Paper ID - 039

Hydraulic modelling of headpond with lateral spillway weir structure for the Tamakoshi-V hydroelectric project, Nepal

Pradyumna Machhkhand[1]

[1]*CEO, Gomati Hydroinformatics Analytics & Engineering Pvt. Ltd., H.No.348, Chhote Atarmuda, Adarsh Nagar, Raigarh (Chhattisgarh) 496001, India*
Email: pradyumna.machhkhand@ghyiae.com
Telephone/Mobile No.: +91 9999 326876

Abstract

The proposed operation of Tamakoshi-V hydroelectric project (TKVHEP), Nepal is completely determined by the discharge released from the power plant of Upper Tamakoshi hydroelectric project (UTKHEP), which led to the diversion of discharge from the already existing tailrace race tunnel (TRT) of UTKHEP to the interconnecting tunnel (ICT) that connects the said TRT and the headpond of TKVHEP; the flow in the TRT, the ICT, and the headpond being open-channel flow. Initially, the size of the headpond and the adjoined lateral spillway weir of TKVHEP were tentatively adjusted meeting the submergence criteria of the intake. However, in order to optimize the headpond size, the other criteria have been fixed by modelling the headpond reach (from the outlet point of the UTKHEP to the end of the headpond) using a physically-based and one-dimensional numerical model. The maximum discharge from the UTKHEP plant is Qmax = 68m^3/s. The normal depth of flow from the established hydraulic model corresponding to this discharge at headpond end has been observed at El.1155m, which is also the lowest regulated water level (LRWL) in the headpond, thereby meeting the intake's submergence criteria. Furthermore, the backwater development at the headpond due to sudden closure of TKVHEP plant and the propagation of wave towards the power tunnel have been modelled by considering the upstream boundary condition as constant discharge Qmax and the downstream boundary condition as transient flow at the headpond location in the model, which is based on the results of surge analysis (separately conducted) of the pressurized water conductor system of the TKVHEP. With the applied boundary conditions, the modelled headpond reach has been iteratively simulated, thereby changing the headpond dimensions and the crest length of the lateral spillway weir for each run. The crest level is fixed at El.1158.1m (0.1m above the recommended highest regulated water level, HRWL = El. 1158m) in the headpond. From the optimized model results, the maximum stage at headpond is observed at El.1159.1m and the design discharge through the lateral spillway weir has been deduced as the sum of inflow Qmax and the maximum transient flow opposite to the direction of inflow.

Keywords: *TKVHEP; UTKHEP; TRT; ICT; headpond; open-channel flow; lateral spillway weir; transient flow; pressurized water conductor system; surge analysis*

1. Introduction

The Tamakoshi-V hydroelectric project (TKVHEP) is a dependent project that has been proposed to depend solely upon the operation of the power plant of Upper Tamakoshi hydroelectric project (UTKHEP). The key salient features of the UTKHEP are the Upper Tamakoshi Dam on the upstream of Tamakoshi River (Location 27°55'28.44"N 86°12'48.59"E; source: Google Earth), the intake at Upper Tamakoshi Reservoir, the headrace tunnel, the desander, the surge shaft, the pressure shaft, the power plant, and the tailrace tunnel (TRT). The power plant of UTKHEP receives inflow from the Upper Tamakoshi Reservoir via the headrace tunnel (HRT) and the pressure shaft. The turbines in the power house are high head Pelton turbines. With all units running in the power plant, the design maximum discharge that can be released from the UTKHEP plant is Qmax = 68m^3/s. As the power house of the UTKHEP is underground, the rock caverns have been excavated to construct tail pit to convey the released water from the turbines to the TRT, which further carries the released tail water as open-channel, thereby finally discharging into the Tamakoshi River. The TRT takes the shortest possible length between the UTKHEP tailrace exit location and the outfall location on the right bank of the Tamakoshi River.

The schematic view of the cascade arrangements of the UTKHEP and TKVHEP has been displayed below.

