Dam Management in Mexico

Cajon de Peña Dam, Jalisco State

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Summary

Dams are classified based on their use under 3 types: storage (for water supply, irrigation, power generation, recreation, fish farming, etc.), diversion (to provide the hydraulic load required for their diversion into ditches, canals or other conveyance systems) and regulation (to retard stormwater runoffs, groundwater recharge, sediment control, etc.).

During extraordinary hydrometeorological events, it is important for the safety of dams, population and infrastructure located downstream to maintain a permanent surveillance on the climatological, meteorological, hydrological and hydraulic forecast scenarios in order to reduce the risks that could be generated by a sudden discharge or dam failure.

Proper monitoring enables adequate and timely decision-making on storage management through an operation policy in accordance with the evolution of the reservoir and rainfall forecast.

In this article, the policy implemented by the National Water Commission to monitor weather events and on storage levels management of the country's dams is described. Its implementation has reduced the risk of damage to the population and infrastructure located downstream, as well as to the dam.

The operation of the Cajon de Peña dam in Jalisco during Hurricane Patricia in 2015 is particularly analysed.

Keywords: surplus work, design flood, OHWL (Ordinary High Water Levels), EHWL (Extraordinary High Water Levels), Minimum Water Level Operation (MWLO), operating policy, risk, CTOOH (Technical Committee of Hydraulic Works Operation), SGT (Division for Technical Affairs, Conagua), hydrological forecast, volume, safety, modelling.

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Objective

Assessing the importance of the operation and management of storage dams in the country in order to prevent damage to their structures, and infrastructure and communities living downstream and preserve as much as possible storage to meet the commitments on drinking water, irrigation, generation or other uses.

Introduction

The National Water Commission (CONAGUA), through the Technical Division (SGT) has the authority to monitor and assess the development of severe weather events that may influence the basins, channels and storage dams, and implement actions to mitigate their negative effects.

In order to meet this objective, the variation of storage levels in the 205 major dams in the country are recorded; information from 1,000 weather stations and 600 hydrometric stations is gathered; and ocean water temperature and weather are monitored.

This allows determining in a timely manner, the potential formation of an extraordinary flood that could rapidly increase the volume stored in the reservoir.
This is done by evaluating expected inflows and determining the discharge through opening of control structures and surplus works. This allows reducing dam failure risks and preventing damage to the population and infrastructure downstream, by defining the operation policy to carry out timely controlled discharges and issue early warnings alerts to the population.

Background

In Mexico, policy management of Hydraulic Works including reservoirs is dictated by the Technical Committee of Hydraulic Works Operation (CTOOH), which is a multidisciplinary group composed of experts in different areas of knowledge.

Various scenarios on the evolution of weather events and their potential impact on streams and dams in the country are analysed in the CTOOH for the most appropriate collegial and technical decision-making on operation of dams.

In order to support this decision-making, SGT provides evidence, such as: record of reservoir evolution; hydrological forecast of reservoirs for inputs of 2, 25, 50, 75 and 98% of occurrence through continuity equation modelling, channel capacity downstream of dams, whose water volume causes no damage, water volumes extracted under irrigation schemes, drinking water demand or requirements of the national electricity system.

This Committee also keeps track of seawater temperature. Normally, hurricanes get their start over 27° C.

Hurricane season in the Pacific begins 15 May and in the Atlantic 1 June, both ending 30 November; during this period monitoring is increased as hurricanes generally evolve dramatically and with erratic trajectories.

SGT has reviewed over recent years the operating policies of the 50 dams that have such policy, changing the "abrupt" extractions for smoothed discharges in order to reduce damage downstream; the "steps" below OHWL were removed and design floodwaters were revised to update protocols.

SGT steps up its efforts during weather events as in the case of Hurricane Patricia in 2015, the most intense hurricane in history.

Hurricane Patricia

From September 2014 to March 2016 an anomaly in the Pacific region temperature occurred, creating favourable conditions for hurricane development, Table 1. This situation worsened during October 2015.

