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Research Paper

Modification of Culvert Design on Discharge Channel: A Case Study in Indonesian Coal-Fired Power Plant

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Abstract

The construction of a new CFPP in Indonesia, which was located next to three existing power plants and utilized an existing discharge channel, faced the problem of insufficient capacity of the existing discharge channel to deliver water to four power plants. The problem occurred not only because of the overcapacity of the cooling water flow proposed by the new CFPP but also because of the small size of the culvert located in the discharge channel. This paper discusses several methods to overcome this problem by enlarging the culvert area or by removing the culvert from the channel and replacing it with a bridge. A hydraulic study was investigated using the HEC-RAS software by utilizing inputs obtained from the existing channel geometry and flow measurement data. It was found that additional culverts on both sides with a size of 2 m x 4 m and 3 m x 1 m could reduce the water level by 1.12 m and 0.39 m, respectively. Meanwhile, removing the culvert provided a significant water level reduction of 1.39 m. Enlarging the culvert was chosen as the solution to the discharge channel capacity issue since removing the culvert would require temporarily closing the channel during construction and stopping the operation of the existing power plant.

Keywords: *coal-fired power plant; cooling water system; culvert design; discharge channel; HEC-RAS modelling.*

Introduction

Coal-fired power plants (CFPP) require huge amounts of cooling water to condense the steam in the condenser on the power plant's steam cycle to produce electricity. A once-through circulating water method can be utilized to deliver the cooling water from the sea or a river directly to the condenser when the water source is abundant. The cooling water is delivered to CFPPs via an intake channel and is discharged from the condenser through a discharge channel to deliver the water back to the sea. Maintaining the conveyance capacity of the intake and discharge channels is an important aspect to ensure the continuous operation of the CFPP. A schematic illustration of a condenser in a CFPP is shown in Figure 1.

The construction of a new CFPP in Indonesia next to three existing CFPPs, which utilized an existing discharge channel, faced the problem of insufficient capacity of the existing discharge channel to deliver the water to the four power plants. The three existing CFPPs had been commercially operated since 2011 and 2013, while construction of the new CFPP was started in 2016. The condenser discharge water is delivered to the sea via a 2-km long existing discharge channel. A culvert is located 850 m away from the seal pit, as illustrated in Figure 2. The discharge channel was designed to deliver 57.13 m^3/s to the four units. The three existing CFPPs utilized a cooling water discharge flow of 42.85 m^3/s, leaving a spare capacity of 14.28 m^3/s discharge water flow for the new CFPP.

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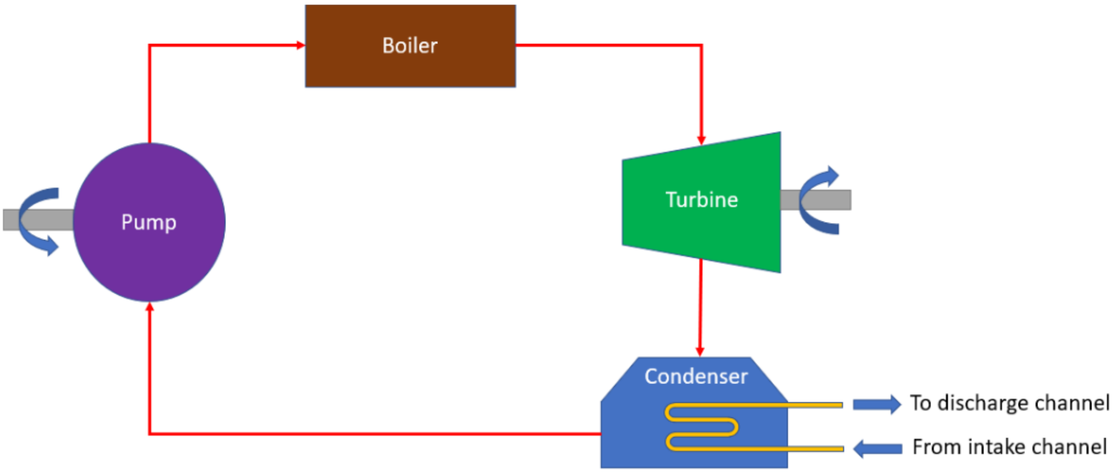


Figure 1 Condenser in a coal-fired steam power plant.

During the design stage of the new CFPP, the cooling water flow proposed was 16.05 m^3/s, which was greater than the spare capacity allowed based on the existing discharge channel design capacity. Moreover, based on the preliminary study it was also found that the culvert was too small to deliver cooling water to the four CFPPs. Overtopping will occur on the waterway before the culvert if the four power plants are operated together.

This paper discusses the analysis and solution for the discharge channel capacity problem by analyzing the hydraulic behavior of the channel and the culvert. The water surface of the open channel flow is interdependent with water depth, water flow capacity, and the channel slope, which can be analyzed using an empirical method [1]. One-dimensional flow finite difference modeling using the HEC-RAS software can solve the unsteady flow analysis in channels [2]. Re-designing incapable culverts in discharge channels is possible by utilizing the HEC-RAS software [3].

(a) (b)

Figure 2 (a) Top view of the discharge channel route; and (b) existing culvert design.

