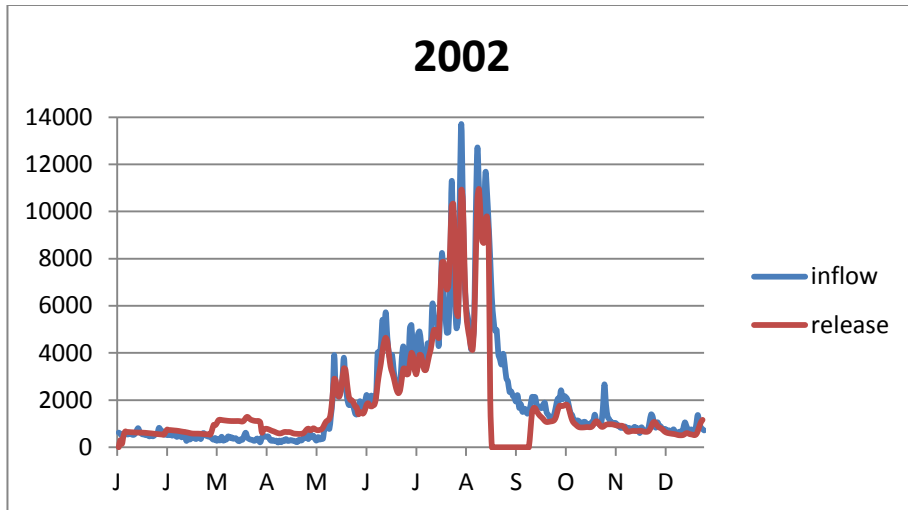
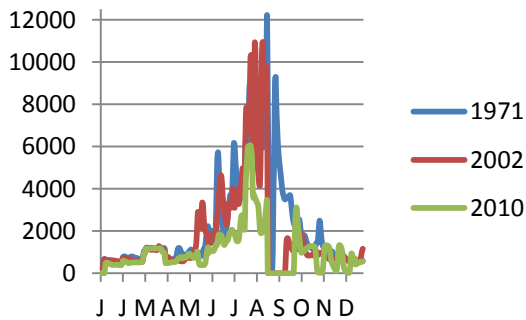
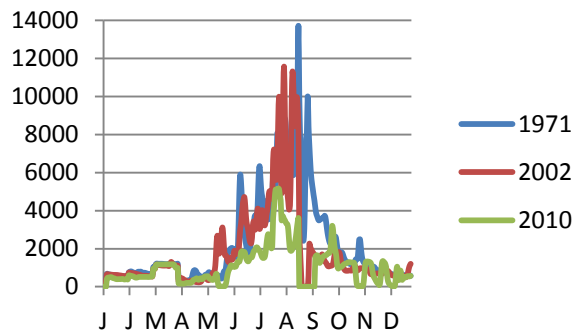


Figure 4.0-36. Historical inflow and calibrated release of Hoa Binh reservoir in 1971, 2002, and 2010

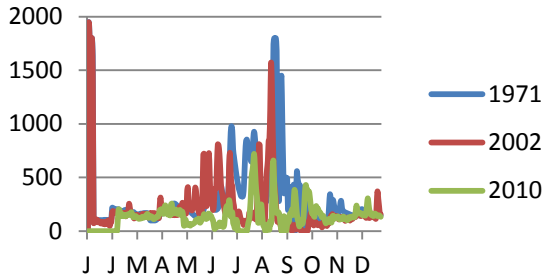
Hoa Binh reservoir's release decision



Son La reservoir's release decision



Thac Ba reservoir's release decision



Tuyen Quang reservoir's release decision

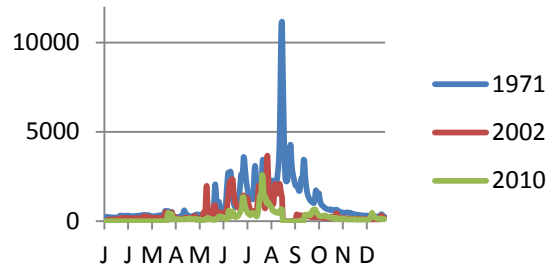


Figure 4.0-37. Release decisions in year 1971, 2002, and 2010

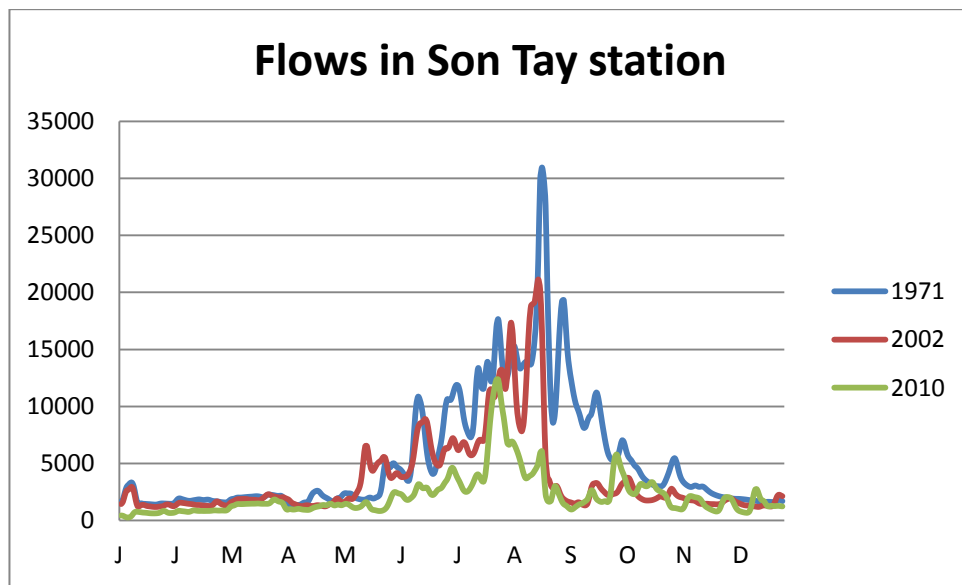


Figure 4.0-38. Flows in Son Tay station in 1971, 2002, and 2010

CHAPTER 5

CONCLUSION AND DISCUSSION

5.1. Discussion

This study has presented the model of the Red River reservoir system, set up by using HEC-ResSim program, and different proposals for alleviating flood problem and supplying water demand in the Red river delta.

The Red river system was described (*sections 1.1, 1.2 and 1.3*) and its main problems and objectives were identified (*section 2.1*) and (*section 2.3*). The model of the system had passed the validation (*section 3.2.3*) before different modifications of the historical operating rules were applied (*section 4.1*).

The results of the new operating rule, the ‘new regime’ curve (*section 4.1.3*) are particularly attractive since the defined storage volume target has met all the required objectives. *Figure 5.0-1* and *Figure 5.0-2* demonstrate the operating scheme of the reservoir system in year 2010. It is shown that, in a particular year, the regulated flows are below the critical water level and surplus the demand of water supply.