Date	Anomaly Temp.	Date	Anomaly Temp.
Sep 14	0.5	July 15	1.6
Oct 14	0.5	Aug 15	2.1
Nov 14	0.9	Sep 15	2.3
Dec 14	0.8	**Oct 15**	**4.9**
Jan 15	0.5	Nov 15	3.0
Feb 15	0.6	Dec 15	2.8
Mar 15	0.6	Jan 16	2.6
April 15	0.8	Feb 16	2.4
May 15	1.0	Mar 16	1.7
June 15	1.3		

Table 1. Anomaly in the Pacific temperature

Hurricane Patricia can be regarded as the most intense tropical cyclone ever observed in the Western Hemisphere with maximum sustained winds of 346 km/h.

Originating from a sprawling disturbance in the Gulf of Tehuantepec in mid-October 2015, Patricia was first classified a tropical depression on 20 October. Exceptionally favourable environmental conditions fuelled explosive intensification on 22 October, Patricia grew from a tropical storm to a hurricane.

At first it was considered as serious as Hurricanes Kenna and Odile, however, within hours on 23 October at 3:30 am it became a Category 5 hurricane beating Hurricane Linda, as the most intense hurricane in the Pacific. Table 2.

Hurricane	Date	Max winds (Km/h)	Pressure (hPa)
Patricia	20-24 Oct 2015	346	872
Linda	9-17 Sept 1997	295	902
Kenna	22-26 Oct 2002	270	913
Odile	10-19 Sept 2014	220	918

Table 2. The most intense hurricanes in the Pacific

It was considered the most intense hurricane ever recorded in Mexico and worldwide, it was forecasted to cause potentially catastrophic damages, images 1 and 2.

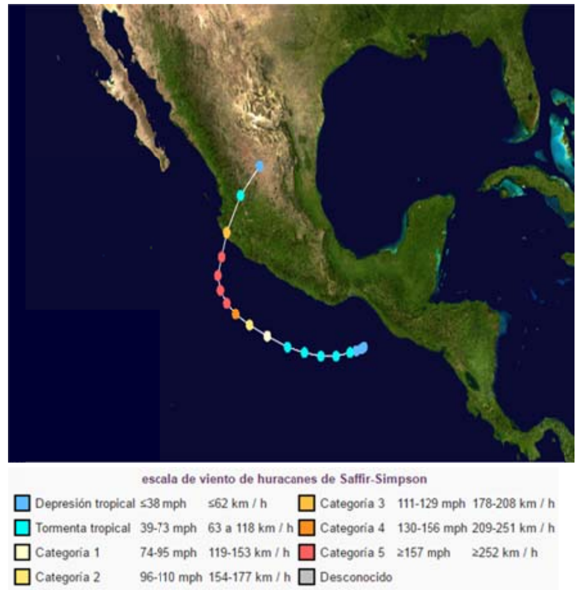

Image 1. Hurricane Patricia Trajectory

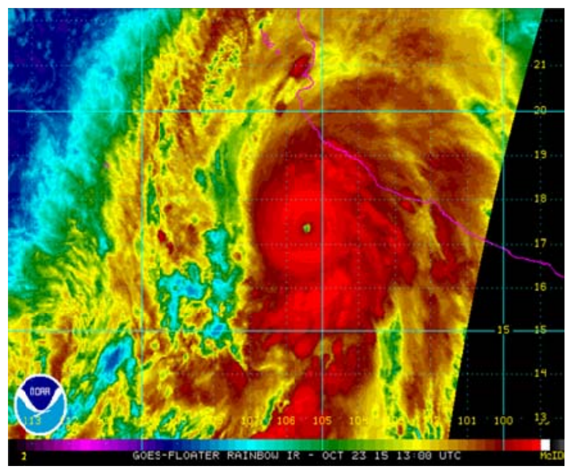

Image 2. Hurricane Patricia at 7:00 hrs 23/Oct/2015

Based on the information provided by forecasting models on the evolution and movement of weather phenomenon, it was determined Hurricane Patricia would affect with torrential rains of 150-250 mm in central, coastal and mountains of Colima and Jalisco States where Tomatlan river basin is located.

Between 20 and 24 October CONAGUA issued 15 weather warnings to inform the public and federal, state and municipal governments on the evolution of Hurricane Patricia to timely implement civil protection protocols. Population at risk was evacuated, and shelters were installed.

According to Weather Alert No. 068-15, 23 October 2015, the National Water Commission reported at 18:00 hrs. Mexico Central Time, that Category 5 Hurricane Patricia would make landfall in the vicinity of Tenacatita, Cuestecomate and Navidad Bays, a region where the towns of El Estrecho, La Manzanilla and Melaque are located, in the municipalities of La Huerta and Cihuatlán, Jalisco, image 3.

