Designing a Hypolimnetic Oxygenation System for Reservoir Water Quality Improvement (Case Study: YamchiDam Reservoir)

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Abstract

The entry of various contaminantsinto the reservoirleads to the growth of algae and the consumption of dissolved oxygen in water. Due to the occurrence of thermal stratification, the amount of dissolved oxygen is reduced and even anaerobic condition can occur. This situation, in addition to aquatic mortality, leads to the production of hydrogen sulfide and ammonia and the release of reduced phosphorus, iron and manganese from the sediment to the water, which ultimately adversely affects the smell, color and taste of water. The study of the Yamchi dam shows the occurrence of anaerobic condition in hypolimnion layer during summer. Therefore, a hypolimnetic oxygenation system wasproposed as a structural solution for this reservoir. In this paper, after determination the boundary of thermal stratification, the amount of hypolimnetic oxygen demand (HOD) was calculated, and then the condition of the reservoir after oxygenation was predicted using governing equations of linear oxygenation systems and plum model. The results showed that in the current situation, the HOD of the Yamchi dam is about 6 grams of oxygen per square meter per day. System details are provided in article.

Keywords: Yamchi Dam, hypolimnetic oxygen demand, plum model, thermal stratification.

1. INTRODUCTION

Oxygenconsumptionprocess occurs in lakesand reservoirs due to oxidation of reduced chemical species, algal, and aquatic respiration, andaerobic decomposition of organic matter [1;2; 3; 4;5].Reservoirs over timeundergo seasonal stratification, creating a warmer, less-denseepilimionlayer at the top, a transitionary thermocline or metalimnionlayer at the middle, anda colder, more-dense hypolimnion layer at the bottom [1].The density gradientlimits oxygen transfer from the surface layer to the lower layer (hypolimnion layer)[1; 2].Reduction ofdissolved oxygen (DO) in the hypolimnion layeris exacerbated asalgae, which grow in the photic zone, complete their life cycleand are degraded as they settle through the water column. This settling organic detritus undergoes aerobic decomposition in the presence of DO, which contributes to water columnoxygen demand (WOD). Incompletely oxidized detritus settlesthrough the hypolimnion and accumulates on the bottom,becoming incorporated into the sediment and contributing tosediment oxygen demand (SOD). The sum of both WOD and SOD in the hypolimnion is an overallhypolimnetic oxygen demand (HOD) [6; 7; 1; 8].HODcan causeanaerobic conditions by completely depleting oxygen in thehypolimnion if the HOD exceeds the amount of DO availablein the hypolimnion [8; 9; 10; 11].

TheYamchi reservoir has been exposed to nutrification in recent years, due to the obtaining of various pollutants, especially urban and industrial wastewater and runoff as well as agricultural drainage.Acute problems such as unpleasantsmell and color of the reservoir have attracted more attention to the issue of water quality in this reservoir. One of the suggested remedies for this reservoir is the structural solution, along with the non-structural solutions.Among the structural solutions, hypolimnetic oxygenation system, as an effective solution,is considered in this paper.

Several successful and unsuccessful methods of reservoir aeration and oxygenationare employed to increase hypolimnionoxygen concentrations around the world.[1;12; 13; 14; 15; 16; 17; 18].But no case study of hypolimnetic oxygenation system of Iranian's reservoirs have been published to date.

2. MATERIALS AND METHODS

Yamchi water quality study was performedbetween 2016 to 2018. During this time, one year allocated to monthly water quality sampling from 3 monitoring stationsat different depth of thereservoir (fig. 1).Physicochemical parametersalong with heavy metals and microbial factorswere measured based on the methods recommended in the standard method book.In addition, CTD multiparameter probe was used to drown water quality profiles in monitoring stations.After that, this datawas usedas an input for reservoir water quality model (CE-QUAL-W2) to simulate reservoir water quality and predict the thermocline cycle.Finally, CTD profiles and monitoring datawere usedfor oxygenationplum model.