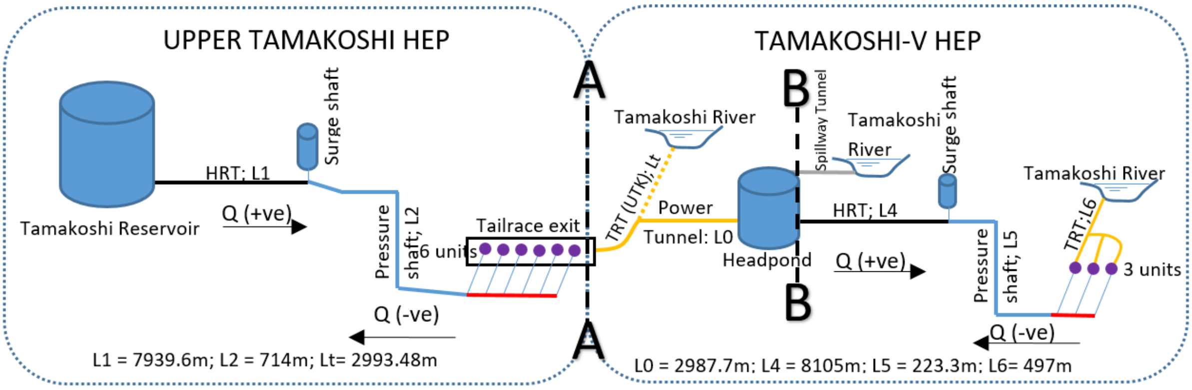


Figure 1 Schematic view of the cascade arrangements of the UTKHEP and TKVHEP projects

1.1 *Planning and development of Tamakoshi-V hydroelectric project*

In the above Figure 1, the frame left to the section A-A represents the scheme of UTKHEP, whereas the frame right to section A-A includes the TRT that takes off from the tailrace exit of the UTKHEP and the frame also represents the TVKHEP. Initially, the TRT of UTKHEP was constructed to discharge into the Tamakoshi River; the alignment of the TRT being displayed in Figure 1 as dotted line.

Subsequent to the development of UTKHEP, the developer, Nepal Electricity Authority (NEA) planned to tap the release from the UTKHEP power plant so that a new hydroelectric project known as Tamakoshi-V hydroelectric project could be developed. In this context, as soon as the feasibility study was completed, the NEA awarded the detailed engineering design works to Lahmeyer International GmbH, where the author carried out the related design works as a hydraulic design and modelling expert. The present paper describes the hydraulic design of the headpond, where multi-objective optimization of the headpond is essential and it also illustrates how the objectives are achieved.

As indicated in Figure 1, the diversion of TRT was proposed for the development of TKVHEP. The frame right to the section A-A represents the scheme of TKVHEP (hereafter, both the TRT from UTKHEP and the diverted interconnecting tunnel (ICT) as a link to the headpond are clubbed together and called the power tunnel) as displayed above. The salient features of key elements of both the projects have also been displayed above. The section A-A to section B-B represents the reach of the open-channel flow that is conveying through the power tunnel and the headpond. In fact, the zone for hydraulic modelling of the headpond is between section A-A and section B-B. The focus of this paper is the hydraulic modelling of the proposed headpond, which also includes the hydraulic design and model study of the appurtenant structures related to the headpond of TKVHEP.

The proposed headpond is underground and is mounted with escape/lateral/side weir spillway to discharge the overflow from the headpond to the spillway outlet tunnel (open-channel) whose outfall is located at the right bank of the Tamakoshi River. It is important to understand the source of inflow to the TKVHEP in order to describe the proposed physical general layout of the TKVHEP itself. The source of the inflow to the TKVHEP project is the tail water release from the UTKHEP power plant. The following key factors have been considered while planning the TKVHEP as tabulated below.

Table 1 Key factors for planning and development of Tamakoshi-V hydroelectric project

Serial No.	Key Factors
1	The re-alignment of already constructed TRT of UTKHEP by taking maximum advantage of the existing alignment.
2	The point of diversion to be at an optimum distance to the proposed intake site of TKVHEP.
3	The lowest regulated water level (LRWL) shall be such that it meets the submergence criteria of the intake of the TKVHEP and is not less than the water level corresponding to the normal depth at the headpond during maximum inflow from the UTKHEP.

Serial No.	Key Factors
4	While UTKHEP is in operation and in case the handpond encounters backpropagation of flow through the intake due to shutting down of TKVHEP plant, an escape structure (lateral/side weir) is to be integrated with the headpond so that the flow could be discharged through the weir.
3	The underground headpond structure is to be optimally designed and located such that at any instance due to any backpropagation of water from the system must not affect the maximum tail water level (EL 1162.35m) at the tail pit of UTKHEP below the turbines.

The proposed schematic layout plan of the TKVHEP featuring the start of the TRT of UTKHEP till the headpond has been refurbished below:

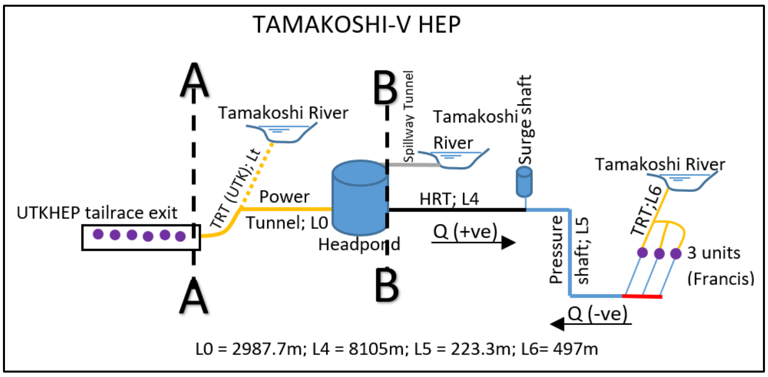


Figure 2 Schematic view of TKVHEP project

The headpond structure is one of the salient features of the project Tamakoshi-V hydroelectric project (TKVHEP), Nepal. The headpond has been planned to receive the discharge (open-channel flow) via the power tunnel and to create head for the TKVHEP; the intake being at the end of the headpond, which connects the head race tunnel (HRT) of TKVHEP. Therefore, the inflow to the headpond entirely depends upon the operational release from the UTKHEP plant. The sketch of the general layout plan of the headpond, the power tunnel, the side weir spillway, and the spillway tunnel have been displayed below.

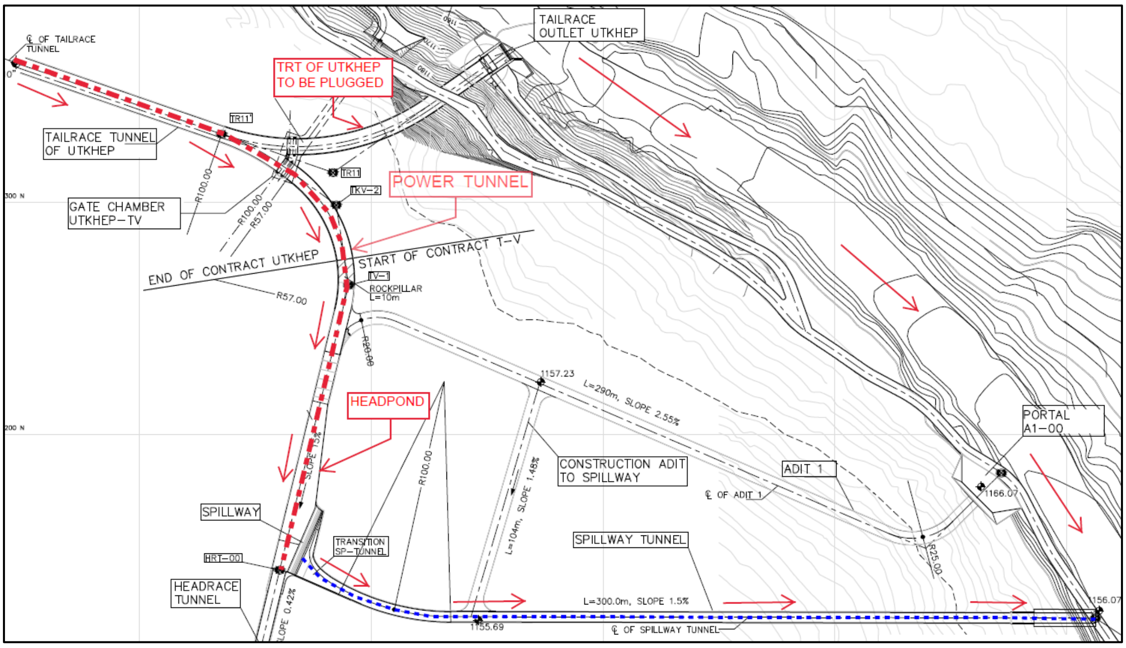


Figure 3 Sketch of the general layout plan of the headpond, the power tunnel, the side weir spillway, and the spillway tunnel of Tamakoshi-V HEP (not to scale)

Initially, the headpond was designed based on the concept given by NEA during the feasibility stage, thereby keeping the highest regulating water level (HRWL) at EL. 1158m and the lowest regulating water level (LRWL) at EL.1155m. In fact, these data were the bases for the surge analysis conducted during detailed engineering stage. However, as the impact of surge development in the headpond on the UTKHEP power plant must be a part of the present study, the other design criteria have also been set and examined to optimize the size of the headpond. It is noted that the headpond design must be synchronous with the UTKHEP as well as with the TKVHEP without having any impact on the targeted energy of both the projects. This leads to the development of multiple criteria to optimize the headpond as described in the subsequent section.

2. Hydraulic design criteria of headpond

As the headpond and the power tunnel are proposed as open-channels and are to be constructed underground, the optimal design of headpond must conserve the principles of open-channel flow by maintaining sufficient freeboard in the power tunnel and the headpond. The hydraulic sections of these structures are rectangular with vertical lined walls on either side and with lined surfaces, whereas the freeboard sections are partly rectangular with finished arch cover. The sketch of the sections of the power tunnel and the headpond have been displayed below.

