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Research Article

CFD Analysis to Predict Flow Behavior for Design and Operation of Tarbela Dam Reservoir for Different Environmental Conditions

Muhammad Abid[1], Muftooh Ur Rehman Siddiqi[2], Adnan Aslam Noon[3], Muhammad Tahir[4], Aamer Sharif[5], Shahana Mujeeb Siddiqi[6], Naveed Ullah[7], Tufail Habib[7], Muhammad Shayan[8]

[1]*Department of Mechanical Engineering, COMSATS University, Islamabad, Pakistan*
[2]*Mechanical, Biomedical and Design Engineering Department, School of Engineering and Technology, Aston University, England*
[3] *Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan*
[4]*Department of Mechanical Engineering,Bahauddin Zakariya University, Multan, Pakistan*
[5]*Department of Mechanical Engineering, CECOS University of IT and Emerging Sciences, Peshawar, Pakistan*
[6]*Communication and Works Department, KP, Pakistan*
[7] *Department of Mechanical Engineering University of Engineering and Technology, Peshawar, Pakistan*
[8] *Pak Atlantis Pumps PVT LTD. Pakistan.*

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ABSTRACT

Tarbela Dam is one of the world largest filled dams with a capacity of 13.69 km^3. It is the backbone of Pakistan, and it is used for both power generation and irrigation. Like all dam reservoirs, sedimentation decreases the life of the Tarbela dam reservoir and affects the power generating unit and tunnel equipment's and instruments. The Finite Volume Method was used to conduct a CFD analysis to investigate different parameters that influence sedimentation. The analysis was carried out using multiphase flow (air and water) considering the summer season for maximum reservoir inflow and discharge water through spillways and tunnels. Boundary conditions were applied to a 3D geometric model that had been meshed. The spillway outlet was found to have the highest velocity. Near the spillways outlet and tunnel inlets, strong vortex motion was observed. WAPDA were suggested to redesign tunnels 3 and 4 in order to reduce sediment inflow, as well as to improve the design of the spillways.

1. Introduction

The reservoirs produced 19 % of the world energy supply and 30-40 % of the world irrigation supply [1]. The development of new reservoirs has been reduced due to socio-environmental impact and the lack of suitable sites, especially in Pakistan and other

Corresponding e-mail: m.siddiqi5@aston.ac.uk (Muftooh Ur Rehman Siddiqi)

developed countries [2]. The insidious problem is that a reservoir's capacity loss of 1 to 2 % goes typically unnoticed for many years. The ever-increasing conflicts among competing sectors, such as irrigation, hydropower, water supply navigation, ecology, demonstrate the synergetic effect of reduced development and increased loss of existing storage [3]. The need to use existing reservoirs and dams sustainably and optimally cannot be oversimplified, especially as the possibilities for developing new reservoir projects become bleaker day by day [4]. The Tarbela Dam, located in the Indus Basin, was built in early 1970 with a water capacity of 19.69 km^3 [5]. It is the only primary storage reservoir and one of Pakistan's largest earth-filled dams. The original dam purpose was to control irrigation releases of more than 6.4 MAF, but it now produces up to 3500 MW of electricity, meeting nearly 32 % of Pakistan power needs [6]. In this study, the FVM method is used to simulate the water flow reservoir and analyze the sediment flow in the reservoir. The Tarbela dam reservoir consists of two auxiliary dams, two spillways, i.e., service and auxiliary spillways, and six tunnels. The dam has a length of 9000 feet and a height of 470 feet above sea level. The auxiliary spillway has nine gates, while service spillways have seven gates. The gate of each spillway is 58 feet high and 50 feet wide. In this study, the FVM method is used to simulate the water flow reservoir and analyze the sediment flow in the reservoir. The Tarbela dam reservoir consists of two auxiliary dams, two spillways, i.e., service and auxiliary spillways, and six tunnels. The dam has a length of 9000 feet and a height of 470 feet above sea level. The auxiliary spillway has nine gates, while service spillways have seven gates. The gate of each spillway is 58 feet high and 50 feet wide [6]. The three tunnels of the Tarbela dam are used for power generation and irrigation, while the other three tunnels are only used for irrigation purposes [7]. Chen et al. [8] provided a computational fluid dynamics (CFD) based erosion prediction model and its usage in hydropower and oil field geometries.

Gary et al. [9] discusses the Lagrangian approach to particle tracking; others used the same approach for one-way coupling. The second–moment closure model or Reynolds stress model (RSM) to analyses turbulent flow in Tunnel 1, and different coefficients are taken from [10-12]. Lagrangian particle transport and Eulerian multiphase approaches are combine with the RANS method for sediment particle deposition in turbulent flow [13].

Sedimentation is a huge problem for the Tarbela dam reservoir, and it is affecting its life. Abid et al. [11] looked into suspension and particle deposition in a horizontal pipe flow. The fluid velocity, fluid density, and particle diameter investigated the deposition phenomena.