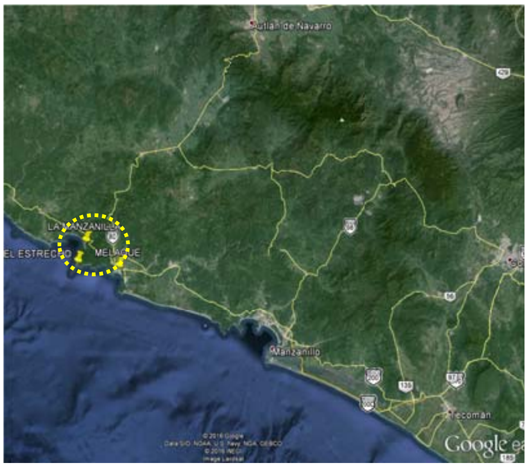

Image 3. Hurricane Patricia impact zone, 23 October 2015, 18:00 hrs

The eye of Patricia had a diameter of 10 km and was expected to continue entering southern Jalisco during the subsequent hours with sustained winds of 305 km / h winds, gusts of up to 380 km/h moving toward the north-northeast at 22 km/h.

According to the bulletin issued on 25 April 2016, the World Meteorological Organization (WMO) confirmed Hurricane Patricia had maximum sustained winds of 346 km/h.

Due to the magnitude of the hurricane, severe damage could be expected from the combination of strong winds and high rainfall over a large radius of influence, image 4. Mexican authorities successfully implemented an unprecedented emergency protocol based on based on the bulletins issued by CONAGUA and drawing on experience from previous disasters. Thousands of people were evacuated from their homes and over 1,000 shelters were created.

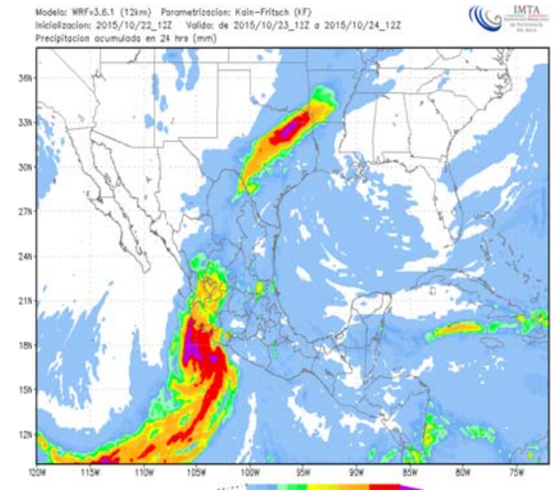

Image 4. Rainfall forecast between 23rd and 24th October 2015

CONAGUA through SGT monitored the hurricane and the conditions and evolution of dams likely to receive sudden inflows from rainfall generated by the hurricane.

Thus, 29 dams remained under permanent surveillance in order to carry out in a timely manner the management, control and discharge of storage volumes that were deemed necessary, image 5 Table 3.

Image 5. Hurricane Patricia trajectory

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Name dam	Present	NAMO	% fill
	(hm 3)		
Aguamilpa, Nay.	4850	5540	87.55
El Cajón, Nay	1899.64	2551.7	74.45
La Yesca, Jal.	1687.55	2292.92	73.60
José Ma. Morelos, Mich.	482.9	540.8	89.29
Cajón de Peña, Jal.	480.87	466.69	103.04
Trigomil, Jal.	248.92	250	99.57
Trojes, Col.	219.41	220.81	99.37
Tacotán, Jal.	149.34	149.24	100.07
Basilio Badillo, Jal	134.2	145.72	92.09
San Juanico, Mich.	57.6	60.48	95.24
La Vega, Jal.	49.48	44	112.45
Laguna de Amela, Col.	38.11	38.34	99.40
Vicente C. Villaseñor, Jal.	14.44	14.44	100.00
Laguna Colorada, Jal.	13.32	12.8	104.06
Tenasco, Jal.	5.97	10.5	56.86
Copándaro, Mich.	6.19	6.5	95.23
El Trigo, Jal.	2.58	4.4	58.64
Santa Elena, Dgo.	14.7	15.1	97.35
Santiago Bayacora, Nay.	130.15	130.05	100.08
Guadalupe Victoria	83.09	84.75	98.04
Achimec, Zac.	7.17	6.74	106.38
Excame, Zac.	51.82	71.61	72.36
El Chique, Zac.	139.48	139.95	99.66
Tayahua, Zac.	31.63	31.6	100.09
San Pedro Piedra Gorda, Z	0	5	0.00
San Marcos	s/d	3.5	s/n
El Cazadero, Zac.	22.14	22.13	100.05
Jocoque, Ags.	10.97	10.98	99.91
Niágara, Ags	16.33	16.19	100.86