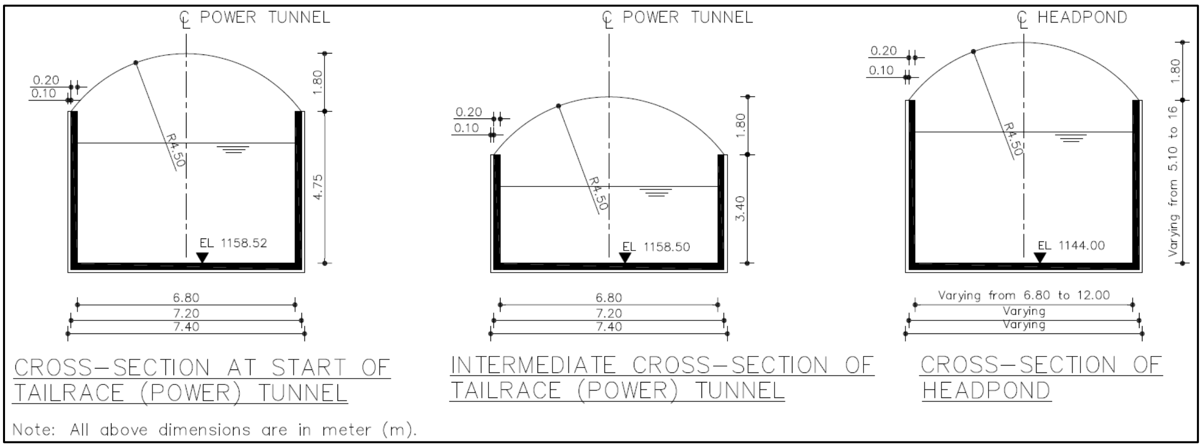


Figure 4 Sketch of the sections of the power tunnel and the headpond

The hydraulic design criteria have been described in the subsequent sections below.

2.1 *Area-Capacity curve*

The area-capacity curve shall be based on the optimum size of the headpond as a result of hydraulic modelling of the headpond considering all the modelling criteria.

2.2 *Submergence for intake*

As the intake will receive controlled flow from UTKHEP, it is necessary to check the normal depth of flow at the intake when it receives the maximum release of Q = 68m^3/s from UTKHEP. The submergence shall be such that it suffices the required submergence depth criteria at Q = 68m^3/s and the LRWL at the intake remains unaffected.

2.3 *Spillway weir crest*

The spillway weir crest level shall be based on the model study of the headpond integrated with the spillway weir. It is to be ensured that the crest elevation is high enough as compared to the water levels in the river where the spillway outlet is discharging.

2.4 *Effect of backwater*

The effect of backwater shall be based on the critical condition, that is, when the headpond receives the maximum discharge from the UTKHEP, at the same instant the maximum transient flow in the reverse direction towards the headpond is witnessed due to sudden load rejection at TKVHEP considering the case of maximum magnitude of transient flow resulting from the surge analysis. The impact of this on the water level at the tail pit of UTKHEP shall not exceed the designed maximum tail water level (EL.1162.35m).

2.5 *Freeboard*

The freeboard in the power tunnel and the headpond must be greater than 1m from the maximum water levels in the system.

3. Hydraulic modelling of the headpond

In order to meet the above multiple criteria for hydraulic design of the headpond, the hydraulic modelling (physically-based numerical model) of the headpond and related structures become inevitable. The reaches of the headpond hydraulic model constitute the power tunnel reach (start point is where the TRT of UTKHEP begins) and the headpond reach (end point is where the intake/headrace tunnel of TKVHEP starts).

3.1 *Model setup*

The documents, Final Design Tailrace Tunnel *(Longitudinal Section, Cross-Section and Detail), 2011* and Tamakoshi V HEP Field Investigation and Data Collection: Detail Design Headworks Headpond Longitudinal Section Plan and Section *(Longitudinal Section, Cross-Section and Detail*), 2017, have been the bases for setting up the model:

3.1.1 *Applied convention*

Following conventions have been applied:

a) depending upon the sectional change in the power tunnel and the headpond at varying intervals, both the reaches have been divided into 8 numbers of cross-sections for model study, which have been further divided/interpolated for model requirements;
b) as the power tunnel and the headpond are open channels, the one-dimensional (unsteady state) numerical modelling software, HEC-RAS by USACE has been used to model the system;
c) the critical condition in the headpond shall be the scenario where the Tamakoshi V plant shuts down suddenly when the UTKHEP is still discharging the maximum flow of $68m^3/s$; and
d) the simulation date and time 05 September 0000 hours to 05 September 0025 hours are merely indicative of start time 0 sec to end time 1500 sec.