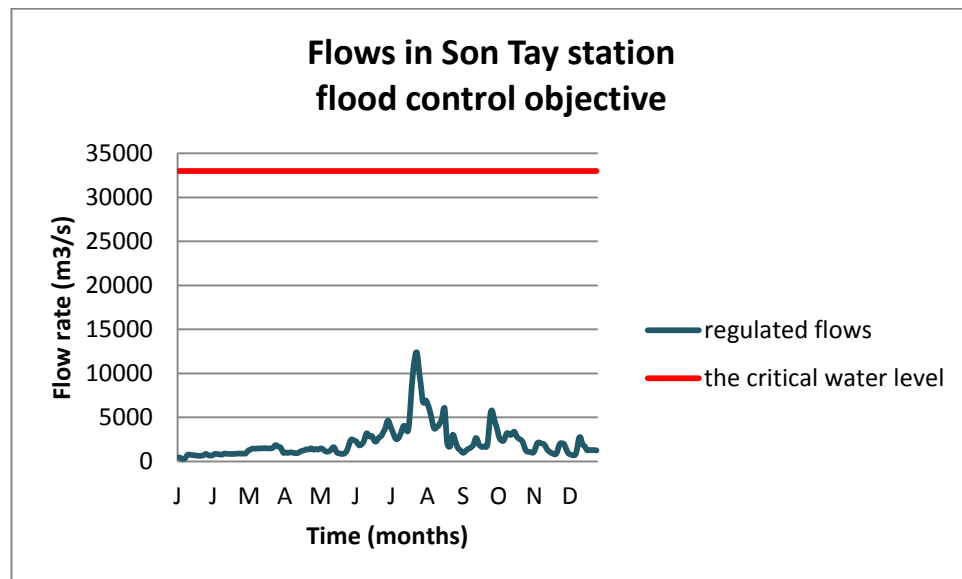


Figure 5.0-1. Year 2010, flows in Son Tay station: regulated flows vs. the critical water level

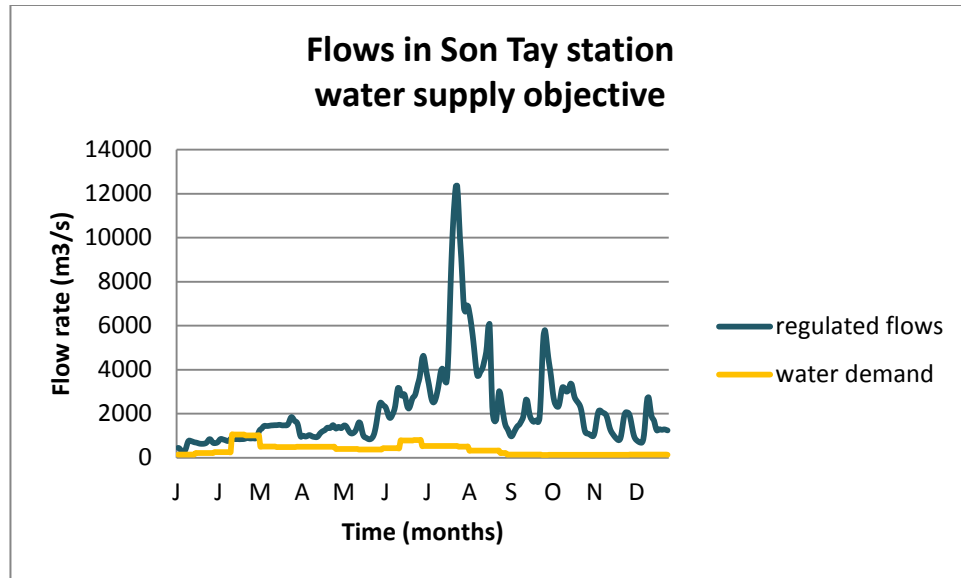


Figure 5.0-2. Year 2010, flows in Son Tay station: regulated flows vs. water supply demand

The tandem reservoir operation (*section 4.2.2*) also needs to be stressed. It is based on the Implicit System Storage Balance method. A system of two reservoirs is managed in order to reach the desired storage. In this project, the tandem reservoir operation is implemented for Son La and Hoa Binh reservoirs. In comparison with the system controlled separately, the results are marginally better. This is due to a significant difference of two reservoir storages, while Son La reservoir active capacity is 6.5 billion m³, Hoa Binh's one is only 5.6 billion m³.

Moreover, HEC-ResSim provides a suitable set of rules, which is effective in setting constraints like Flow Rate of Change Limit Rule or Downstream Control Function Rules (*section 3.2.2*) and simulating the relation between inflow and release or between storage and release.

5.2. Concluding remarks

All the results presented in this thesis rely on several simplifying assumptions and particular definitions that would deserved further discussion.

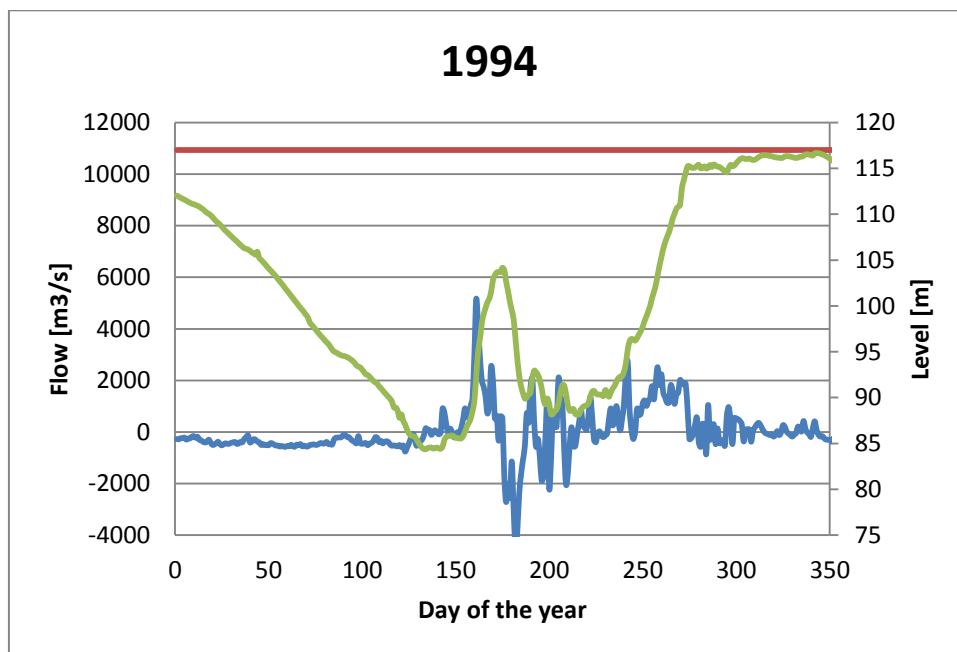
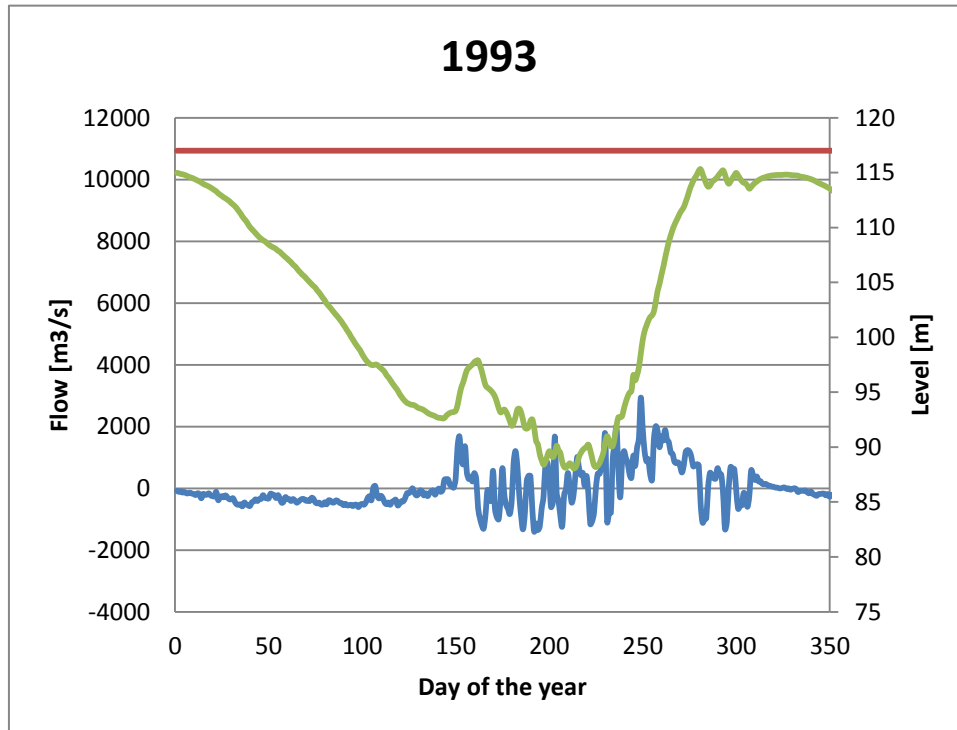
Firstly, the analysis focuses on two main objectives of flood control and water supply, while neglecting other important issues like hydropower production, riverbed erosion, and ecosystem conservation. These objectives could be taken into account by the HEC-ResSim program and be delved.