Table 3. List of dams under surveillance during Hurricane Patricia

Of all dams under surveillance, the Cajon de Peña dam was considered to be the most at risk, because it was located approximately 60 km from the eye of the hurricane; it would be the first landfall impact zone; it had a storage of 480 hm^3, 5% higher than OHWL (466.69 hm^3); it is a curtain of graduated materials, Chart 1 and image 6; and about 13,000 inhabitants were living downstream, according to INEGI census of 2010.

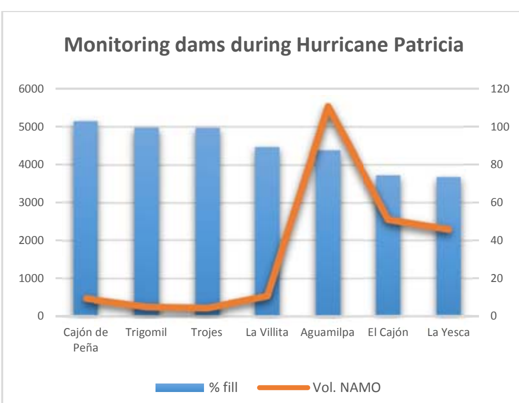

Chart 1. Most relevant dams by storage capacity kept under surveillance during Hurricane Patricia.

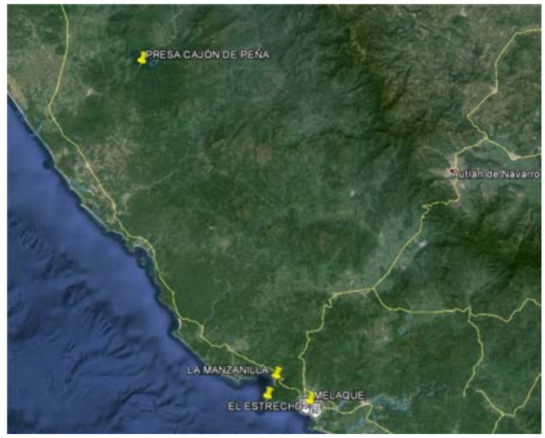

Image 6. Location of Cajon de Peña dam in reference to Hurricane Patricia impact zone

The remaining dams despite having significant storage capacity were below 80% OHWL capacity.

Cajon de Peña Dam in Jalisco State

Overview

It was built between 1974-1976 by the Secretariat of Hydraulic Resources (SRH). It is located in the Tomatlan River, coordinates 19° 59' 30" north latitude and 105° 12' 10" west longitude, 16.8 km upstream of Tomatlan, Jalisco, image 7.

Image 7. Aerial view of the curtain and spillway

The dam consists of a main curtain and four closing dikes of graded materials. The curtain has a length of 1015m, maximum height of 68m from the excavation, crown width of 10m to a 142m elevation; clay core covered with selected gravel-sand filters, bank 0.7: 1 on both sides; gravel-sand supports were placed on filters to a side bank 2:1, covered with muck and tumbled stones. image 8.

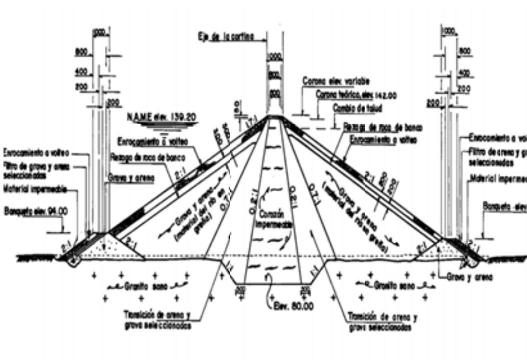

Image 8. Max curtain section

The main dam design characteristics are shown in Table 4 and Chart 2.