3.1.2 *Brief description of the applied software, HEC-RAS*

The software, HEC-RAS developed by USACE is designed to perform one-dimensional (1D) and two-dimensional (2D) hydraulic computations numerically for a full network of natural and constructed channels. The HEC-RAS model comprises two major components; steady flow and unsteady flow. In the present study, both the components have been used. The steady component has been used to calibrate the model, whereas the 1D unsteady component has been used to model the power tunnel and the headpond reaches. The physical laws which govern the flow of water in a stream or channel are expressed mathematically in the form of partial differential equations:

Conservation of mass (continuity) equation:

$$\frac{\partial \mathrm{Q}}{\partial x} + \frac{\partial \mathrm{A}}{\partial t} + q_1 = 0 \tag{1}$$

Conservation of momentum equation:

$$\frac{\partial \mathrm{Q}}{\partial t} + \frac{\partial \mathrm{QV}}{\partial x} + \mathrm{gA}\left(\frac{\partial h}{\partial x} + S_f - S_o\right) = 0 \tag{2}$$

where:

Q	=	discharge,
A	=	total flow area,
q_1	=	lateral inflow per unit length,
x	=	distance along waterway,
t	=	time,
V	=	velocity,
g	=	acceleration due to gravity,
h	=	depth of flow,
S_f	=	frictional slope, and
S_o	=	bed slope.

3.1.3 *Cross-sections of the modelled reach*

The modelled reach has been divided into two parts, viz., the power tunnel reach and the headpond reach. The assignment of cross-sections in the reaches have been listed below.

Table 2 Cross-sections of the power tunnel and the headpond

Cross-sections (XS)	Distance from the immediate downstream XS (m)	Remarks
XS 8	10.00	Power tunnel reach
XS 7	7.80	Power tunnel reach
XS 6	2853.71	Power tunnel reach
XS 5	22.06	Headpond reach
XS 4	44.66	Headpond reach
XS 3	17.00	Headpond reach
XS 2	32.54	Headpond reach
XS 1	0.00	Headpond reach

3.1.4 *Model calibration*

Using the above geometry and the available data of water levels at the TRT exit, a steady state model in HEC-RAS has been developed and calibrated. The Manning's roughness (n = 0.014) has been applied and the results concur with the previous study (NEA, 2016). For the hydraulic modelling of headpond, the Manning's roughness shall be n = 0.014.
It has been observed from the results that at Q = 68m^3/s, the water surface elevation at the headpond reaches EL 1155.08m. Later, the unsteady component of the HEC-RAS has been utilized to simulate the transient behavior of flow in the headpond as described in the subsequent sub-sections.

3.1.5 *Initial and boundary conditions*

The initial conditions and the upstream and the downstream boundary conditions have been tabulated below.

Table 3 Initial and boundary conditions

Station ID	Station name	Initial condition	Upstream boundary condition	Downstream boundary condition
XS ID - 8	Power tunnel	Q = 6.8 m^3/s	Inflow hydrograph	-
XS ID - 1	Headpond	-	-	Transient flow hydrograph

The upstream boundary condition is the inflow hydrograph with constant flow of 68 m^3/s for the duration of time equal to 1500 sec at an interval of 1 sec.

The downstream boundary condition is the transient flow time series (duration 1500 sec) at the headpond due to load rejection scenario for minimum roughness case, which has been explained in the same report (Detail Engineering Design and Tender Document Preparation of Tamakoshi V Hydroelectric Project, Chapter 4, Lahmeyer International GmbH, Germany, 2018). The upstream and the downstream boundary conditions have been displayed in the figure below.

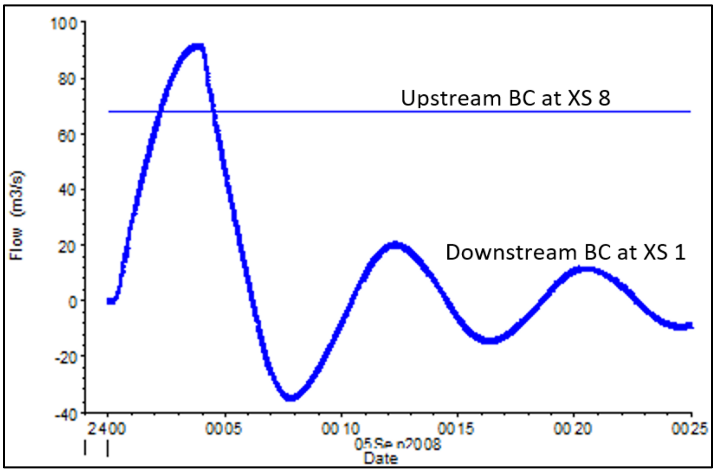
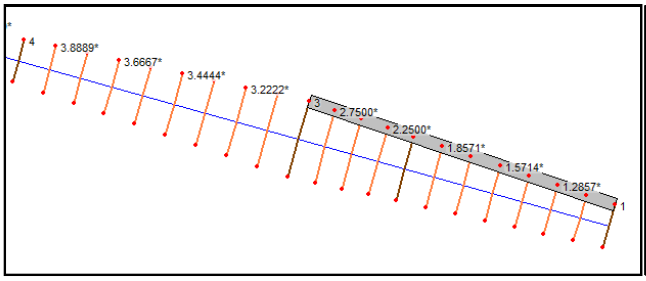