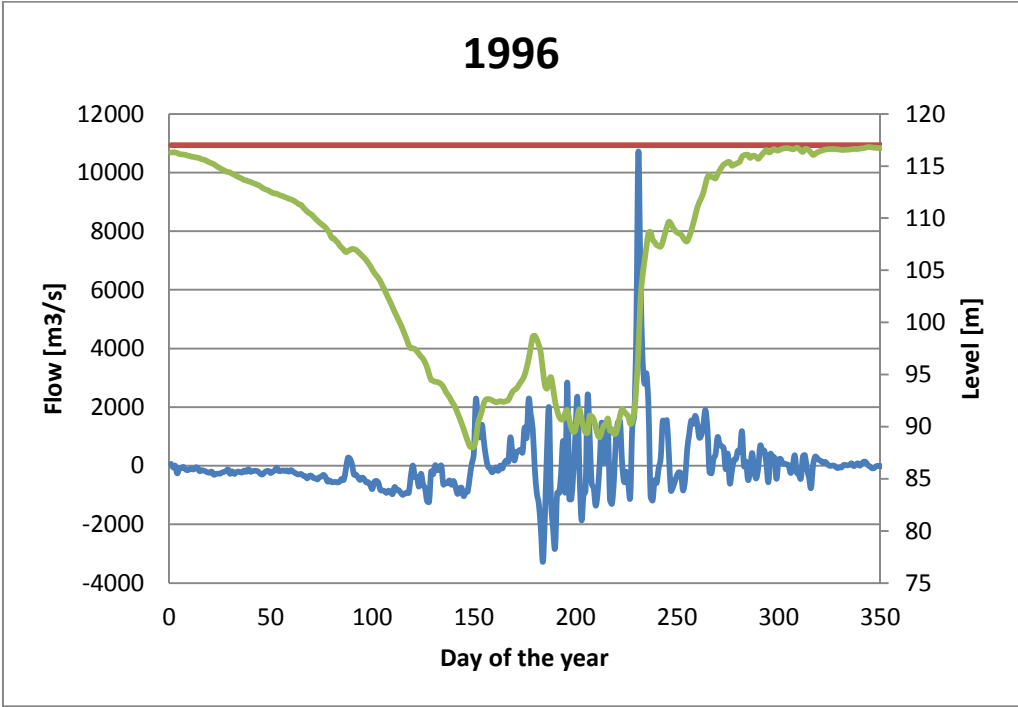
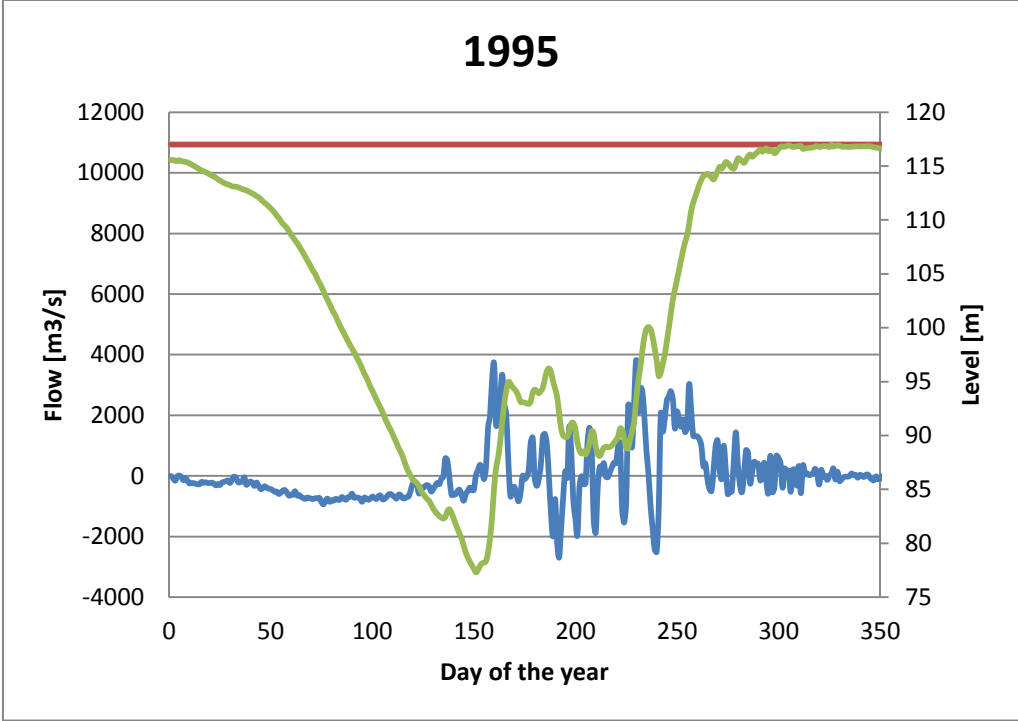
Secondly, besides identifying storage volume target (rule curves), storage zones, each associated with a particular release policy should be considered. Moreover, robustness of results presented in this thesis to model assumptions should be checked by uncertainty analysis.