2. Sedimentation

Reservoir sedimentation is a major problem at Pakistan Tarbela reservoir. This huge storage reservoir on the Indus River, built between 1968 and 1974, plays an important role in water supply for agriculture, electricity generation, and flood control. The reservoir's initial capacity has been lowered by 30 % due to sediments (11600 Mm^3). The foreset slope progress towards the dam raises the possibility of shutting the low level exits that supply water downstream to the irrigation system and power plant [2]. The Indus River contains a large amount of sediment. This is largely owing to the glaciers erosive action, which supplies much of the flow. Over 200 million tonnes of suspended sand, washload are projected to be deposited totally in the reservoir, accumulating in the shape of a delta that grows toward the dam. Tarbela Reservoir was projected to be filled with the sediment within 30 years when the project was designed, however sediment rates have been lower than expected [14].

The phenomenon of sediment erosion is extremely complex, and various factors play a role in erosion intensity. Finnie is used to performing the analysis, which included Langrangian particle tracking and an Eulerian-Eulerian multiphase approach. The potential of reservoirs of Tarbela dam is reduced by sediment deposition and delta formation [15].The main parameters governing sedimenta tion in lakes can be divided into three categorie s: such as biological, chemical, and physical (hydrological) [16]. The flow at the inlet of small tributaries was blocked due to sediment deposition and delta formation. Reservoir potential is further reduced as a result of the creation of pools. Tarbela lake seizes Indus water, which contains a heavy load of sedimentation. Melting snow in the Himalayan and Karakorum regions induces erosion of upland catchments during the spring and summer [7, 16]. Tarbela dam possessing Indus water, contains a large amount of sediment (approximately 265 metric tonnes per year), resulting in a noticeable decrease in reservoir capacity, as shown in Table 1.

Table 1. Reduced capacity of Tarbela Lake

Year	Capacity	Reduction MAF
2017	Gross	3.305
	Live	2.668
	Dead	0.642
2018	Gross	3.437
	Live	2.839
	Dead	0.687
2019	Gross	7.982
	Live	6.876
	Dead	0.686

The sedimentation delta profile from 1974 till 2019 is shown in (Fig. 1). A decrease in reservoir capacity not only decreases the life of the reservoir, which is a national security issue for Pakistan but also damage the equipment for power generation such as turbines and tunnels [17, 18].

Currently, the tunnel inlets are at the ground level and suck sediment particles directly. Thus a considerable percentage of sediment particles damage the turbines and tunnels. This direct suction of the sediment particles at ground level can also activate the melting of the sediment mountain, which is over 250 feet high from the tunnel inlets. This could exponentially decrease the reservoir's life and clog the tunnels, thus halting the system for power generation. To avoid continuous and permanent damage to the reservoir, raising the tunnel height and checking multiple operational parameters were suggested. This study aims to analyze the fluid flow after raising tunnel inlets. The objectives are to simulate different operational, environmental, and hydrological parameters based on the seasonal variations and predict water and sediment flow.

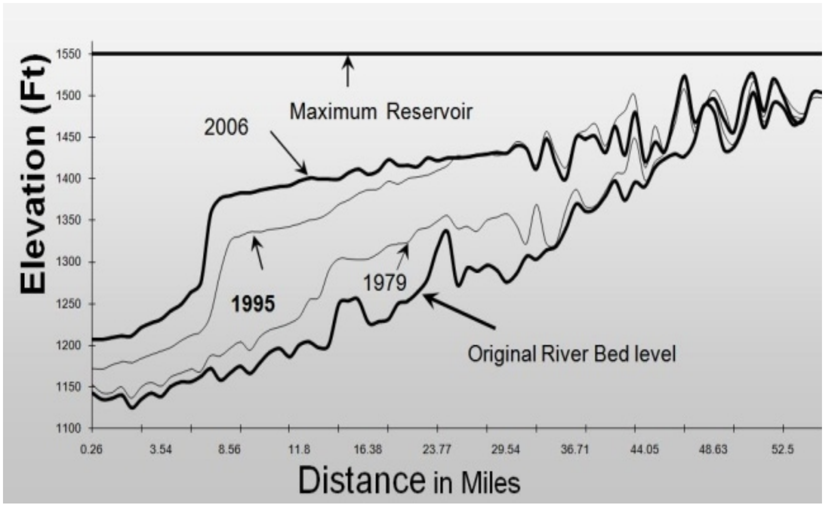


Fig. 1. Sedimentation profile for 1974 to 2019 [19]

3. Methodology

A 3D geometric model, based on the actual Tarbela Dam reservoir, was developed and meshed for Finite Volume Analysis. The height of the tunnel inlets was raised in the model. Multi-phase flow simulation with air and water was carried out in the reservoir using computational fluid dynamics. Case studies were carried out to mimic water flow for different hydrological, operational, and environmental conditions. The Tarbela Dam reservoir was designed and operated based on the results of these studies. The calculated results and summary of input parameters conducted on a model for the case studies (A, B, and C) are shown in Table 2. Case study A represents summer, while case study B & C represents winter conditions. Tunnel 1 is open for all case studies, while the second opening of the tunnel varies from a case to case.