Several studies regarding optimization of existing CFPPs to improve power plant efficiency and reduce their environmental impact have been conducted. Sultana *et al*. [4] examined the use of waste PVC from CFPP cooling towers to create compression-molded goods. Nugroho *et al*. [5] investigated the usage of CFPP fly ash to remove dye color from the water. Lisafitri *et al*. [6] researched utilizing microorganisms to purify CFPP fly ash from heavy metals. Tontu *et al.* [7-9] have investigated efficiency improvement in a CFPP desalination plant, condenser, and electro-chlorination plant in power plants. None of these studies discussed the performance of a channel in a power plant. Meanwhile, studies on the effect of culvert and bridge constructions on open channel flow have also been investigated. Han *et al*. [10] have discussed the impact of the water level of a bridge construction and dredging on flood management and sedimentation in the extension of a railway project on the Weihe River in China.

Jaeger *et al*. [11] discusses several improvements using CFD simulation to maximize water flows in misaligned culverts by adding smooth transitions for flow direction. Adeogun *et al*. [12] performed a hydraulic assessment of ten culverts along a certain road in Nigeria using the HY-8 software. The research showed that three culverts needed to be enlarged, while the remaining seven culverts had enough capacity to accommodate the design flow. Mamoon *et al*. [13] conducted a hydraulic analysis of a river crossing a bypass road in Bangladesh with the HY-8 software. The study of culvert performance using a future climate scenario revealed that nine of the analyzed culverts would need to be modified. Nwaogazie and Agiho [14] studied the redesign of a culvert in Port Harcourt, Nigeria. The existing culvert was modified using circular and box culverts, showing that a box culvert has lower headwater elevation compared to a circular culvert.

From the above references, none of the research mentions about redesigning a culvert in a CFPP using several alternatives to enlarge the culvert area and to improve the discharge flow. This paper can be used as a reference for the improvement of CFPPs in which the culvert starts to deteriorate or is inadequate to handle the water flow in a channel.

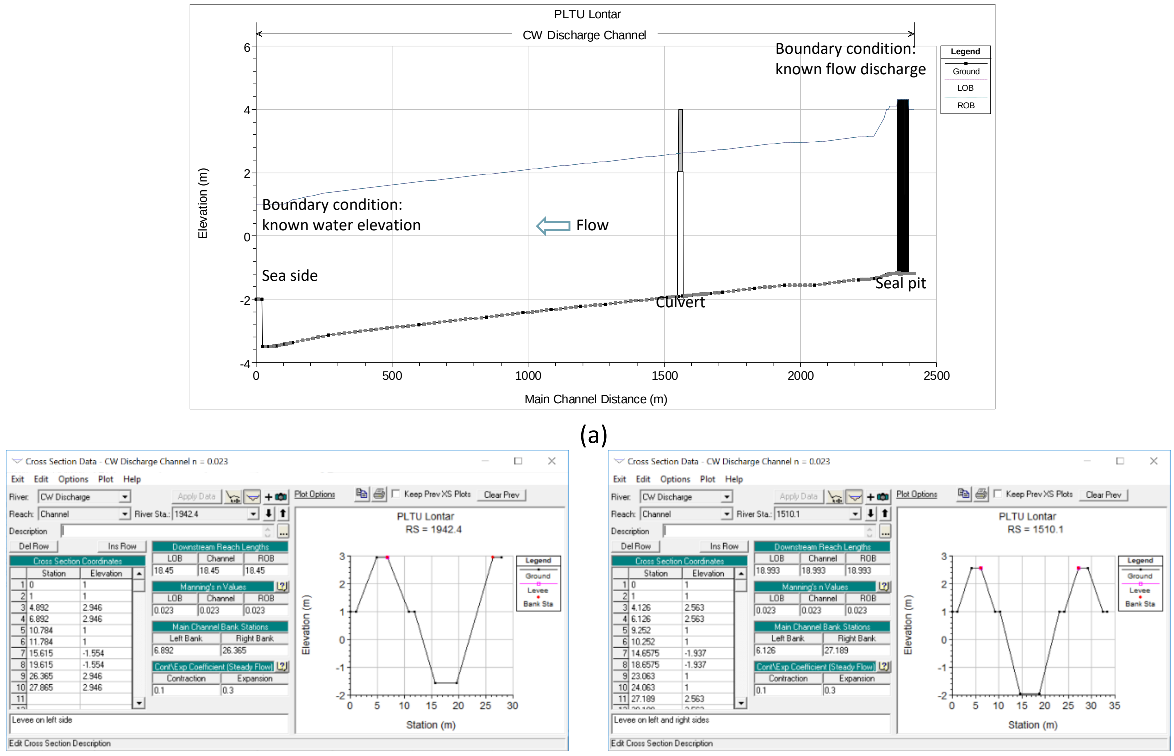
Material and Method

CFPP requires a circulating water system to condense the steam from the steam turbine in the condenser. The circulating water system can either use a once-through system or a closed circulating water system. The once-through system circulates the water from a large water source to a condenser via an intake structure and delivers the water back to the source via a discharge channel [15]. The cooling water can be delivered via an open-channel flow or in a closed conduit. Open channel flow can be described as a water flow that has a free surface.

A culvert is a structure that is used to convey water streams in channels that intersect with railroads or vehicle passages. There are several types of culverts, such as reinforced concrete box culverts, pipeline culverts, or curved culverts, and can be manufactured on-site. Multiple culverts can be applied in a channel depending on the culvert dimension and channel width [16]. Flow behavior in a culvert mainly depends on the culvert's dimension, inlet shape, Manning coefficient of the channel, inclination, and culvert outlet conditions. Improving existing culvert discharge can be achieved by enlarging the culvert's dimensions [17].