Figure 5 Upstream and downstream boundary conditions

3.1.6 *Lateral/side spillway weir at the headpond*

The considered lateral/side spillway weir in the headpond shall be iteratively modelled, thereby changing the crest level and the crest length of the weir for each run till the optima crest level and length are achieved. The schematic plan and sections of the weir in the HEC-RAS model have been displayed in the figures below.



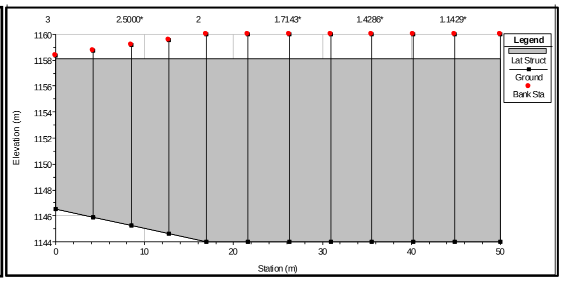


Figure 6 Schematic plan (left frame) and section (right frame) of the weir in the HEC-RAS model

4. Results and discussions

The unsteady model discussed above has been simulated for 1500 sec. The longitudinal profile with maximum water surface elevations along the power tunnel and the headpond has been displayed in the figure below.

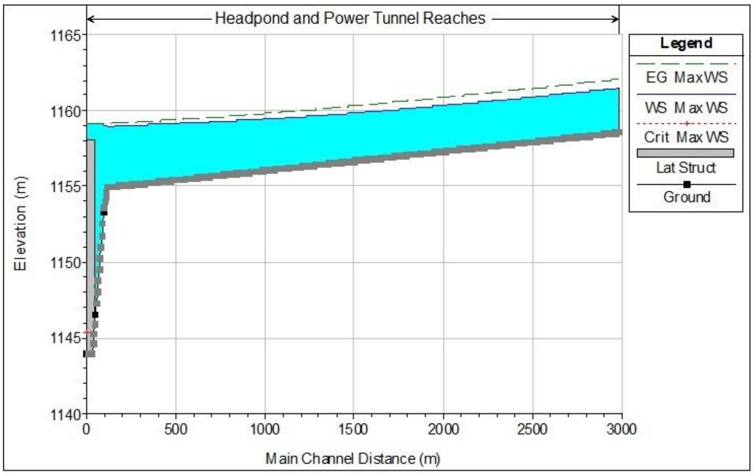


Figure 7 Maximum water surface profile in the power tunnel and headpond reach

The above water surface profile has been further elaborated in the figure below.

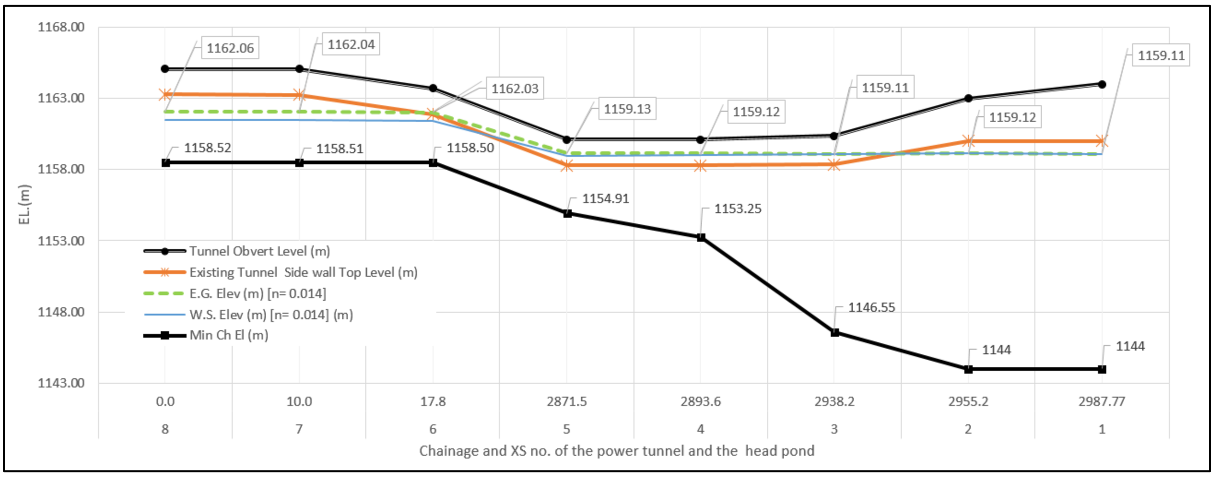


Figure 8 Maximum water surface profile with details of the power tunnel and the headpond