	Elevation (masl)	Storage (hm^3)
Crest	142.00	
EHWL	139.20	707.69
OHWL	130.37	466.69
Weir crest	123.90	321.02
Dead volume	104.98	55.00

Table 4. Design characteristics

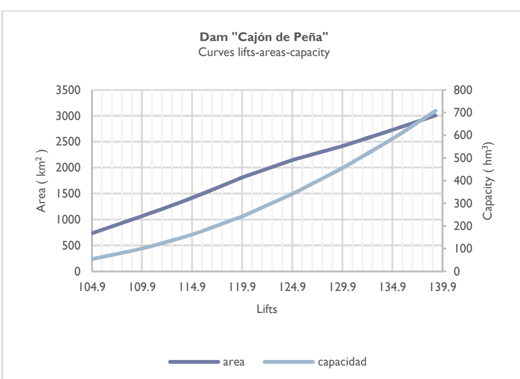

Chart 2. Areas-capacity-elevations Curve

It has two intake works; the high intake was built under dike num. 2 for a 40 m^3/s capacity and another one using the diversion tunnel with a maximum capacity of 80 m^3/s.

Design flood is 4,380 m^3/s, spillway is located on the right side of the curtain, it has direct discharge into the channel, controlled by five radial gates, 8m width, 12m height, for a regularised discharge of 4,000 m^3/s. image 9 and 10.

Image 9. Opening gates

Image 10. Storage almost at its peak

This dam often has high storage volumes, generating spills in different months due to the high potential of the Tomatlan River runoff, in comparison to the reservoir capacity, Chart 3.

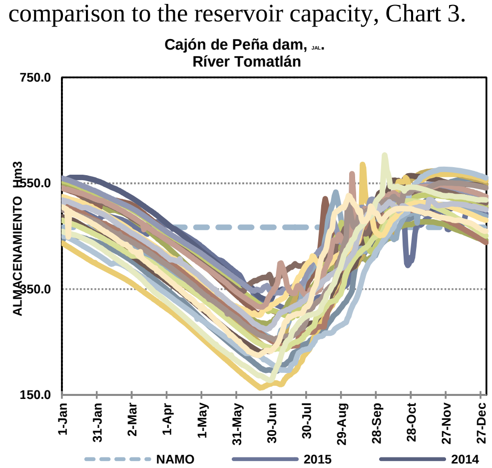

Chart 3. Historical Storage of Cajon de Peña dam, Jalisco

Dam management in 2015

As previously described, CONAGUA through the SGT keeps national dams under permanent surveillance, checking dam levels before the onset of the rainy season or during an extraordinary weather event.

This was the case of Cajon de Peña dam prior to the rainy season of 2015.

By the end of the dry season, the dam stored volume was 476.74 hm^3, which is higher than its OHWL (466.69 hm^3), Chart 4; preventive withdrawals were conducted to allow for new storage to receive runoffs generated during the following rainy season.

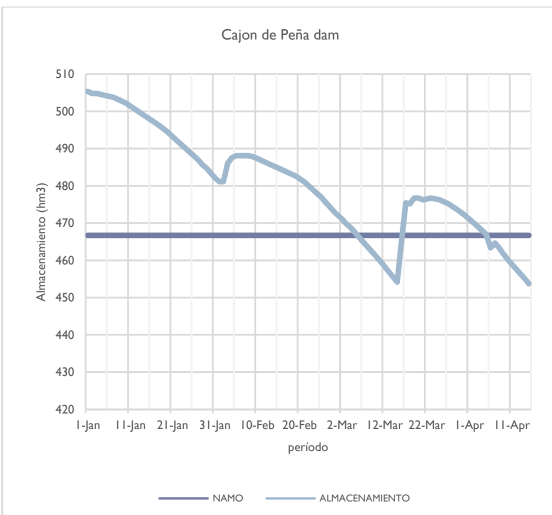

Chart 4. January-April 2015 Storage

These control withdrawals were conducted under the Gate Operating Policy endorsed by the Division of Technical Affairs (SGT) and the Lerma-Santiago-Pacific (OCLSP) Basin Organization.