Existing Discharge Channel Geometry

The existing discharge channel in this study was a trapezoidal open channel that conveys the condenser cooling water discharge from the seal pit to the open sea. The discharge channel base width and depth were 4 m and 3 m, respectively, with a 1.5 m high levee on both sides of the channel. The length of the discharge channel was approximately 2,400 m. The discharge channel longitudinal section arrangement is shown in Figure 3(a). The discharge channel had a 0.0003 slope, as indicated in Figure 3(b) and (c), while the cross-section of the upper and lower discharge is depicted in Figure 3(b) and (c).



(a)

Cross Section Data - CW Discharge Channel n = 0.023

River: CW Discharge

Reach: Channel River Sta.: 1942.4

Description:

Cross Section Coordinates

	Station	Elevation
1	0	1
2	1	1
3	4.892	2.946
4	6.892	2.946
5	10.784	1
6	11.784	1
7	15.615	-1.554
8	19.615	-1.554
9	26.365	2.946
10	27.865	2.946
11		

Downstream Reach Lengths

LOB	Channel	ROB
18.45	18.45	18.45

Manning's n Values

LOB	Channel	ROB
0.023	0.023	0.023

Main Channel Bank Stations

Left Bank	Right Bank
6.892	26.365

Cont\Exp Coefficient (Steady Flow)

Contraction	Expansion
0.1	0.3

Levee on left side

Edit Cross Section Description

(b)

Cross Section Data - CW Discharge Channel n = 0.023

River: CW Discharge

Reach: Channel River Sta.: 1510.1

Description:

Cross Section Coordinates

	Station	Elevation
1	0	1
2	1	1
3	4.126	2.563
4	6.126	2.563
5	9.252	1
6	10.252	1
7	14.6575	-1.937
8	18.6575	-1.937
9	23.063	1
10	24.063	1
11	27.189	2.563

Downstream Reach Lengths

LOB	Channel	ROB
18.993	18.993	18.993

Manning's n Values

LOB	Channel	ROB
0.023	0.023	0.023

Main Channel Bank Stations

Left Bank	Right Bank
6.126	27.189

Cont\Exp Coefficient (Steady Flow)

Contraction	Expansion
0.1	0.3

Levee on left and right sides

Edit Cross Section Description

(c)

Figure 3 Computational domain of the discharge channel: (a) longitudinal section of the discharge channel; (b) discharge channel cross-section in the upper section; (c) discharge channel cross-section in the lower section.

The culvert dimension is 4 m in span, 4 m in height, and 21.30 m in length, as shown in Figure 4.

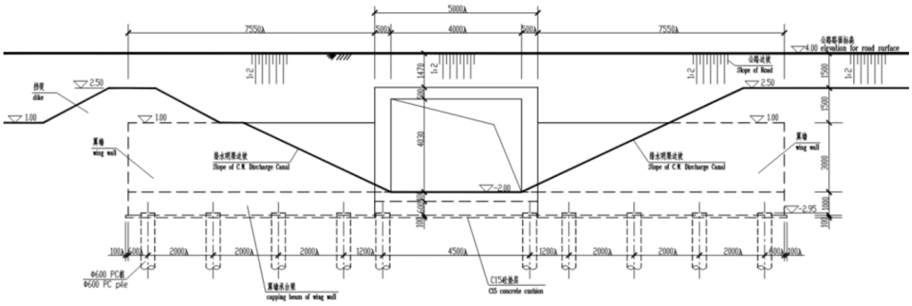


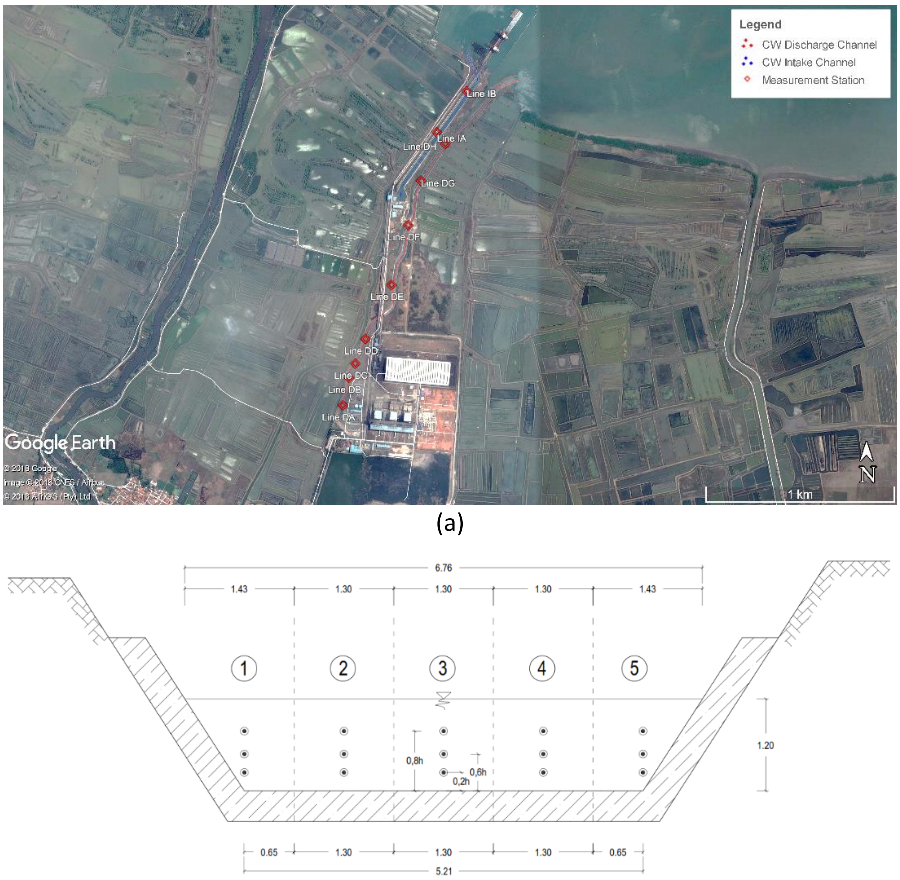
Figure 4 Existing culvert dimensions (in mm).