2.1. STUDY SITE

The Yamchi Damis located in Ardabil province in the northwest of Iran, at the geographic coordinate 38^{o} $4^{/}11^{//}$ north, and 48^{o} $4^{/}54^{//}$ east, on the Balekhlichai River (fig. 1). The Yamchi Dam is an embankment dam, with a height of 67 meters from foundation, and a normal reservoir volume of 82 million cubic meters (MCM).In addition to agricultural water supply, the dam also supplies a significant portion of Ardabil metropolitan drinking water.

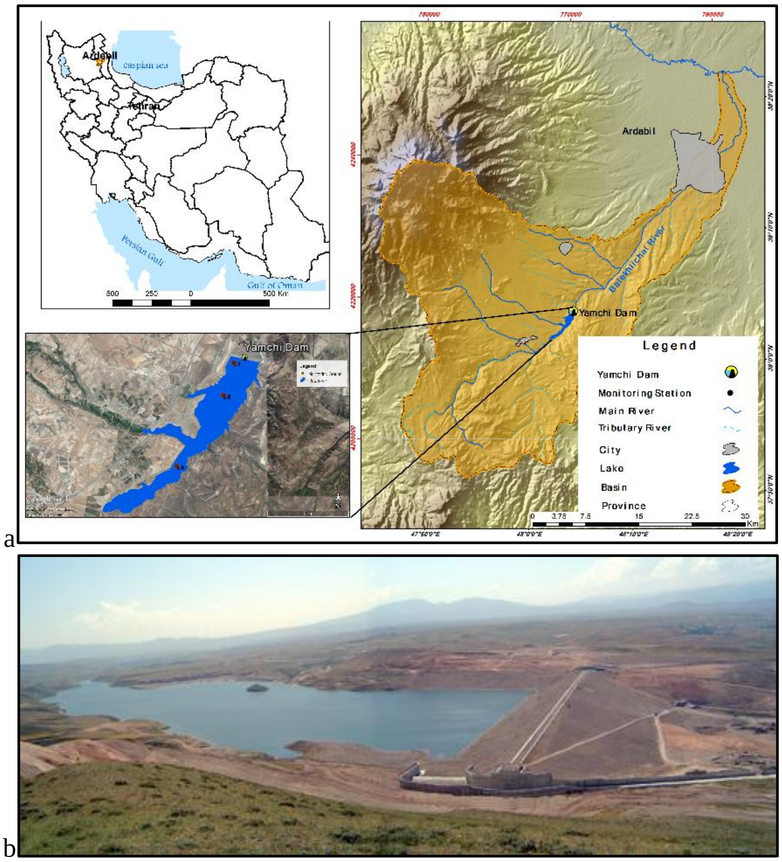

Figure 1. a) Yamchi Dam Basin, Its reservoir and monitoring stations b) view of Yamchireservoir

2.2. DATA COLLECTION

An OCEAN SEVEN 316Plus CTD multiparameter probe (20 Hz sampling rate)(fig. 2) was used to collect temperature and dissolved oxygen profiles on a longitudinal transect at three locations in Yamchi reservoir (L1, L2 & L3 in fig. 1). A combo water tester Handheld IP67 8603 was used in conjunction with the CTD to obtain and control the profiles at lower vertical resolution on 0.5 m.Monthly data were collected from April 2016 to April 2017. This study focuses on capturing dissolved oxygen and temperaturecondition in the reservoir, before, during and after period of stratification.

2.3. DATA ANALYSIS

In order to calculate HOD, first analyzing vertical temperature profile is needed to determine the boundary between the metalimnion and hypolimnion, and the corresponding hypolimnetic volume. Fig. 3 showstemperature and dissolved oxygen profile in the deepest point of Yamchi reservoir (L1). Other points of reservoir (L2 and L3) have a similar trend.