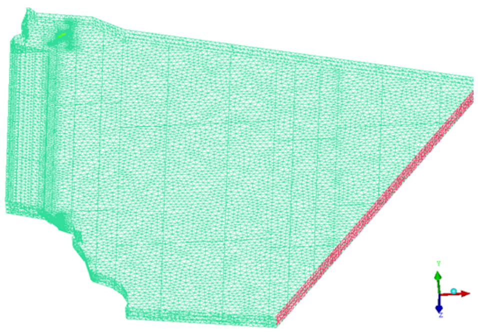
Table 2. List of parameters [20]

Cases		Input		Output	
Case Study	Season	Water inflow ×105(kg/sec)	Spillways and tunnel opening	Free surface average height (m)	Hydrostatic Max Pressure (MPa)
A	Summer	118	SS,T1	124	1.258
B	Winter	4.3	T1,T2	83	0.884
C	Winter	4.3	T1,T3	83	0.872

T = Tunnel, SS= Service Spillways, AS= Auxiliary Spillways

3.1 Modeling, meshing and material properties

Using data and drawings from the Water and power development authority (WAPDA) Pakistan, a 3D model of the Tarbela reservoir was created using the Finite Volume Method (FVM) that included the main embankment dam, six tunnels, service spillways, auxiliary spillways and the original reservoir base. Initially, the tunnel inlets were changed and raised to a height of 46.8 m, as per Muhammad et al. and Ahmad et al. [6, 21]. Due to the expected velocity gradient near the spillways and tunnels, 1 7,701 tetrahedral elements with a maximum element size of 30.5 m are generated initially using ICEM CFD® as shown in Fig. 2a-c. Due to the larger size of the elements, this mesh could not accurately predict free surface, so an adaptive mesh technique was used to solve the problem, and the number of elements was increased to 25, 89, and 215. The two iterations of adaptive meshing are shown in Fig.2d and e, where the element is applied around the predicated free surface. In CFD analysis of the reservoir, the main bottleneck was meshing [22]. Mesh was refined around areas of concern, for tunnels and spillways. Air and water were taken as materials at atmospheric pressure and 25 degrees Celsius. The material models and the detail used in the current study are as shown in Table 3.



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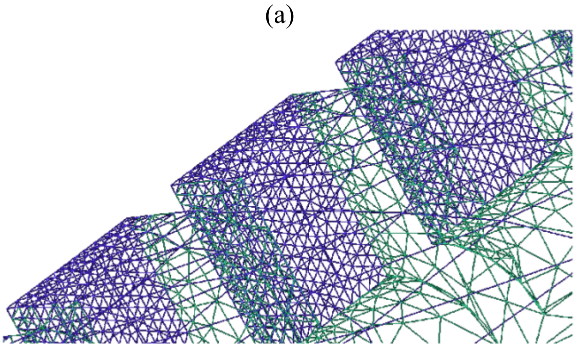

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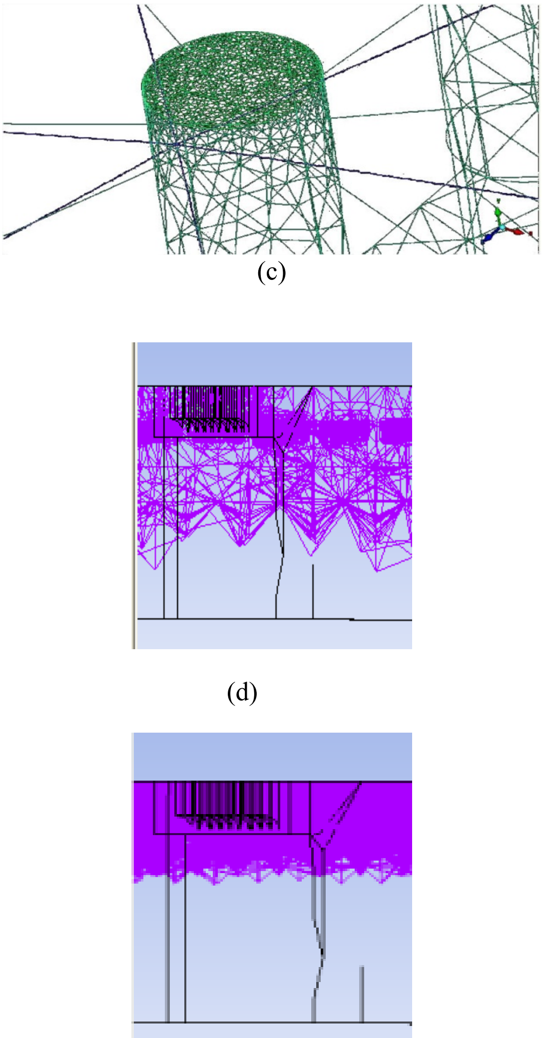


(c)

(d)

(e)

Fig.2. Fine mesh geometry; (b) Spillways, (c) Tunnel 1 (d) first refinement level, (e) second refinement level

Table 3. Material model details

Property	Water	Air
Thermodynamic State	Liquid	Gas
Dynamic Viscosity	8.899×10-4 kg/ m.s	1.831×10-5 kg/m.s
Reference pressure	1.0 atm	1.0 atm
Molar Mass	18.10 kg /kmol	28.85 kg /kmol
Density	1000.0 kg /m³	1.174 kg/m³
Reference Temperature	25°C	25°C
Gravity	9.8 m/sec²	9.8 m/sec²

3.2 Boundary conditions and solution

Water and air entered the domain via the inlet and escaped through spillways and tunnels. For the summer and winter seasons, two different inflow conditions were used. The maximum and minimum water inflows in the reservoir at 116 x 105 kg/sec, and 4.2 x 105 kg/sec were calculated using the volume of fluid method for the summer (flooding seasons) and winter seasons respectively. Table 4 summarizes the boundary conditions and results. The average values of velocities were used as outflow conditions for the tunnels [23] and determined empirically in Table 4.