Tidal Movement Data

The water level used for simulation was taken from site investigation data of the power plant. The highest sea water level data, i.e., +0.56 m above MSL, was used for the simulation to ensure that the water in the discharge channel could be delivered to the sea at high tide.

Flow Measurement

Flow velocity and water measurements were conducted using a current meter and an AZ instrument. Direct flow measurements using a meter stick (staff gauge) were also conducted to verify the cross-section area at the measurement stations. The measurement was conducted in eight discharge channel stations, shown in Figure 5(a). In each station, the flow area was divided into five segments, and in each segment, the velocity was measured at three points of depth, which were 0.2H, 0.6H, and 0.8H, with H being the depth from the water surface, as depicted in Figure 5(b).



(a)

(b)

Figure 5 (a) Location of measurement station, (b) sketch of velocity measurement (in m).

The average velocity of each segment was calculated with the following equation:

$$\overline{V_i} = \frac{V_{0.2H} + V_{0.6H} + V_{0.8H}}{3} \tag{1}$$

Furthermore, the average velocity for each station could be obtained by averaging the velocity of each segment with the following equation:

$$\overline{V} = \frac{\sum_{i=1}^{n} \overline{V}_i \times A_i}{\sum_{i=1}^{n} A_i} \tag{2}$$

where, $V_{0.2H}$, $V_{0.6H}$, and $V_{0.8H}$ are the velocities at 0.2H, 0.6H, and 0.8H, respectively (m/s); H is the depth from the water surface (m); i is the segment number; n is the number of segments for each station; A is the flow area (m^2); and $\overline{V}$ is the mean velocity (m/s).

The result of the Manning coefficient from this measurement was 0.023. The Manning coefficient was used to calibrate the flow model and represent the actual discharge channel condition in the hydrology study.

The roughness coefficient was calculated by using the following equation:

$$n = \frac{S_f^{1/2} R^{2/3}}{V} \tag{3}$$

where n is the channel roughness coefficient, also known as the Manning coefficient; S_f is friction slope; R is the hydraulic radius (m); and V is the average velocity (m/s).

Discharge Channel Simulation

A hydraulic analysis was carried out to analyze the discharge channel conveyance capacity using the existing and future power plant cooling water flow rates, as shown in Table 1.

Table 1 Circulating water flow rate.

Circulating Water Flow Rate	Description
42.85 m^3/s	Design condition for three existing plants
57.13 m^3/s	Design condition for four power plants
58.90 m^3/s	Design proposal for four power plants

One-dimensional flow finite difference modeling using the HEC-RAS software can solve the unsteady flow analysis in channels [2]. HEC-RAS was used to analyze the existing discharge channel conveyance capacity using one-dimensional flow modeling [18]. By applying the finite difference method on Eq. (1) to Eq. (3), the flow area and flow velocity could be numerically solved; hence, other variables such as water surface elevation, flow depth, and flow velocity were obtained by using the following equations:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \tag{4}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + gA\left(\frac{\partial Q}{\partial x} + S_f\right) = 0 \tag{5}$$

where:

A	: flow area (m^2)	V	: flow velocity (m/s)
Q	: flow rate (m^3/s)	t	: time (s)
g	: acceleration of gravity (m/s^2)	x	: distance along flow direction (m)
q_l	: lateral flow rate ($m^3/s/m$)	z	: water surface elevation (m)
S_f	: friction slope		

The simulation flowchart to find a solution for the existing discharge channel is shown in Figure 6.

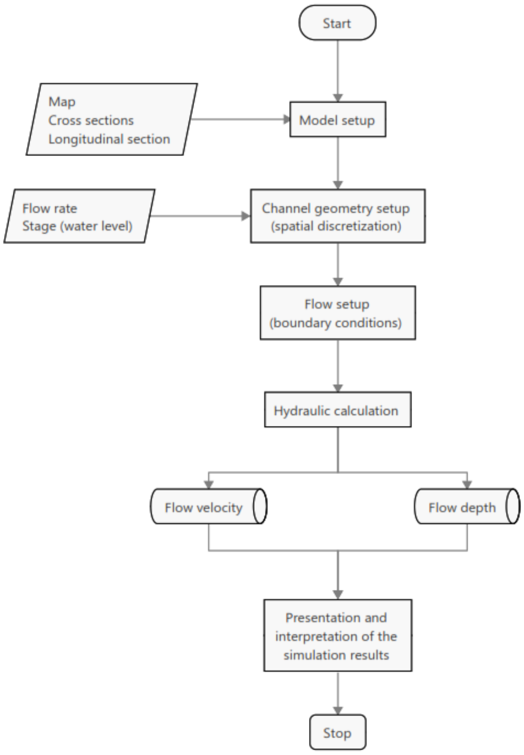


Figure 6 The procedure of flow simulation by using an HEC-RAS flow model.