a
b

Figure 2. a) Using CTD in Yamchi reservoir; b) Reading CTD data on the boat

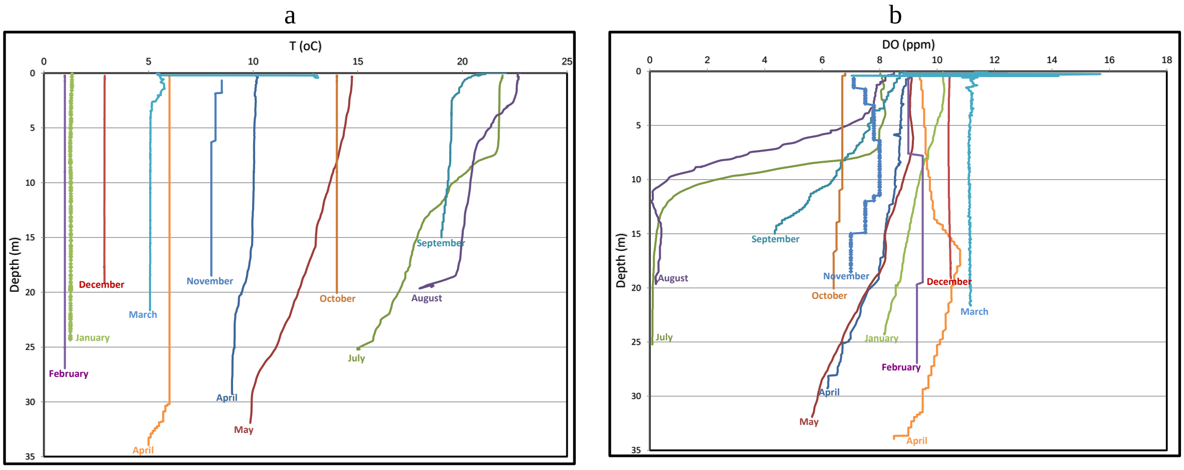
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Figure 3. a) Temperature profile b) dissolved oxygen profile at the deepest point of Yamchi reservoir using CTD

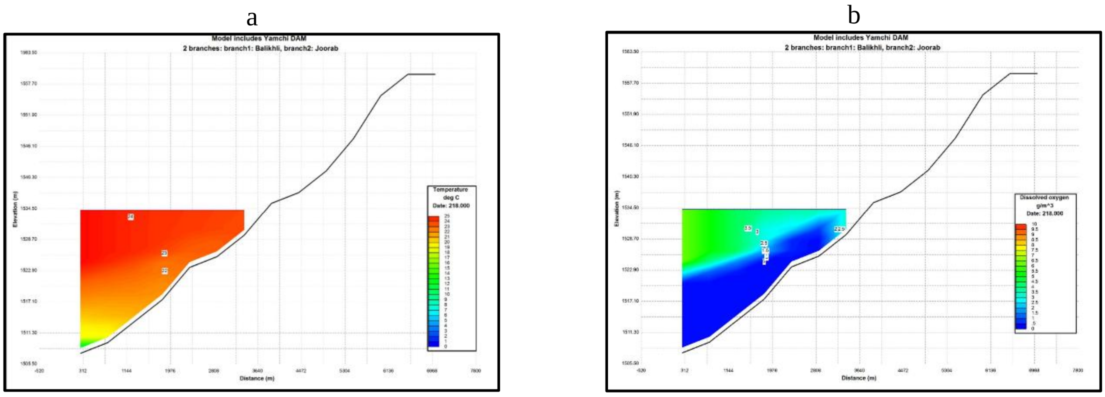
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Figure 4. a) Temperature longitudinal profile b) dissolved oxygen longitudinal profile in summer, based on CE-QUAL-W2 model output

Temperatureprofile (fig. 3.a)and CE-QUAL-W2 simulation output (fig. 4.a)shows that thermal stratification of the Yamchi reservoir begins in late spring(May).In summer with the increasing of air temperature, thermal stratification intensifies and lastsuntil the end of summer (September).According to fig. 3.a, the sharpest change in temperature profile occurs in July (Tir in SHcalendar). Subsequently, with the onset of autumn, and with the decreasing in air temperature and the beginning of autumn winds, the reservoir becomes mixed.This situation will continue until next spring.

Dissolved oxygen profile (fig. 3.b)and CE-QUAL-W2 simulation output (fig. 4.b) shows that in summer, simultaneous with the thermal stratification,the amount of dissolved oxygen in the hypolimnetic layer is reduced and hypoxic condition occur. The worst caseoccurs in August and July, and partly in September (Tir, Mordad and shahrivarrespectively in SH calendar), which the amount of dissolved oxygen in the hypolimnetic layer reaches near to zero. Fish mortality has also been observed during these months.