A flow of up to 67 m^3/s was withdrawn from the second half of March until 5 April once the OHWL was reached, and the dam was let to freely evolve; withdrawals were made through the water intake only to meet irrigation commitments.

Start of the rainy season: Earliest significant runoffs

Dam volume decreased to a minimum storage of 312.48 hm^3 on 12 July, during the rainy season, chart 5. A decrease of 164.26 hm^3 in the stored volume and an inflow of 44.2 hm^3 were registered between 19 March and 12 July.

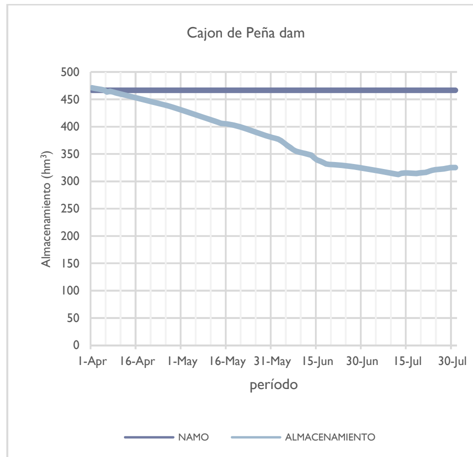

Chart 5. Storage in April-July 2015

From 4 September to 8 October, an average inflow of 110 m^3/s was recorded; between 11-30 September and 5-8 October, it was decided to release an average flow of 100 m^3/s from the spillway and intake work, chart 6 and Table 5

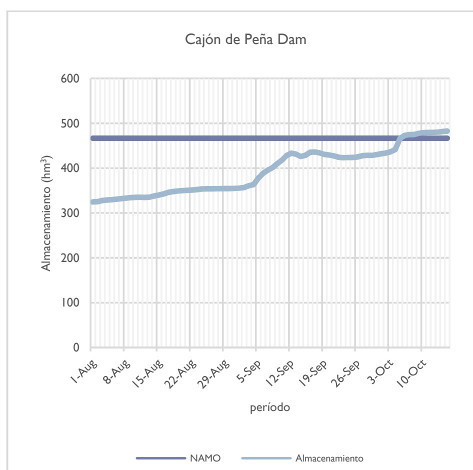

Chart 6. August-October 2015 Storage

Date	Withdrawal (m^3/s)	Stored volume (hm^3)	Overall %

			stored
5 October	175	466.43	99.9
6 October	92.14	473.13	101.4
7 October	92.14	475.19	101.8
8 October	92.14	474.93	101.8
9 October	46.78	477.77	102.4
13 October	23.53	480.61	103.0
14 October	10.60	481.89	103.3
15 October	10.60	482.92	103.5
16 October	0	484.47	103.8

Table 5. Evolution of storage 5 to 16 October 2015

Analysis

If the dam had remained with high levels and preventive withdrawals had not been made through the spillway and intake work, the reservoir would have reached a 697.24 hm^3 storage - an elevation of 138.84 m - that is 0.36 m below EHWL (Extraordinary High Water Level).

Following this event, new control withdrawals were set to maintain sufficient capacity in the reservoir to control an extraordinary flow and prevent damage downstream from a sudden release, since rainfall events were expected.

Runoffs from Hurricane Patricia

On 20 October the dam storage recorded was 489.62 hm^3, nearly 5% above OHWL, withdrawals were conducted to allow for new storage to receive expected runoffs, as well as to prevent the reservoir level to reach or exceeded EHWL. If this situation had occurred, it would had lead to structural damage as it is an earthworks dam, and under no circumstances would be possible to allow water level exceed the EHWL projected, Chart 7 and Table 6.

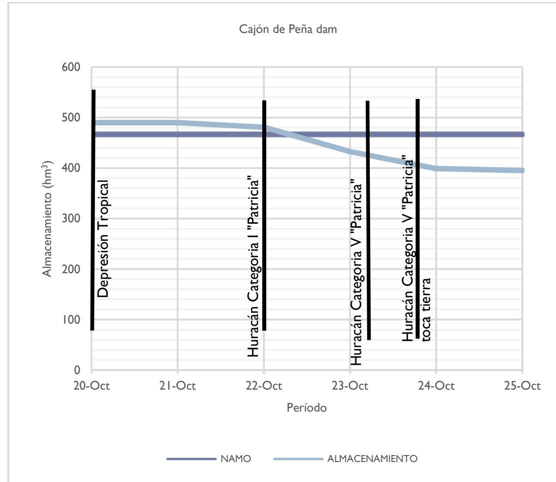

Chart 7. Evolution of the reservoir during Hurricane Patricia

Date	Withdrawal (m^3/s)	Stored volume (hm^3)	Overall % stored
21 October	99.54	489.62	104.9
22 October	351.17	480.86	103.0
23 October	658.59	432.47	92.7
24 October	421.40	398.86	85.5
25 October	0	394.98	84.6