Flow Simulation Scenarios

A series of simulation runs were performed to investigate the discharge channel capacity against the flow rates. Table 2 shows the simulation scenarios to find out the best solution. Cases 01 to 03 were the simulations where the geometry of the discharge channel was according to the as-built drawing. Cases 05 to 07 were simulations with a modified discharge channel geometry.

Table 2 Flow simulations in the cooling water discharge channel of the CFPP.

Simulation Number	Flow Rate (m^3/s)	Sea Water Level (m)	Manning Coefficient	Description
Original discharge channel geometry according to the as-built drawing				
01	42.85	+0.56	0.02	Three existing plants in operation
02	57.13	+0.56	0.02	Original channel geometry, future flow rate according to the original design
03	58.90	+0.56	0.02	Original channel geometry, future flow rate according to existing study
Modified discharge channel geometry				
05	58.90	+0.56	0.02	Culvert removal
06	58.90	+0.56	0.02	Additional culverts 2 x 4 m
07	58.90	+0.56	0.02	Additional culverts 3 x 1 m

Result and Discussion

Result of Measurement

The measurement was done in three days. During the flow measurements, the cross-section at the measurement stations was measured by using direct measurement with a meter stick (staff gauge). Figure 5(b) depicts the cross-sections at the flow measurement stations in the discharge channel. As can be seen, the actual (present) shape of the cross section changed from its original one according to the as-built drawing.

It is not known what caused the deformation of the cross-sectional shape. It may be due to channel settlement, sedimentation, or other factors. The recapitulation result of temperature and velocity measurement is presented in Table 3. The average discharge flow temperature was 38.4 °C.

Table 3 Water temperature and flow velocity measurement result.

Station	Temperature (°C)					V	Q_{ave}
	Seg.1	Seg.2	Seg.3	Seg.4	Seg.5	(m/s)	(m^3/s)
DA	38.5	38.5	38.5	38.5	38.2	1.45	36.58
DB	38.5	38.5	38.5	38.5	38.5	1.34	36.58
DC	38.4	38.4	38.4	38.4	38.4	1.43	38.31
DD	38.4	38.3	38.2	38.2	38.4	1.43	38.31
DE	38.4	38.4	38.4	38.4	38.4	1.50	41.62
DF	38.4	38.4	38.4	38.4	38.4	1.61	41.38
DG	38.3	38.3	38.3	38.3	38.3	1.33	41.72
DH	38.2	38.2	38.2	38.2	38.2	1.28	42.81

Calculation of Roughness Coefficient

The calculation shows that the Manning coefficient for the cooling water discharge channel was 0.02. The detailed calculation is shown in Table 4.

Table 4 Calculation of the circulating water discharge channel Manning coefficient.

Parameter	Unit	Station A	Station C	Average
Velocity, *V*	m/s	1.43	1.43	1.43
Flow area, *A*	m^2	26.10	27.41	
Wetted perimeter, *P*	m	16.047	16.417	
Hydraulic radius, *R*	m	1.626	1.669	1.65
WSE	mMSL	1.454	1.355	
Velocity head	m	0.104	0.105	
Energy elevation	mMSL	1.558	1.460	
H	m			0.098
L	m			227
Friction slope, S_f				0.00043
Manning coefficient, *n*				0.02

Preliminary Analysis

Figure 7 displays the computed water surface for the case of the three existing power plants being operated. Figure 8 shows that the addition of the new power plant elevates the water surface upstream of the culvert, either using a 57.13 m^3/s or 58.9 m^3/s flow rate. Overtopping of the discharge channel upstream of the culvert occurs if the four power plants are operated together. This is due to the culvert not being able to accommodate the water flow of the four power plants due to the small size of the culvert.