Table 4. Tunnels velocities

Tunnel Position	Velocity (m/sec)
1	8.429
2	8.390
3	11.276
4	11.276

Auxiliary spillways, service spillways and also along the free-surface; zero Pascal pressure was applied as they enclosed to the atmospheric pressure. The reservoir walls were not subjected to any slip conditions [24]. The isothermal and incompressible domains were considered [25]. The analysis did not involve sediment particles. The free surface was developed using a $k-\varepsilon$ homogeneous model. The domain for fluid flow was solved using the turbulence model and Navier-Stoke equation, and the turbulence model. The partial differential equations were solved using the SIMPLEC method [26]. A computer cluster was used to solve the equations using parallel processing [27]. The numerical solution converged appropriately, and the results were measured.

4. Results and Discussion

Three parameters were analyzed and discussed i.e., pressure distribution, free surface height and velocity flow field.

4.1 Free Surface Height

The air and water volumes were calculated using the step function. A plot of an iso-surface reflecting the free surface of the water was plotted. Ripples depict air flowing over the free surface of the water on the iso-surface. During the summer season, the average free surface height for case study A was 123 meters. This is beneficial to the reservoir capacity, tunnels and instruments that have been built there. The increased water inflow, 116 x 105 (kg/sec), is responsible for the high free surface level. During the winter, the water surface level in case studies B and C remained low due to the low water inflow of 4.2105 (kg/sec). The delta of sediment can be exposed to free atmospheric conditions under these conditions. As a result, there is a risk that the delta will collapse, and sediment will flow into the main embankment dam. The process is known as delta liquefaction, and it has the potential to block tunnels permanently. It is recommended that a separate study be carried out to examine the sediment delta under various flow and loading conditions—a free surface profile during the flow of water from the service spillways, as shown in Fig.3.

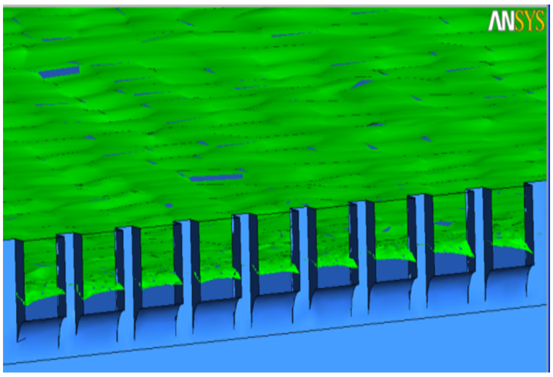
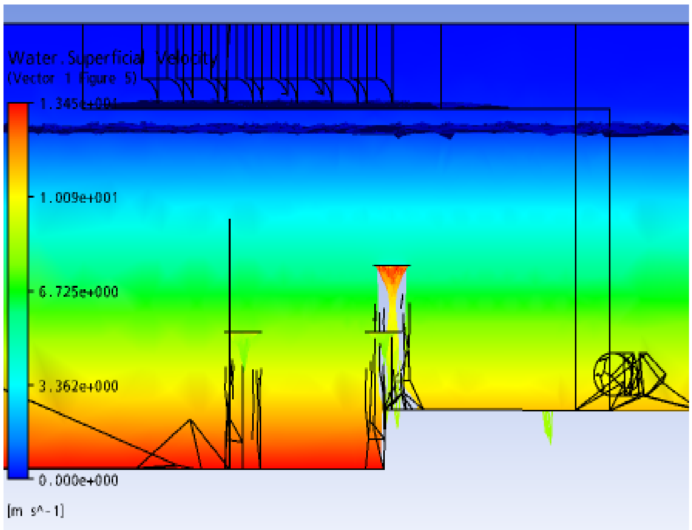


Fig. 3. Free surface profile

4.2 Pressure Distribution

For all of the case studies, the water velocity in the reservoir remains very low. As a result, the hydrostatic pressure distribution formula $p = \gamma h$ can determine the pressure [28]. The SIMPLEC method is used to measure the numerical pressure distribution across the domain, which agrees with the empirical results obtained for all of the case studies [23]. However, due to the conversion of the potential energy of moving water into kinetic energy, there was a small difference between the numerical and empirical results. Since the pressure distribution is hydrostatic, it rises with the depth of the water, as shown in (Fig.4).