Table 6. Evolution of Cajon de Peña Dam, 21-25 October 2015

The average inflow between 23 and 26 October generated from Hurricane Patricia was 206.85 m^3/s, mean discharges from 21 to 24 October was 382.68 m^3/s.
Rainfall was lower than predicted, image 11.

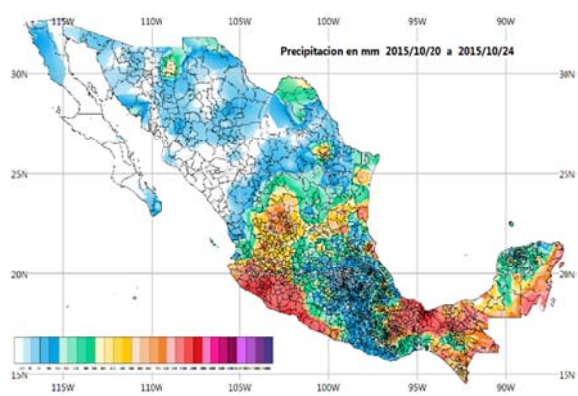

Image 11. Rain accumulated 20-24 October 2015

When inflow decreased after the hurricane, gates were closed and stored water began to increase.

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Analysis

Even though Hurricane Patricia generated lower rainfall than it was expected, the preventive withdrawals helped to avoid the reservoir to reach the forecasted storage levels of 562.10 hm^3 at an elevation of 134.07 masl, i. e. 3.69 m above OHWL and the consequential damage to the dam. The population was evacuated in a timely manner.

In the following days, moisture intrusion from the Pacific generated rainfall in the reservoir area higher than that caused by the Hurricane. Image 12 and Table 7

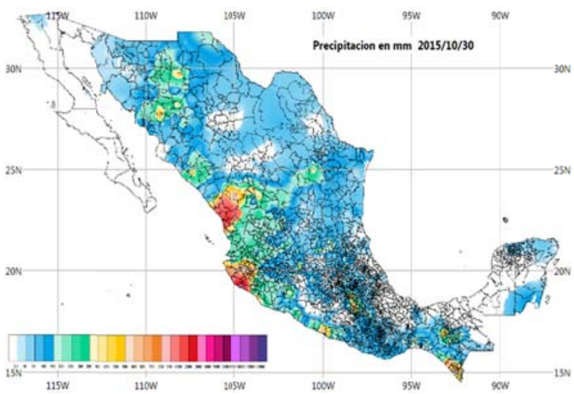

Image 12. Rainfall accumulation on 30 October 2015

day	Station			Rainfall accumulation (mm)
Oct	Cihuatlan	Cajón	Cuale	
23	20.6	6	6.4	339.5 Patricia
24	198	60	48.5	
30	395	88	18.5	709.80
31	90.3	71	47	

Table 7. Rainfall record in the stations next to Cajon de Peña Dam.

This rainfall, the soil saturation, and runoff concentration from the Hurricane at the top of the basin caused significant inflows, with a daily high of 274.38 m^3/s on 30 October and an average of 165.74 m^3/s between 29 October and 4 November. On 1 November the dam reached its OHWL again; and control withdrawals were carried out from the spillway as shown in Chart 8 and Table 8.