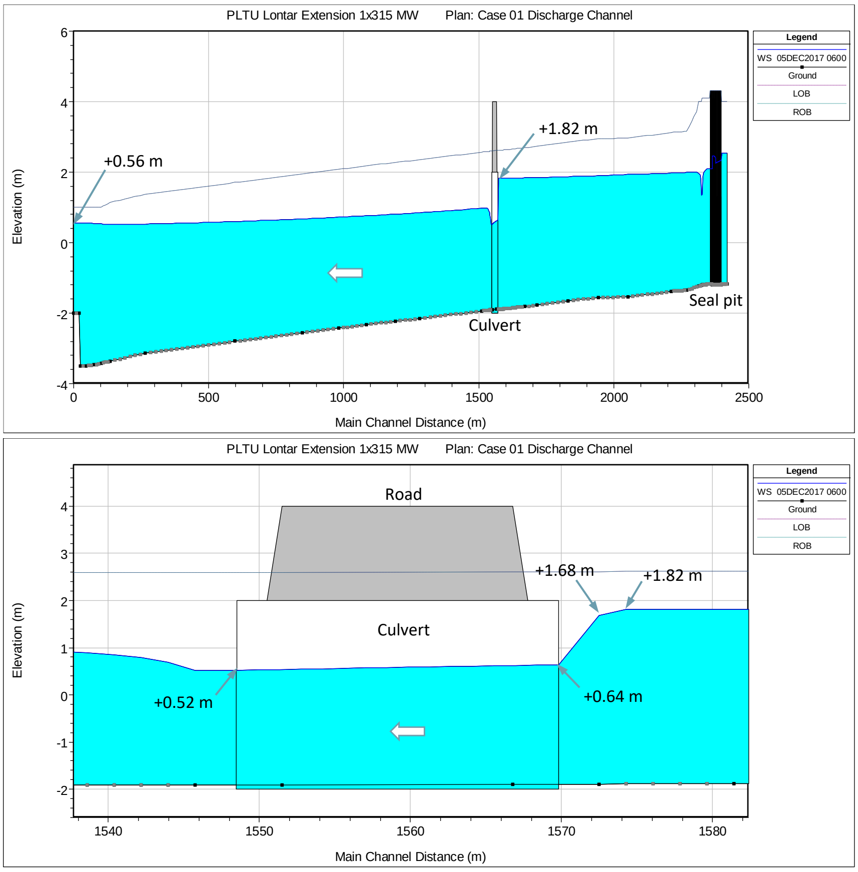


Figure 7 Water level of the three existing CFPPs operated using the existing discharge channel geometry.

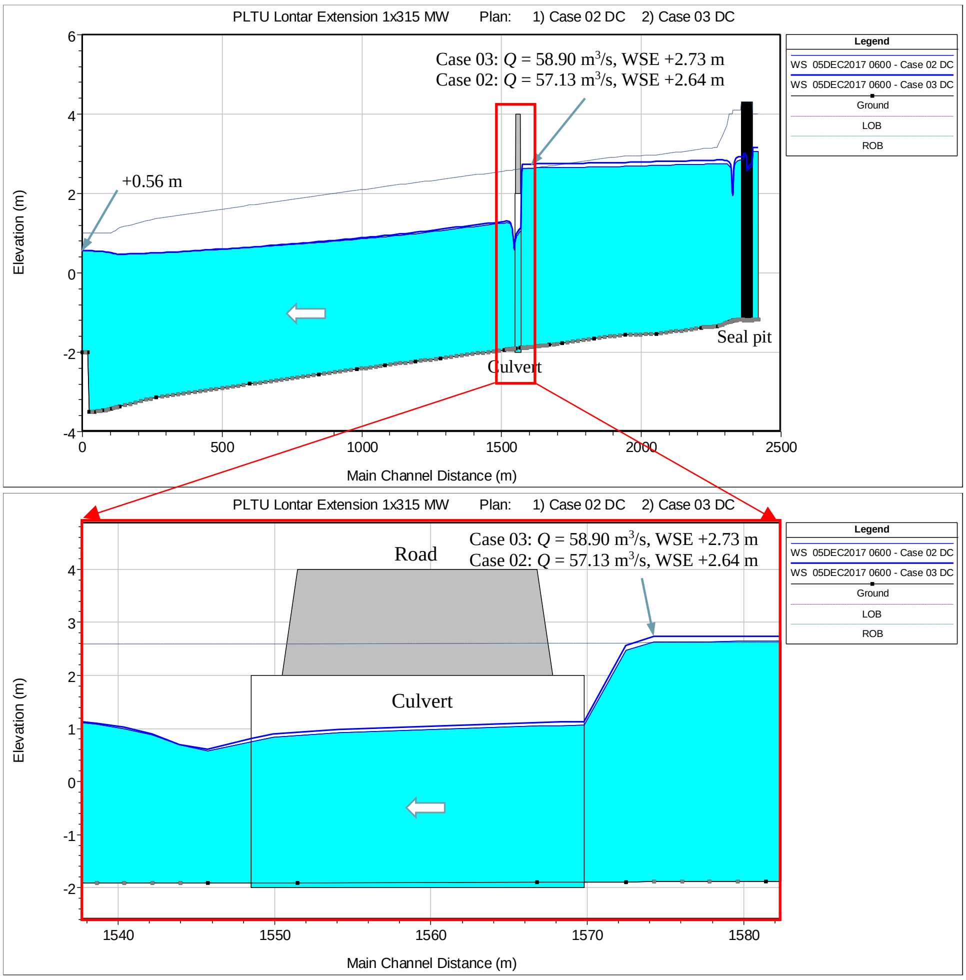


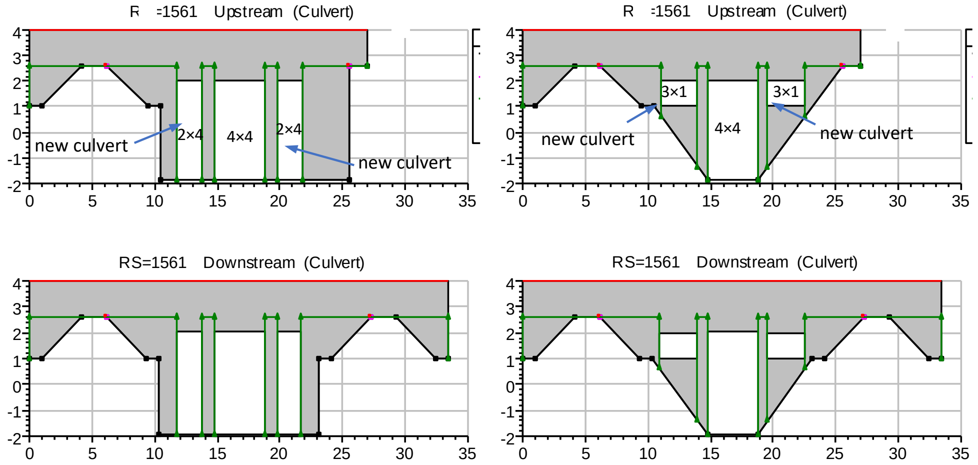
Figure 8 Water level of the four CFPPs operated using the existing discharge channel geometry.