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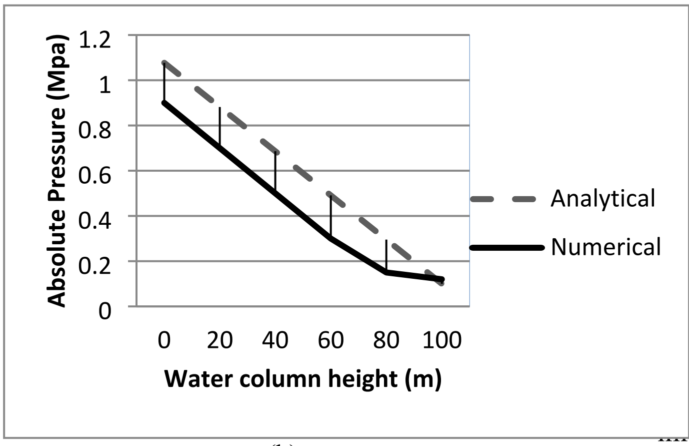


(b)

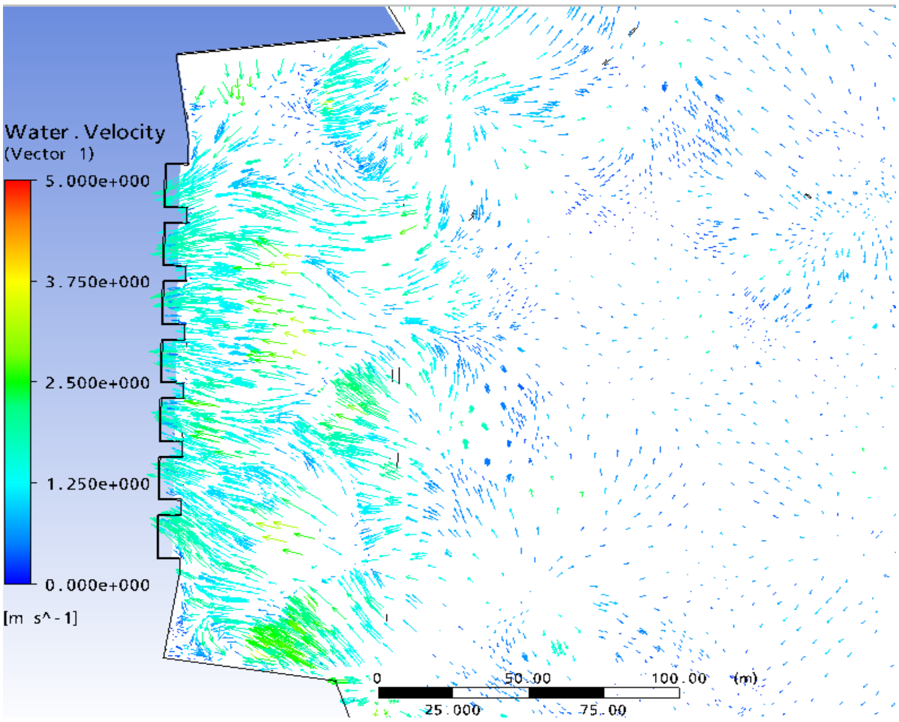
Fig. 4. Pressure distribution; (a) with free surface, (b) with respect to surface height.

4.3 Flow Field

4.3.1 Case study A- Tunnel 1 and Service spillways are open

For this case study, the service spillways d Tunnel 1 were opened. This case study is portant because it depicts the flow of water und the tunnel inlet during summer. The ter in the reservoir is exhibiting a dormant te. The water was rushing towards the exits, the service spillways and Tunnel 1. The ter was drawn from various places along the e stream, not from the base since the tunnel ets were modelled higher than the reservoir's se. In the current situation, the water was wn from the mainstream beside the tunnel et with water velocity varying from 2.5 to 3 m/sec. The water first circulates near the tunnel's base before moving upward and enters the tunnel in a strong vortex motion. The velocity profile at the inlet displays an interesting behaviour due to the water swirling around the tunnel. Water enters the tunnel at varying velocities, generating a circular profile as shown in Fig.5c. Due to the no-slip condition, velocity near the boundary wall is zero. The water velocity increases to 3 m/sec near the boundary layer. A thin layer with a velocity of 6.5 m/sec proceeds, followed by a thick layer with a velocity of 9.5 m/sec. The tunnel is followed by a thick layer with a velocity of 9.5 m/sec. The tunnel inlets cores have a velocity ranging from 6 to 7 m/sec.

During the structural design of the modified tunnels, i.e., 3 and 4, the effect of swirling must be considered. The velocity profile near the service spillways shows a flow pattern similar to by Abid et al. [6], but with a different magnitude. As water approached the moorage area, the velocity increased from 0.5 to 1.5 m/sec, as shown in the encircled region of Fig.5a. When the water reaches the spillways, the water velocity escalates further and reaches 2 m/sec, generating a transition zone.