2.4. GOVERNING EQUATIONS

A. HYPOLIMNETIC OXYGEN DEMAND (HOD)

To determine HOD, vertical CTD profile data were used. The process is as follows [1]:

First analyzing temperature profiles to determine thermocline period, thermocline location, the boundary between the metalimnion and hypolimnion, and the corresponding hypolimnetic volume.

The Yamchi reservoir was thendivided into three sections (based on longitudinal sampling locations) and 0.1-m layers (based on sampling depth and CTD profile). This created a section (x)-layer (z) grid that divided the reservoir into cells.

The volume-weightedtotal mass of oxygen in the hypolimnion was calculated bymultiplying the oxygen concentration ($DO_{x,z}$) by the corresponding cell volume($Vol_{x,z}$)and summing the results for all cells in thermocline period:

$$Mass(Oxygen \quad Content) = \sum_{x=1}^{s} \sum_{z=1}^{n} DO_{x,z} \times Vol_{x,z} \tag{1}$$

Where Mass(Oxygen Content)= total volume-weighted oxygen mass (kg-O_2), $DO_{x,z}$= oxygen concentration in section (x) and layer (z),$Vol_{x,z}$= cell volume corresponding to section (x) and layer (z),s = number of sections, and n = number of layers.

HOD_{mass} (Hypolimnetic Oxygen Demand as a function of oxygenmass) is calculates by plotting hypolimnionoxygen content against time and finding the slope of theregression line through the data [14].

B. LINEAR BUBBLE PLUME MODEL

The bubble plume model equations were originally developed by *Wuest et al. (1992)*[20].but modified by *McGinnis et al. (2001)*[21]., and refined by *Singleton et al. (2007)*[19].

The linear bubble plumemodel is composed of horizontally integrated equations based on the conservation of mass, momentum, and heat. Eight flux equations are solved simultaneously to predictwater flow rate, plume temperature, oxygen and nitrogentransfer and concentration, salinity, and plume rise height,given diffuser geometry and depth, applied gas flow rate,and initial bubble size (Tables 1 and 2)[18].

Table 1- Key Variables of the Linear Bubble Plume Model [18]

Variable	Formula	Unit
Entrainment factor	$E = 2(L+W)\alpha \nu$	m^2/s
Plume water volume flux	$Q = LW\nu$	m^3/s
Momentum flux	$M = LW\nu^2$	m^4/s^2
Temperature flux	$F_T = QT_p$	^oC m^3/s
Dissolved solids flux	$F_s = QS_{\rho\omega}$	kg/s
Dissolved O_2 and N_2 fluxes	$F_{D_i} = QC_i$	mol/s
Gaseous O_2 and N_2 fluxes	$F_{G_i} = \lambda W[L - W(1-\lambda)](\nu + \nu_b)y_i$	mol/s

Table 2- Nonlinear Differential Flux Equations of the Linear Bubble Plume Model [18]

Flux	Equation
Water Volume	$dQ/dz = E$
Momentum	$dM/dz = [(\rho_a - \rho_w)/\rho_p]g\lambda W + [(\rho_w - \rho_p)/\rho_p]g\lambda W[L - W(1-\lambda)]$
Temperature	$dF_T/dz = ET_a$
Salinity	$dF_S/dz = E\rho_a S_a$
Dissolved gas	$dF_{D_i}/dz = EC_a + [4\pi r^2 N/(\nu + \nu_b)]K_L(H_i P_i - C_i)$
Gas	$dF_{G_i}/dz = -[4\pi r^2 N/(\nu + \nu_b)]K_L(H_i P_i - C_i)$