Culvert Modification

Several methods are proposed to enlarge the culvert dimension, such as adding reinforced concrete boxes on both sides of the culvert or removing the culvert and installing a bridge instead. Detailed dimensions of the proposed enlargement are depicted in 0 and Figure 9.

Table 1 Culvert enlargement method.

Simulation Number	Enlargement Method	Dimension
05	Culvert removal	Same as the original channel
06	Additional culverts on both sides of the existing culvert (Option 1)	2 m x 4 m
07	Additional culverts on both sides of the existing culvert (Option 2)	3 m x 1 m



Option 1

Option 2

Figure 9 Enlargement method by additional culverts.

Figure 10 displays the computed water surface comparison when the existing culvert is in place and when the culvert is removed. The reduction of the water surface by this culvert removal is significant. At a station upstream of the culvert, the water surface is reduced by 1.39 m, from +2.73 m to +1.34 m.

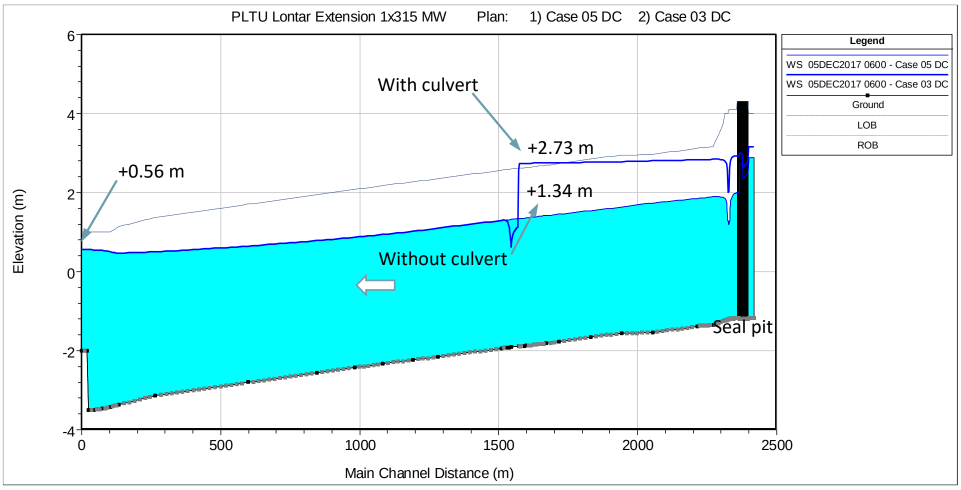


Figure 10 Water surface along the discharge channel after culvert removal.

Figure 11 presents the computed water surface when additional culverts (as shown in Figure 9) have been put in place. Additional culverts succeed in lowering the water surface such that overflow no longer occurs, because the flow capacity becomes larger. Installing additional culverts of 2 m x 4 m and 3 m x 1 m dimensions on both sides of the existing culvert will lower the water level upstream of the culvert to +1.61 m and +2.34m, respectively. The flow in the culvert maintains open channel flow for Option 1 and Option 2. Based on the surface water level inside the culvert as shown in Figure 11, it confirms that simulations 06 and 07 have a fully open channel flow along the culvert.