Water . Velocity
(Vector 1)
5.000e+000
3.750e+000
2.500e+000
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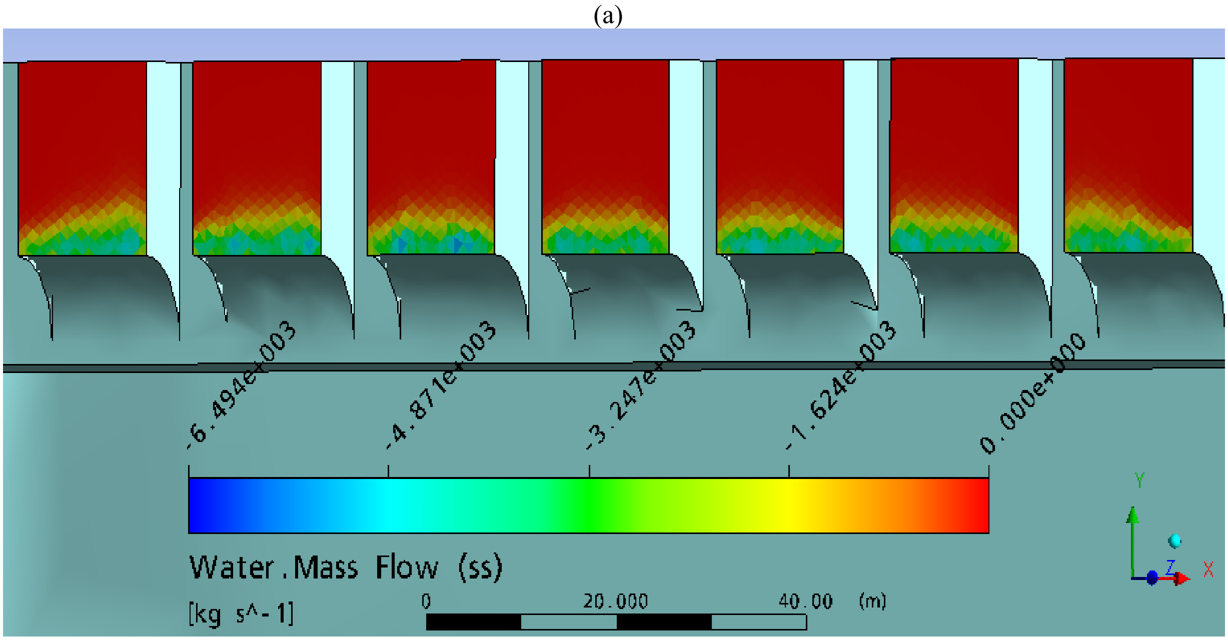
0.000e+000
[m s^-1]
0
25.000
50.00
75.00
100.00
(m)

(a)


-6.494e+003
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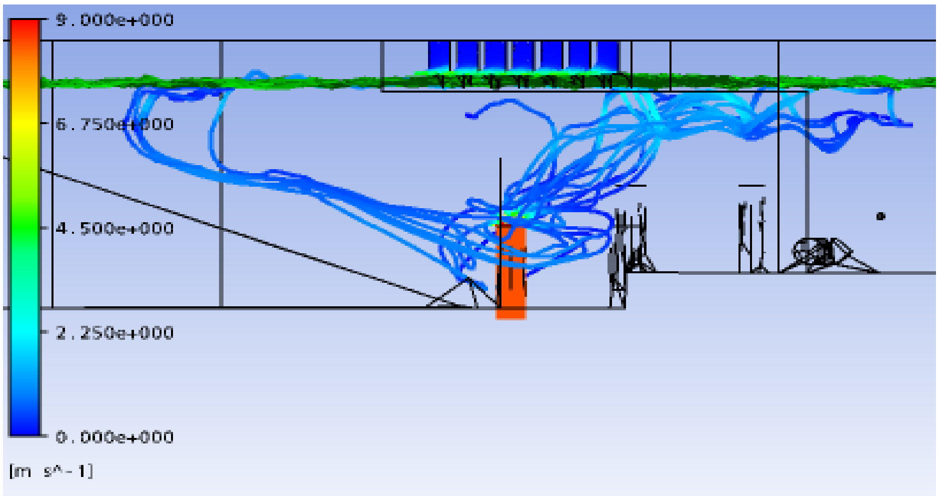


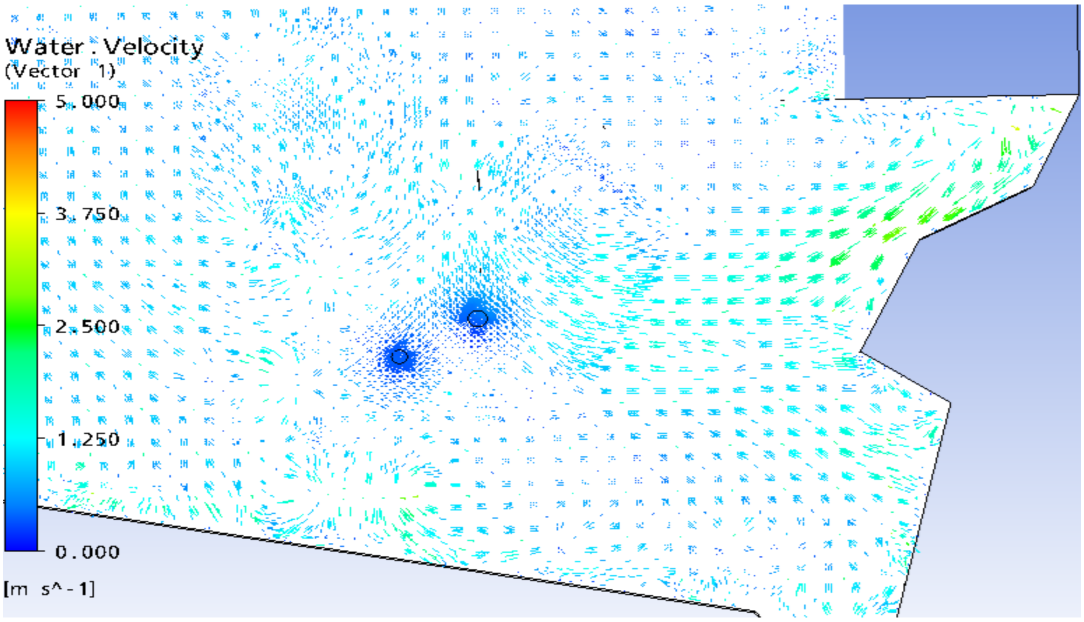
(c)