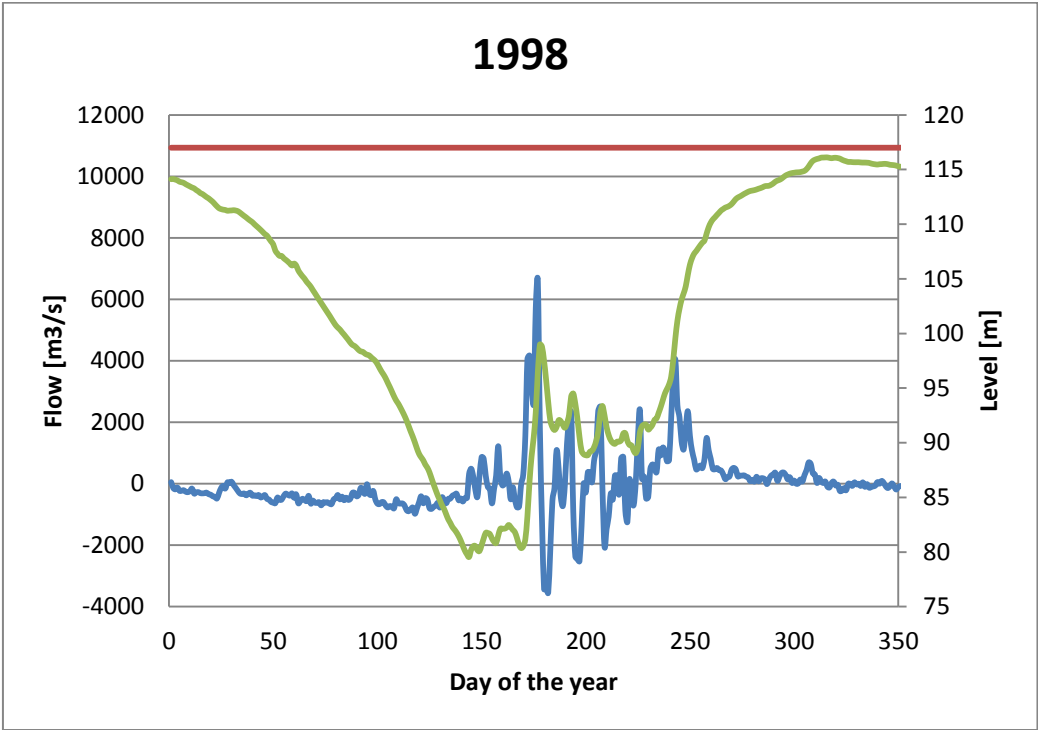
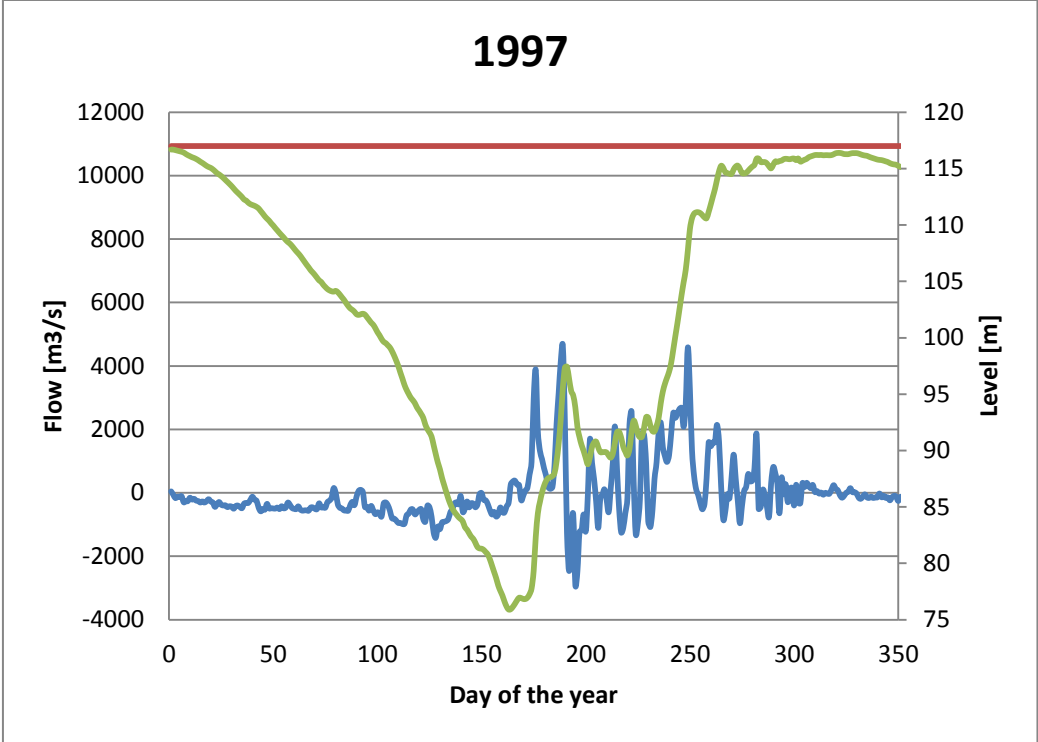
Finally, this thesis may be a preliminary exercise for future study of the coordinate management of this multi-reservoir network. In the Red river basin, there are some others reservoirs under construction, if upcoming research can enlarge the system domain, the heuristic method could be a suitable approach to find the optimal curve.