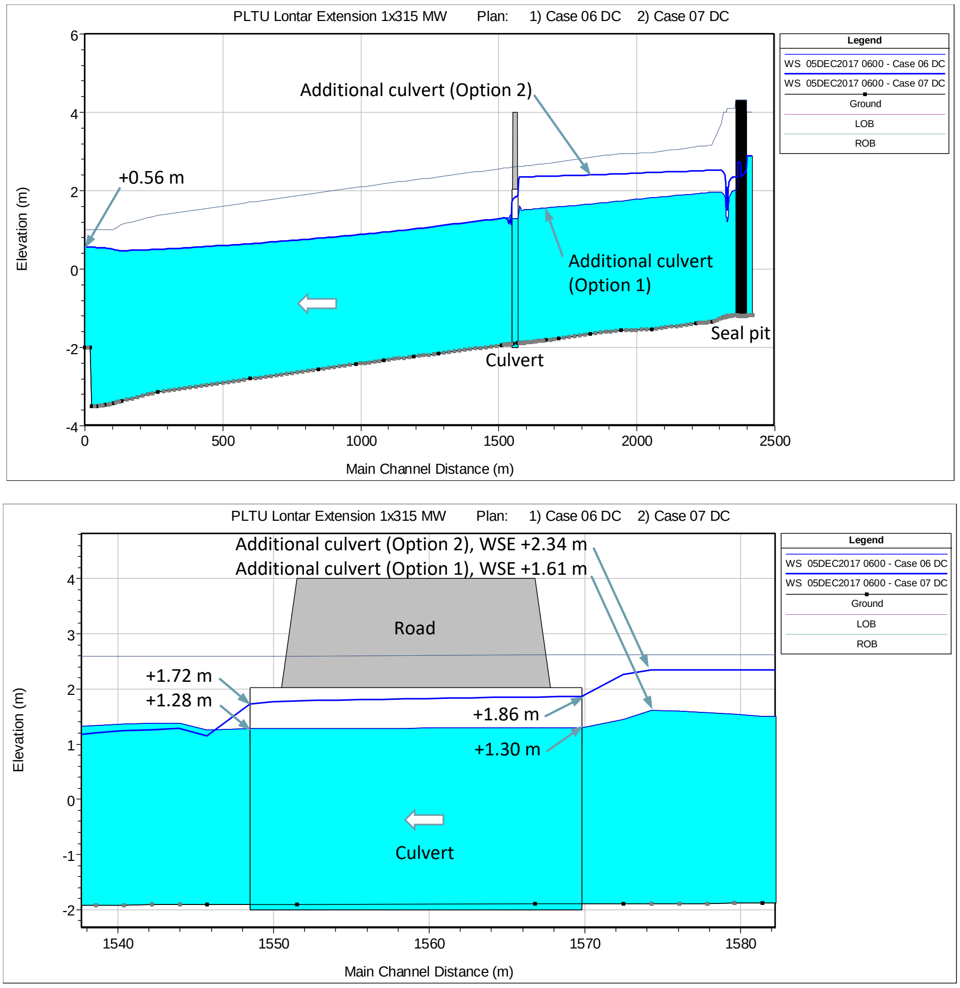


Figure 11 Water surface along the discharge channel with additional culverts.

Simulation Summary

Referring to the HECRAS simulation described in the previous chapter, a summary of the water level in each scenario is shown in Table 2.

Table 2 Summary of the water level upstream of the culvert in every scenario.

Simulation Number	Scenario	Water Level Upstream of Culvert (m)	Levee height (m)	Freeboard (m)	Freeboard > 0.75 m
ORIGINAL CULVERT					
01	Three existing CFPPs	1.82	2.61	0.79	Yes
02	Four CFPPs with 57.18 m^3/s flow	2.64	2.61	-0.03	No
03	Four CFPPs with 58.9 m^3/s flow	2.73	2.61	-0.12	No
MODIFIED CULVERT					
05	Culvert removal	1.34	2.61	1.27	Yes
06	2 m x 4 m culvert	1.61	2.61	1	Yes
07	3 m x 1 m culvert	2.34	2.61	0.27	No

Using the original culvert, the water surface elevation upstream of the culvert will be higher than the levee elevation of +2.61 m. The water level when the four power plants are operated together with a discharge flow rate of 57.13 m^3/s and 58.9 m^3/s is 2.64 m and 2,73 m respectively.

Enlarging the culvert dimension will lower the surface water level upstream of the culvert. Installing additional culverts of 3 m x 1 m and 2 m x 4 m dimensions on both sides of the existing culvert will lower the water level upstream of the culvert to +2.34 m and +1.61 m respectively, while removing the existing culvert will provide the highest water level reduction, yielding a +1.34 m water level.

Since the open channel allowable freeboard for a flow rate of more than 10 m^3/s is 0.75 m [19,20], only Scenario 05 (removal of existing culvert) and Scenario 06 (enlarging the culvert with additional 2 m x 4 m culverts on both sides of the existing culvert) have a freeboard of more than 0.75 m. Kazem *et al*. [21] mention that under uniform flow circumstances, the allowed freeboard for the initial design is 1/6 of the overall depth, hence the allowable freeboards for Simulations 05, 06, and 07 are 0.22 m, 0.27 m, and 0.39 m, respectively. Based on Kazem *et al*. freeboard criteria, only Simulations 05 and 06 have sufficient freeboard.

Nevertheless, the removal of the culvert will impair channel operations and necessitate the shutdown of the current power plant. From an operational point of view, constructing additional culverts is less disruptive than culvert removal. It requires a cofferdam to separate the construction site from the existing channel to allow the existing channel to remain in operation during construction. Therefore, additional culverts are the best option for the solution of the capacity problem of the cooling water channel in this case.

Conclusion

The existing discharge channel does not have sufficient capacity to convey the cooling water flow rate after the operation of a new CFPP. Overflow occurs at the upper reach of the channel (upstream of the culvert). The computed water levels at this reach were +2.64 m and +2.73 m under flow rates of 57.13 m^3/s and 58.90 m^3/s, respectively. These levels are above the levee crest at the station upstream of the culvert, which is +2.61 m. The culvert is the main factor that creates capacity insufficiency of the existing discharge channel. Computed water levels upstream of the culvert were +2.73 m and +1.34 m for the cases with and without a culvert, respectively. Thus, culvert removal significantly lowers the water level in the channel. Overflow does not occur anymore. Reconstruction of the channel by removing the culvert, however, requires temporary closure of the discharge channel. This is not preferable, or even not feasible, since this leads to halting the operation of the existing plants. Additional culverts have also been considered. The study considers two options of additional culverts. Option 1 adds two culverts of 2 m wide and 4 m high on the left and right of the existing culvert, while option 2 adds two additional culverts of 3 m wide and 1 m high. The flow simulation results showed that the surface water elevation at the station upstream of the culverts is +1.61 m and +2.34 m for Option 1 and Option 2, respectively. Additional culverts are less disruptive than culvert removal. It requires a cofferdam to separate the construction site from the existing channel to allow the existing channel to remain in operation during construction. Therefore, an additional culvert considered is the best option to enlarge the conveyance capacity of the existing discharge channel.

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