Fig.5. (a) Service spillways having velocity vectors (b) Spillways gates having mass flow (c) Free surface having stream lines

4.3.2 Case study B- Tunnels 1 and 2 are open

Tunnels 1 and 2, used for power generation, were opened in this case study; tunnels split into several branches [28]. Tunnels 1 and 2 are open all year and play an important role in irrigation and electricity generation, making this case study one of the most important studies. As shown in Fig. 5a, water was sucked from the water surface rather than the ground. In comparison, the tunnels would receive a smaller volume of sediment from the reservoir foundation. The reason for that water is sucked from the surface above the tunnels. Since the water in the reservoir has a higher velocity in the summer, more sediment particles will be moved from the reservoir to the dam wall due to greater momentum. As a result, it is recommended that water outflow be reduced during the winter season. This could be accomplished by opening the minimum distance of tunnels possible. From the water surface to the tunnels inlet, the streamlines are relatively straight.

They begin to swirl as they approach the entrance of the tunnel. When water enters the tunnel from the free stream, the velocity remains nearly three m/sec. A high-velocity gradient is present near the tunnel inlet when water enters the tunnels, and velocity rises abruptly from 3 m/sec to 9 m/sec, as shown in Fig 6. Since this is true in all case studies, it is not recommended that all tunnels be opened simultaneously to reduce the swirling impact during the winter season.



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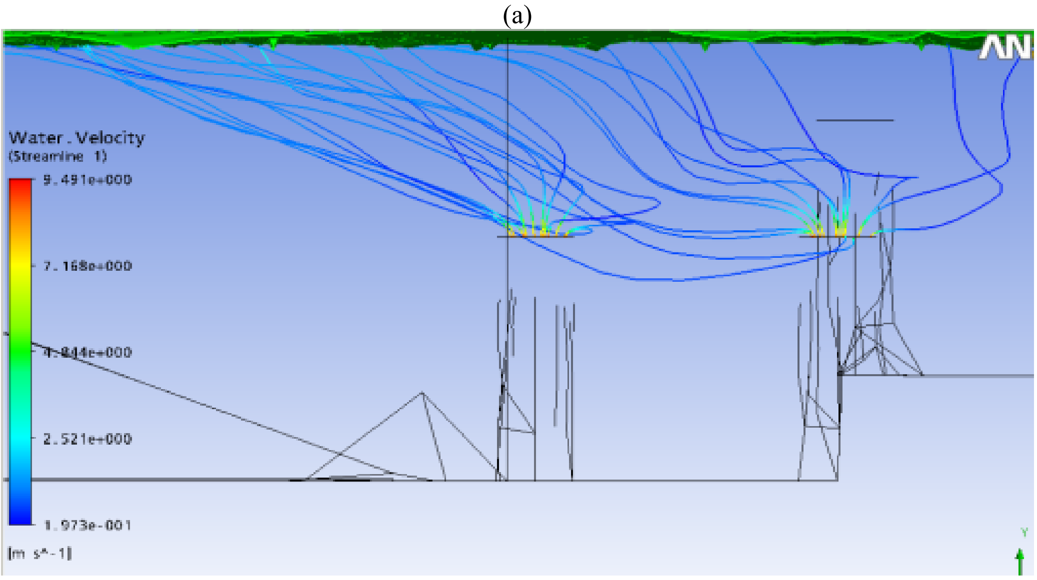
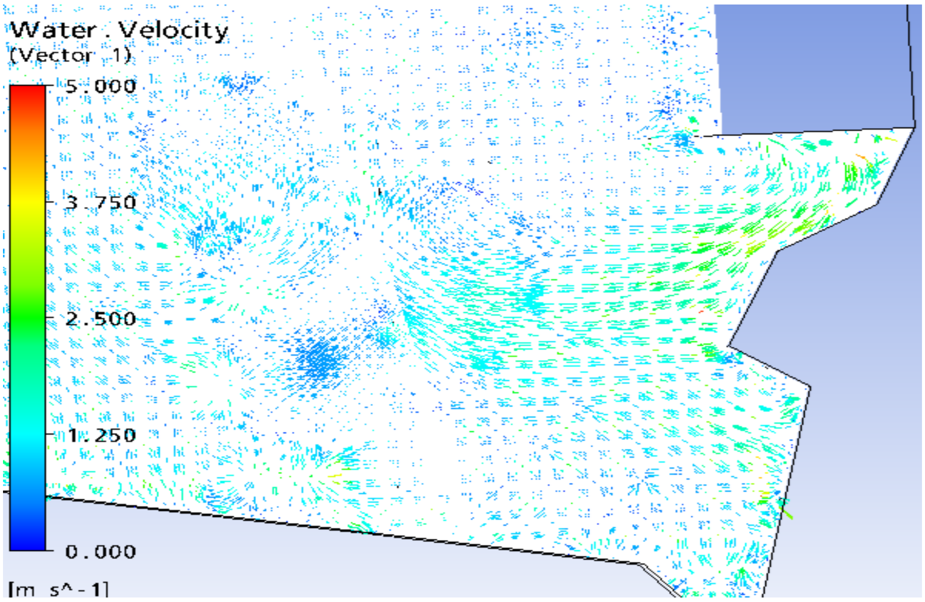