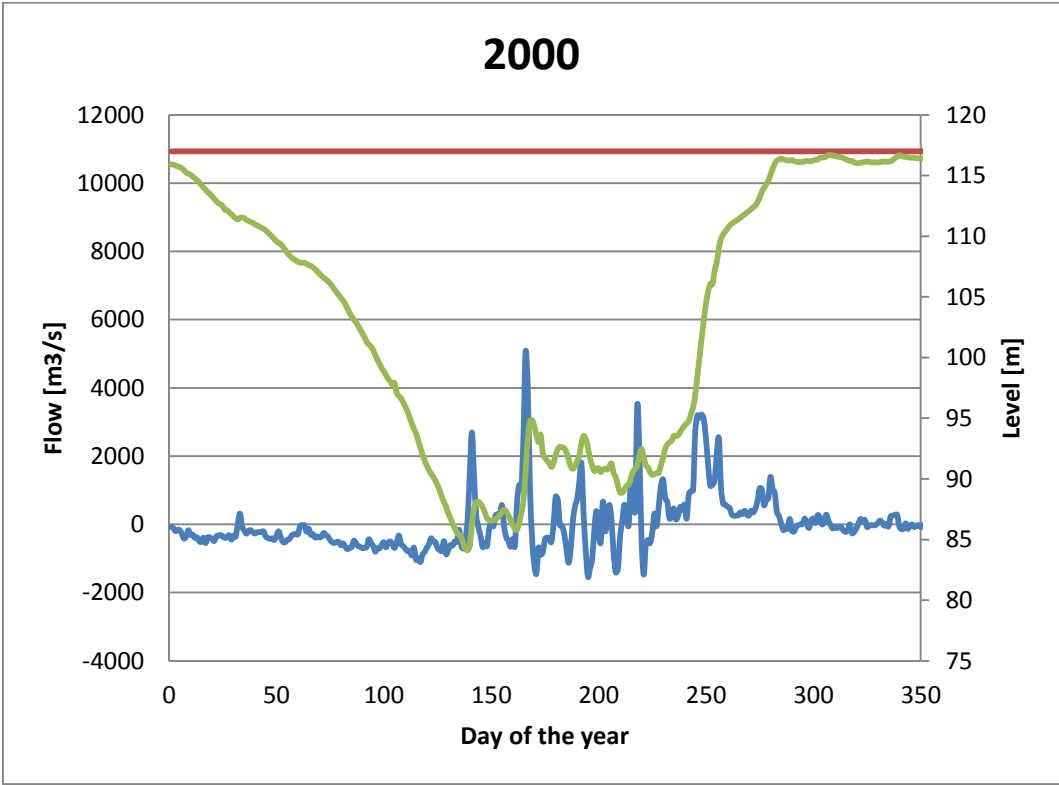
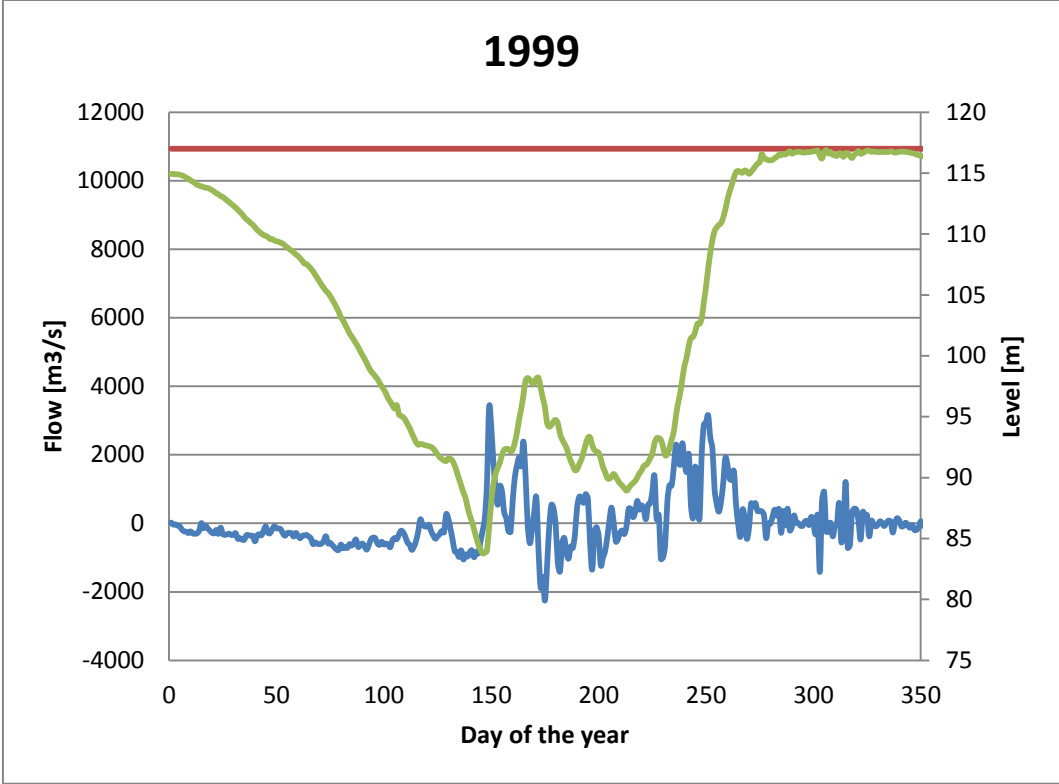
APPENDIX

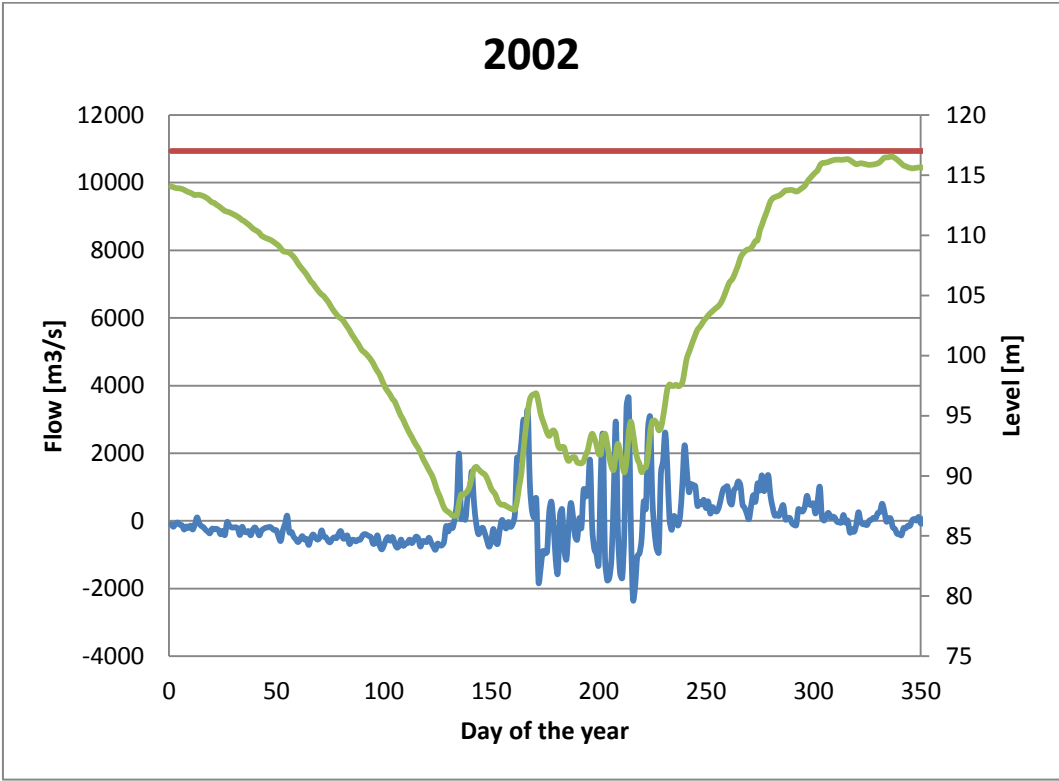
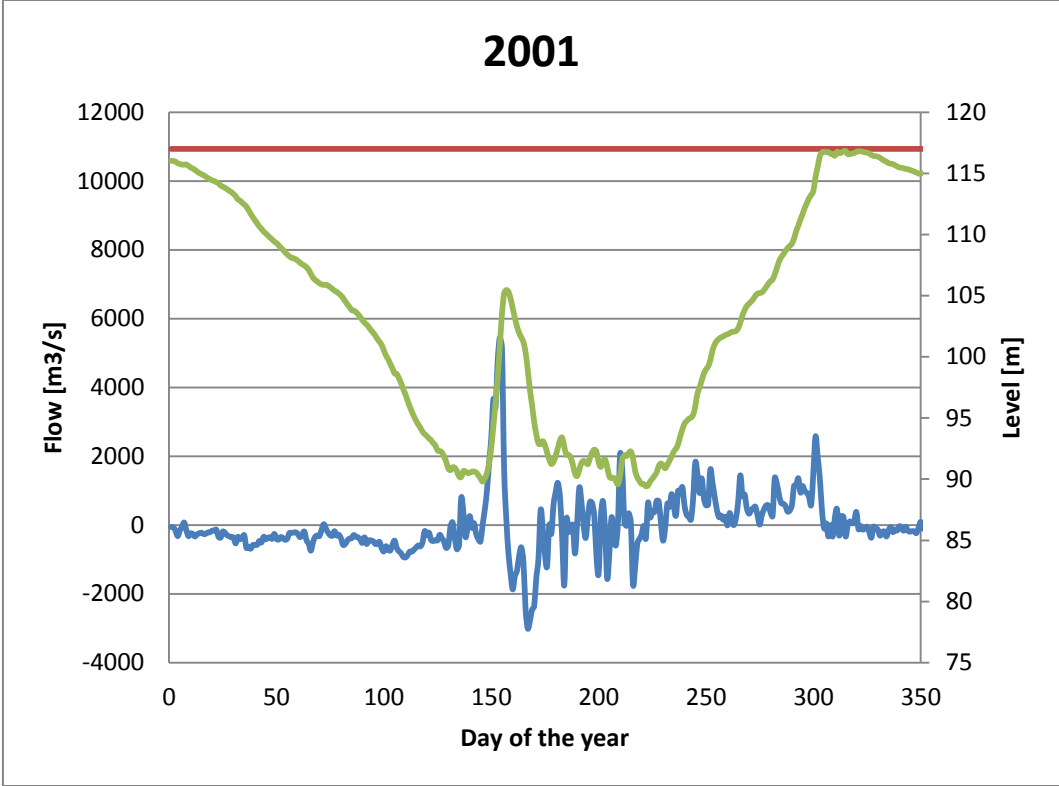
Ho Binh reservoir: Historical inflow minus release (blue line), water level (green line) and normal water level (red line) over the period 1993 – 2009