The above figure displays the invert and obvert levels of the power tunnel and the headpond. It may be noted that minimum cover from the top of the side walls to the obvert levels of the tunnel is 1.8m. As the model has been developed considering the scenario of the transient condition that is critical for the headpond, the resulting maximum water surface profile does not exceed the maximum tailwater level EL 1162.35m of UTKHEP. Secondly, the available freeboard in the tunnel with reference to the maximum water surface levels ranges from 1.1m to 4.89m, which is acceptable and the modelled size of the headpond meets the critical condition scenario.

The results of simulated time series of flow and stage at XS-8 and XS-1 have been displayed in the figures below.

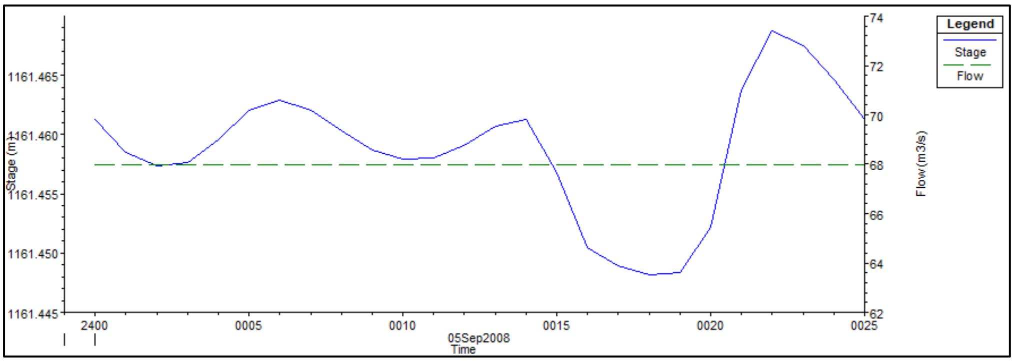


Figure 9 Results of simulated stage-flow time series (time shown in minutes) at XS-8 (the start of the power tunnel)

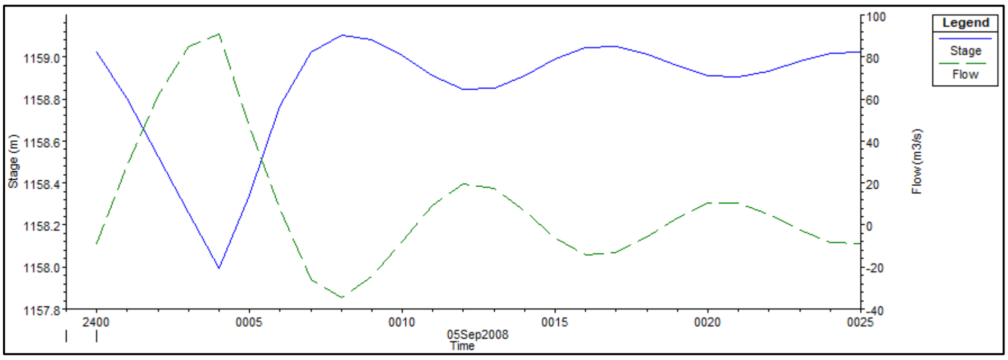


Figure 10 Results of simulated stage-flow time series (time shown in minutes) at XS-1 (the end of the headpond)

Although the maximum stage that has resulted at headpond is 1159.1m, for the purpose of design of spillway chute and the appurtenances, the maximum inflow (Q =68m^3/s) from the tail outlet of UTKHEP and the maximum transient flow (Q =34.8 m^3/s) towards the headpond from Tamakoshi V intake have been summed up to result a design discharge through weir, Qd = 102.8 m^3/s. The same is advisable for the headpond design works.

The water levels of the Tamakoshi River at the spillway outlet of TKVHEP has been referred from the rating curve derived from the river model study considering the reach of the river near the spillway outlet (Lahmeyer International GmbH, Germany, 2018; Detail Engineering Design and Tender Document Preparation of Tamakoshi V Hydroelectric Project). The critical observatory discharges in the Tamakoshi River near the spillway outlet and their corresponding levels have been tabulated below.