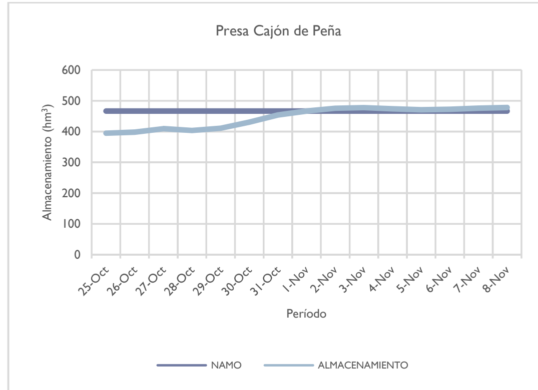

Chart 7. Storage between 25 October and 8 November 2015

Date	Withdrawal (m^3/s)	Stored volume (hm^3)	Overall % stored
31 Oct	107.35	453.73	97.2
1 Nov	0	466.44	99.9
2 Nov	15.24	475.71	101.9
3 Nov	101.33	477.77	102.4
4 Nov	198.07	473.65	101.5
5 Nov	50.27	471.07	100.9
6 Nov	0	472.62	101.3
7 Nov	15.24	475.71	101.9
8 Nov	0	478.29	102.5

Table 8. Evolution of Cajon de Peña Dam, from 31 October to 8 November 2015

Analysis

Although subsequent runoffs from Hurricane Patricia were considered for determining the reservoir management, the entrance of the stream of Pacific moisture was not considered, which generated significant rainfall. Due to the low level of the dam and withdrawals made from 21 October to 8 November, we prevented storage reservoir to reach 684.08 hm^3, at an elevation of 138.99 masl, i.e., 0.21 m below EHWL, avoiding damage to the dam.

By the end of the year, given the timely and adequate management of levels in the dam, storage over the OHWL was reached, Chart 9, in spite that the released flows could be considered as a "waste of water".

The new policy implemented by CONAGUA enabled the following key operation objectives of reservoirs to be met:

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1) Timely implementation of emergency protocols for population evacuation and protection of their property, and creating temporary shelters.

2) Safeguarding structural, hydrological, hydraulic and functional security of the dam.

3) Linking Federal, State and Municipal Bodies and the scientific and technical community in decision-making.

4) Providing sufficient water to meet the required water demands.

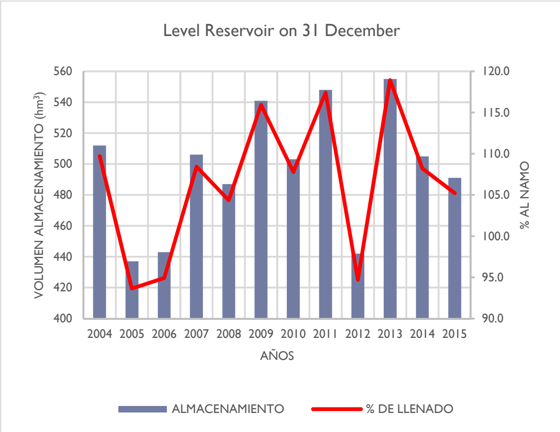

Chart 9. Level Reservoir on 31 December in the period 2004-2015

Conclusions

The operation policy is an ongoing decision-making process to define reservoir storage levels and hence its releases, in order to avoid any damage to the dam and the infrastructure located downstream.

At present the CONAGUA aims to detect and predict impending extreme events in order to formulate early warnings from monitoring and studying of factors that influence the intensity and frequency of disasters.

The temperature rise above 27 ° C in the Pacific Ocean generated conditions conducive to the formation of Hurricane Patricia, thus it is important to keep close watch on this indicator.

In the case of the Cajon de Peña Dam, Jalisco, permanent surveillance allowed for a series of withdrawals to be conducted in a timely manner in order to provide in advance a margin for manoeuvre in case of possible extraordinary inflows and prevent risks

The dam reached a storage volume of 398.86 hm^3, i.e. 85% of its OHWL capacity, as a result of the preventive withdrawals conducted during Hurricane Patricia, 21-24 October 2015, this favourable measure allowed for a have better control of reservoir levels.

If withdrawals had not made in advance during Hurricane Patricia the reservoir would have reached a storage level at an elevation of 684.08 masl, 0.21 m below OHWL, which would have place at serious risk the dam, infrastructure and the population of Tomatlán located downstream.

This new operating policy implemented by CONAGUA in all dams in the country enabled to stored a volume of 491.95 Mm^3, 5.5% above its OHWL capacity by the end of the year, which proves the proper management of the dam.

A gradual variation was achieved in the reservoir levels with these actions, reducing risks of landslides in the slopes or in the dam stability. It also allowed for an acceptable regulation capacity and to avoid damage to the infrastructure and population located downstream from a sudden released volume.

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