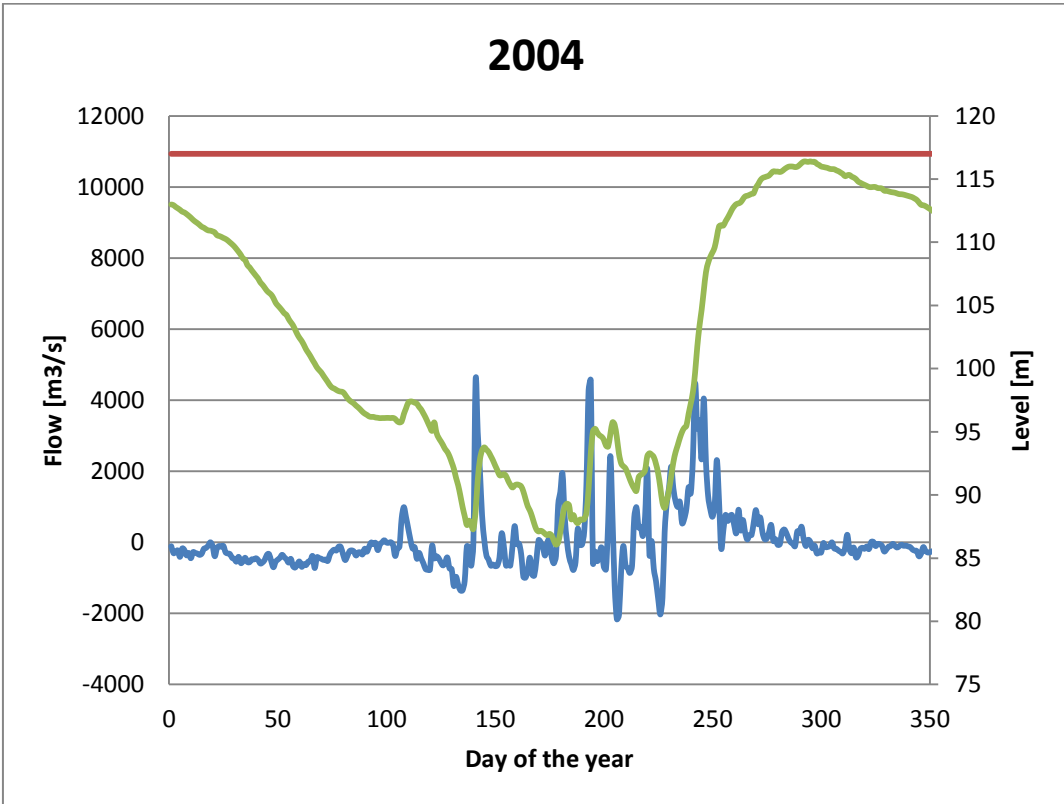
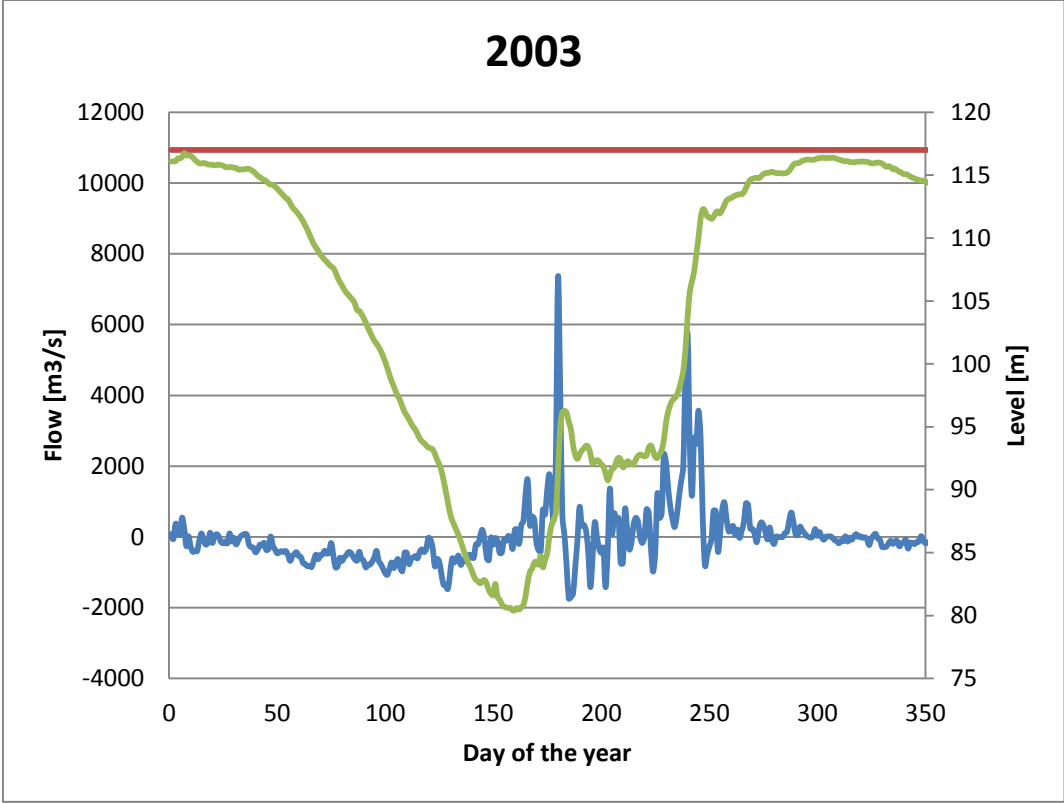