Whereb plume radius (circular bubble plume)(m), d bubble diameter (mm), C dissolved concentration (mol/m3), E entrainment factor (m2/s), F_D dissolved species flux (mol/s), F_G gaseous species flux (mol/s), F_S salinity flux, (kg/s),F_T temperature flux, (C m3/s), Fr Froude number, g gravitational acceleration (m/s2), H Henry's constant (mol/m3/bar), KL mass transfer coefficient (m/s), L plume length (m), M water momentum, (m4/s2), N number flux of bubbles (1/s), P pressure (bar), Q plume flow rate (m3/s), q actual gas flow rate per unit diffuser length (m2/h), RiRichardson number, R bubble radius (m), S salinity (g/kg), T temperature (C), νvelocity (m/s), W plume width (m), y gaseous concentration (mol/m3), Z depth (m), αentrainment coefficient, λ spreading coefficient, ρdensity(kg/m3),G Gaussian profile, O oxygen, N nitrogen, T top-hat profile, a ambient water, b bubble, i gas species, oxygen or nitrogen, o initial, p plume water and gas mixture, w plume water.

3. RESULT AND DISCUSSION

According monitoring data, Yamchi reservoirhas thermal stratification in May, August and July. During these months, the hypolimnion located approximately 10, 7 and 4 m below water surface respectively. As a result, hypolimnionoxygen content was calculated during several days in this time, using equation (1). Finally, by plotting hypolimnion oxygen content against time and finding the slope of the regression line through the data, HOD was obtained.

Fig. 5 shows hypolimnion oxygen content diagramand regression line of Yamchi reservoir during thermocline period. According to this, HOD is estimated at 2210 (kg-O2 per day).Due to various uncertainties in calculation (includingincompletely-oxidized detritus, sediment oxygen demand or SOD, oxygen content in metalimnion, organic material in reservoir, algal growth, estimation of dissolved oxygen,…) some references recommend a safety factor between 2 to 3 [12, 17, 18,]. In this study, after consulting with experts, the factor of 2.5was considered as the safety factor.As a result, HOD is estimated to be 5525 (kg.O2 /day), or 3.4 (L.O2 /min).By considering the surface area of the reservoirduring thermocline period equalto 0.93(km^2), HODwill be about 6 (g.O2/m2 per day).

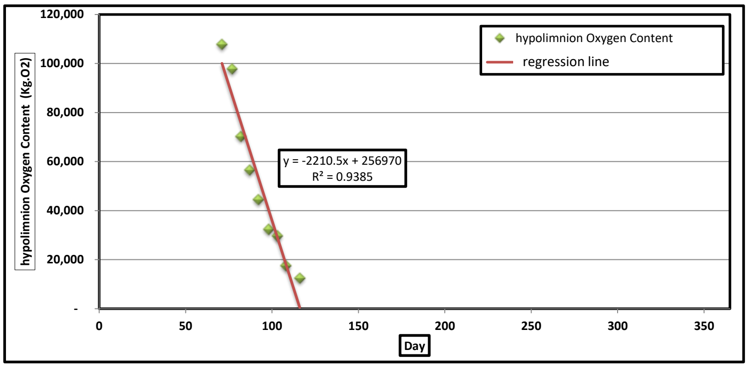

Figure 5. Hypolimnion oxygen content diagram of Yamchi reservoir

A linear bubble plume diffuser is proposed for Yamchi reservoir. Themain components of this system are: oxygen generator with the capacity about 3.4 (L.O2 /min), pump with an applied gas flow rate of 100

SCFM[1], porous pipe with the length of 1200 m, linear bubble plum diffuser on the pipe with bubble size (diameter) equal to 1.16 mm. These numbers are based on oxygenation plum model results.

A schematic of diffuser system is shown in fig 6.a.This system consists of a porous pipe that is spread over the bed of reservoir (fig 6.b. and fig. 7).This porous pipeis filled with oxygen and by going through the holes and entering the reservoir, a mixture of water and oxygen is formed. This mixture due to the density difference with the surrounding water, began to rise upwardslike a plume (fig 8).

The bubble-water mixture is essentially the 'plume'. The plume is entraining cold water from near the bottom. As the plume rises, it loses its momentum because of the density gradient in the water column and the energy to continue to lift the colder/heavier water.At this point, the water in the plume is colder than the surrounding water, but warming when it was entrained from the bottom. The water then falls down to an elevation of equal density water in the bulk hypolimnion.