Table 4 Discharge and water levels of Tamakoshi River near spillway outlet of TKVHEP

River Discharge (Q m^3/s)	Water surface elevation (m)	Lateral weir crest level (m)	Remarks
68	1147.61	1158.10	No impact on weir crest level
300	1149.30	1158.10	No impact on weir crest level
2200	1155.28	1158.10	No impact on weir crest level
2800	1156.24	1158.10	No impact on weir crest level

In the above table, the discharge, Q =68m^3/s is hypothetically considered for the river because it is the maximum outflow from the UTKHEP plant that may spill out to the river due to closure of TKVHEP. The inflow at Upper Tamkoshi dam site when the UTKHEP shuts down is 300m^3/s (Nepal Electricity Authority, 2011; Feasibility Study of Tamakoshi-V Hydroelectric Project. Project Development Department, Engineering Services)). The river discharges, Q =2200m^3/s and Q =2800m^3/s represent the Q_{1000yr} flow and the anticipated extreme flow, respectively. In all the above cases, the water levels in the Tamakoshi River are much below the lateral weir crest level, thereby causing no impact on the headpond structure.

5. Conclusions

Unlike the other forms of cascade hydroelectric projects, where the reservoirs exist on the surface of the rivers, the headpond of TKVHEP is to be constructed underground. As TKVHEP is a cascade development of UTKHEP, the TRT of the UTKHEP, which was initially constructed for discharging into the Tamakoshi River by taking the optimal route shall be diverted to form the headworks for the TKVHEP. The headworks include the said TRT, which is known as the power tunnel in this paper, and the headpond. It is anticipated that during the operation of TKVHEP, for any reason if the THVHEP plant shuts down and the UTKHEP is still in operation, the released water must find an escape. Therefore, the lateral weir at the headpond is found appropriate to serve this purpose. However, as the headpond must be synchronous with operations of both the plants upstream and downstream, the multi-objective optimization of the headpond is essential. The identified objectives are achieved by the one-dimensional hydraulic modelling of the headpond coupled with the transient flow results of surge analysis of TKVHEP as the downstream boundary condition; whereas the upstream boundary condition in the model being the constant maximum flow released from UTKHEP, Q = 68 m^3/s. A number of iterations have been attempted, thereby changing the dimensions of headpond and running the models. The paper presents the final successful model, where all objectives are achieved. The checklist showing the multiple hydraulic design criteria of headpond and the inferences drawn from the hydraulic modelling results have been tabulated below.

Table 5 Checklist of the multiple criteria and the inferences from model study of headpond

Sl. No	Hydraulic design criteria	Inferences from hydraulic modelling	Remarks
1	Area-capacity curve	The HRWL and the LRWL remain unchanged.	Recommended for further inclusion in the project works.
2	Submergence	At maximum inflow from UTKHEP, the required submergence depth merges with the normal depth at the headpond.	Recommended for further inclusion in the project works.
3	Lateral/Side weir	Design discharge = 102.8 m^3/s; weir length = 50m; weir crest level = EL.1158.1m; max. water level above the crest = EL.1159.1m, which is much higher than the water level of Tamakoshi River at the spillway outlet section.	Recommended for further inclusion in the project works.
4	Backwater	Critical transient condition has no negative impact on the UTKHEP power plant or on the headpond.	Recommended for further inclusion in the project works.
5	Freeboard	Sufficient freeboard is available at the power tunnel and the headpond structures.	Recommended for further inclusion in the project works.

As the optimization of headpond size requires multiple criteria and constraints to be met, the inferences drawn from the hydraulic modelling of the headpond, the lateral weir structure, and the power tunnels dictate the same. As a corollary, the recommended length of the headpond length is 116.2m, whereas the recommended invert level in the headpond near the intake is EL.1144m; the same have been included in the model study.

References

Nepal Electricity Authority (2011). *Feasibility Study of Tamakoshi-V Hydroelectric Project.* Project Development Department, Engineering Services, Nepal Electricity Authority, Kathmandu, Nepal.

Lahmeyer International GmbH, Germany (2018). *Detail Engineering Design and Tender Document Preparation of Tamakoshi V Hydroelectric Project*, Nepal Electricity Authority, Kathmandu, Nepal.

JV of Norconsult, Norway and Lahmeyer International GmbH, Germany (2016). *Final Report of Upper Tamakoshi Hydroelectric Project, Consultancy Services for Construction Supervision of Upper Tamakoshi Hydroelectric Project*, Nepal Electricity Authority, Kathmandu, Nepal.

Abbott, M. B, Pitman Publishing Ltd., London, (1979). *Computational hydraulics: Elements of the theory of free surface flows.*

U.S. Army Corps of Engineers HEC-RAS (2008). River analysis system hydraulic reference manual. Institute for water resources, Hydrologic engineering center.