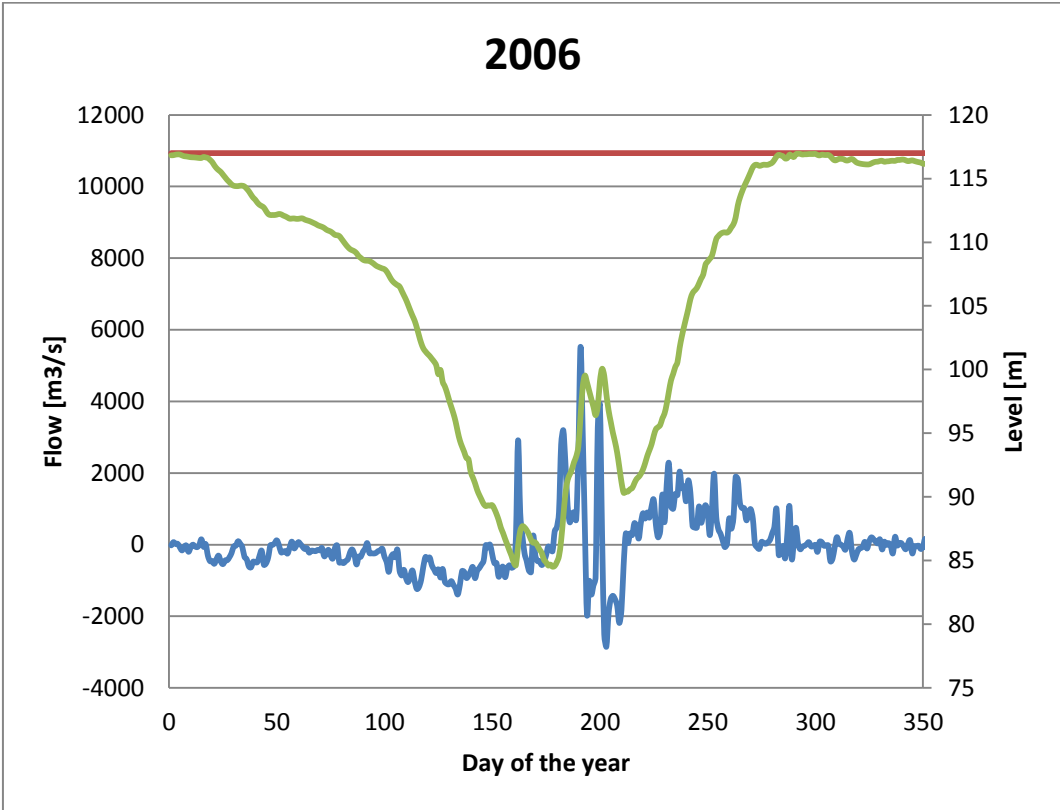
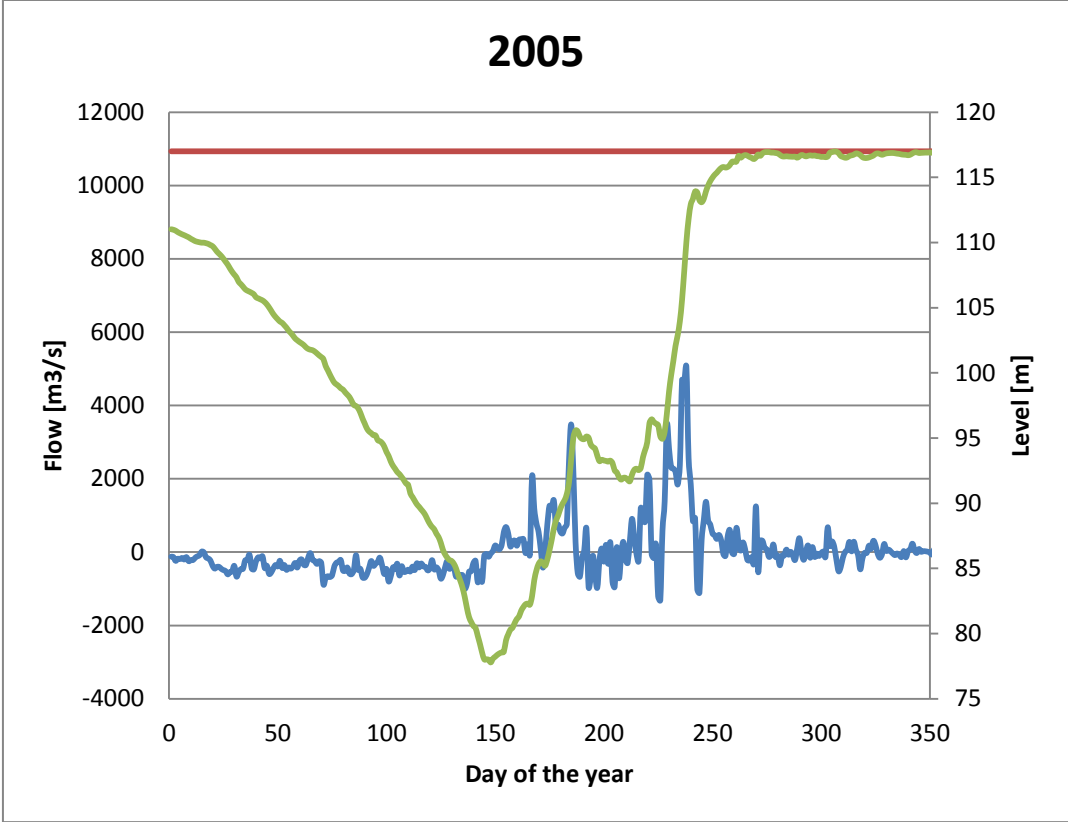