(b)

Fig.6. (a) Velocity vectors over tunnels, (b) Stream lines and free surface.

4.3.3 Case study C- Tunnels 1 and 3 are open

For this case study, Tunnels 1 and 3 are opened for winter conditions. Water was sucked from the surface as predicted, and the water surface level was low, as shown in (Fig.7a and b). Since the free surface is too close to the tunnels, water circulates far less than in other cases. If the tunnel height is raised, sediment from the reservoirs base cannot reach the tunnels. The stabilization of the sediment delta could be affected by low water levels. Sediment flow behaviour may resemble that of case B, as the water in the reservoir speed up, causing more sediment particles to be transported near the wall due to the greater water momentum. With a velocity of 3 m/sec, water streamlines remained reasonably straight from the surface to the tunnel. The velocity of the water increased from 3 m/sec to 9 m/sec as water starting swirl near the tunnel entrance.



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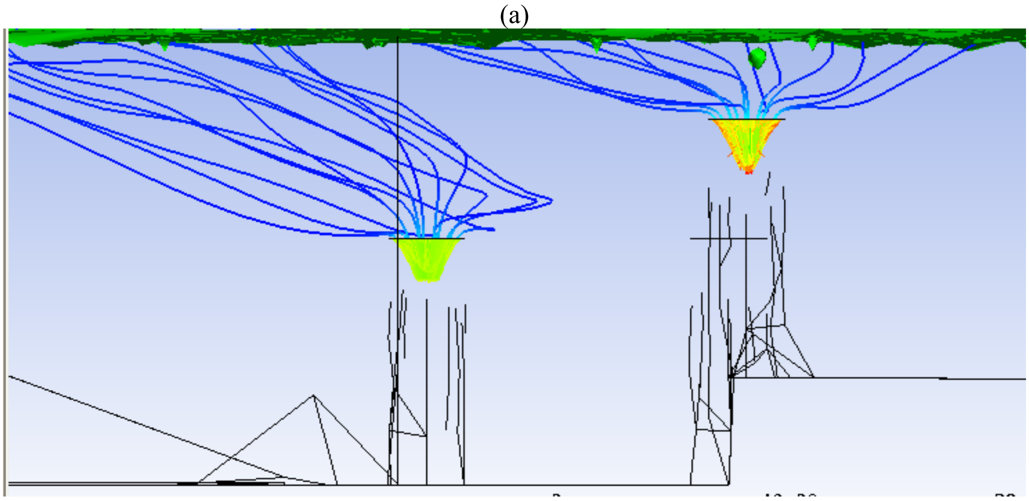

(b)

Fig.7. (a) Velocity vectors over tunnels, (b) Stream lines and free surface.

5. Conclusion

The results of the CFD analysis of the Tarbela dam reservoir concluded that;

The dam spillways should be designed so that dam water does not constrain within the structure until being discharged, as observed in service spillways.

Instead of Service spillways, Auxiliary spillways should be used for discharge because Service spillways would need more maintenance due to chaotic flows.

The sedimentation in the Tarbela dam reservoi r bed was unaffected by flowing water through spillways.

When water entered the tunnels, vortices formed; this effect should be considered during tunnel structural design.

The tunnel of the dam will be choked if the sediment particles accelerate towards the main embankment dam.

The creation of chaotic flows in service spillways is higher than auxiliary spillways. Moreover, spillways should be built to face the water flow in a perpendicular direction for easy flow.

The dam's spillways should be built where there are no sharp edges on the corners and have a deep water reservoir. This will prevent the water from flowing in a turbulent manner.

Since service spillways have a chaotic effect, an auxiliary spillway should be used to save maintenance costs.

To secure equipment installed on power plants, tunnels should be elevated to 47 meters above t he bed level. However, the structure of the tunnels must be designed to accommodate the water vortex motion.

The effect of water flow from tunnels and spillways is localized and has little effect on the sediment delta.

During the winter season, the outflow from the reservoir should be low to avoid sediment delta damage.

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