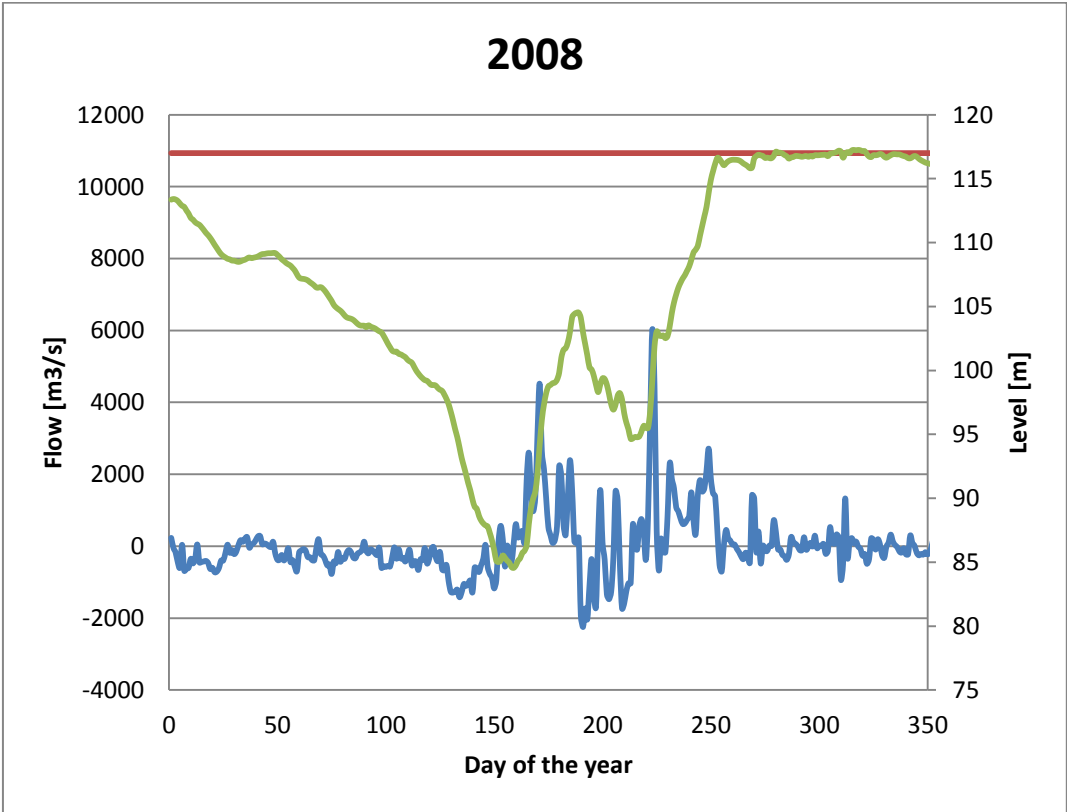
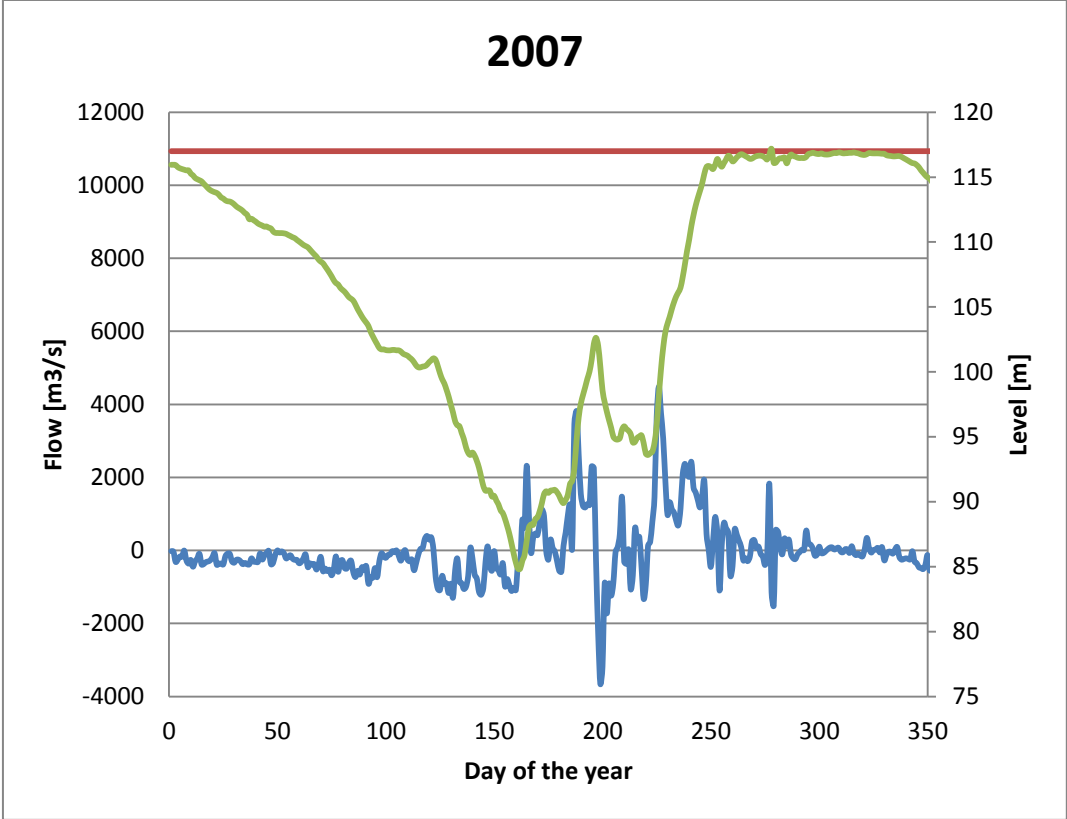


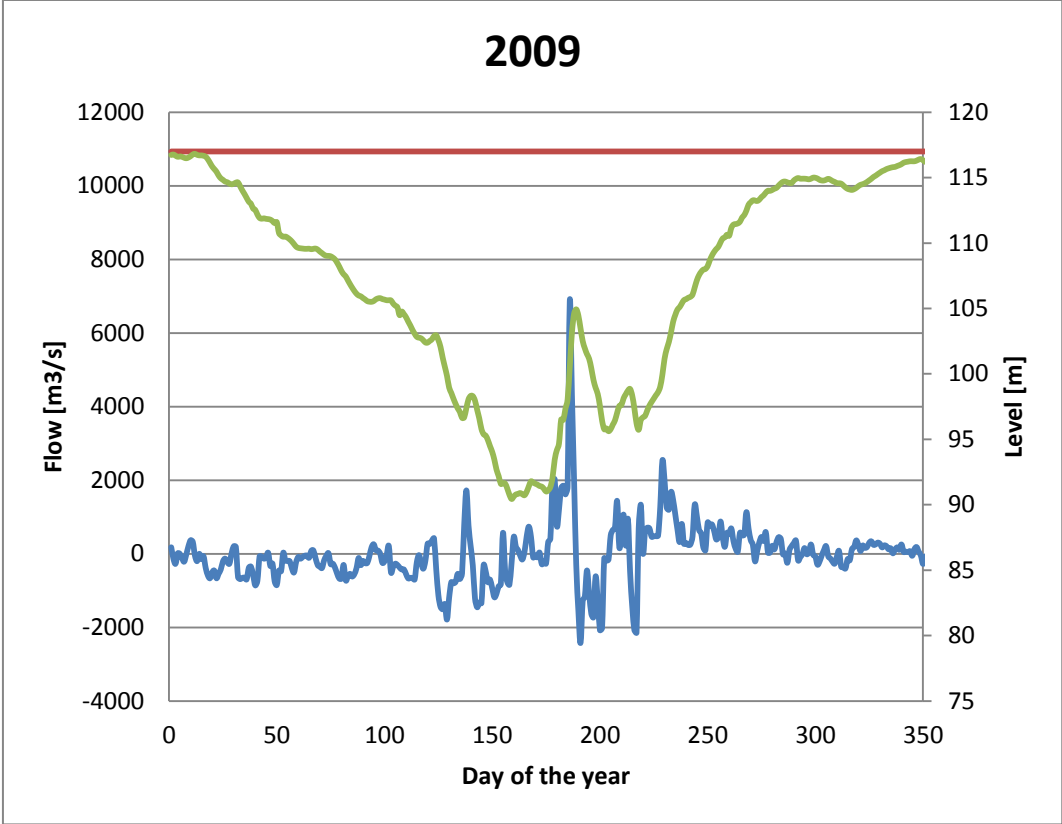












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