The upward movement of bubbles also causes mixing and circulation in water, which also accelerates the transfer of oxygen to water.This mixture continues to rise until it has lost its energy and will no longer be able to rise.At this elevation, it will plunge into ambient waters. Rising elevation of this mixture is one of the important parameters in designing system, and it should be adjusted to fit under the thermocline layer and should not cause distribution in thermocline layer.

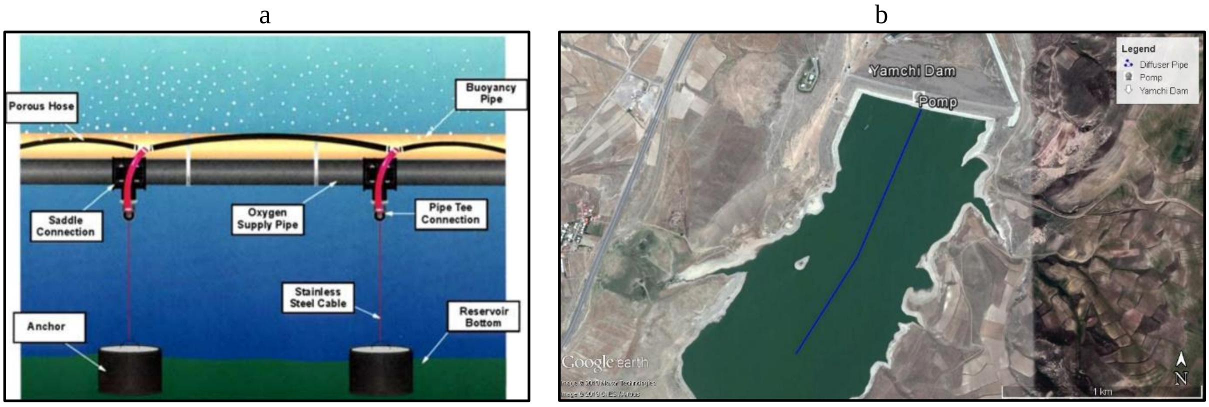

Figure 6. a) Schematic of linear bubbleplume diffuser [18] b) piping in Yamchi reservoir

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[1] standard cubic feet per minute

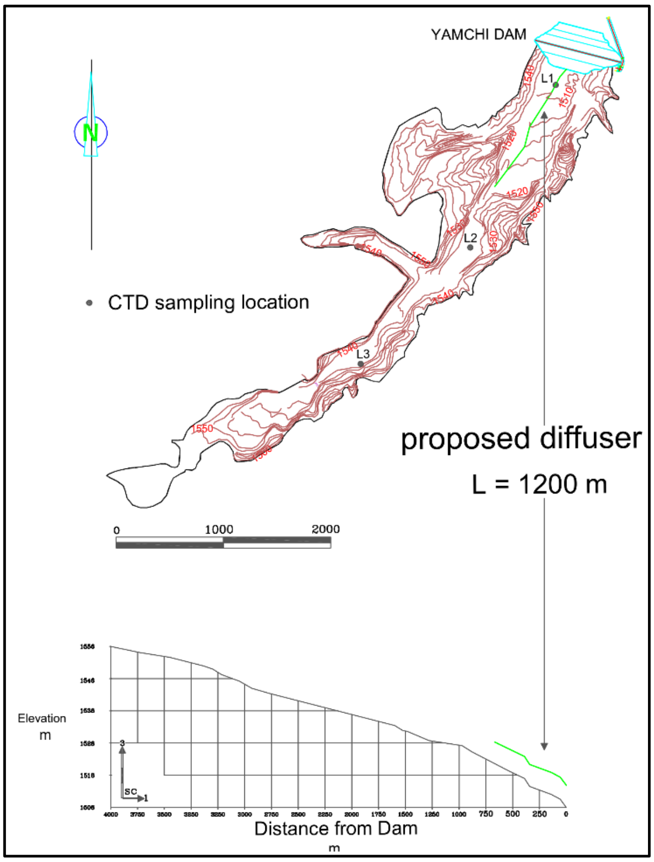

Figure 7. Bathymetric map of Yamchi reservoir, showing location of linear bubble plume diffuser

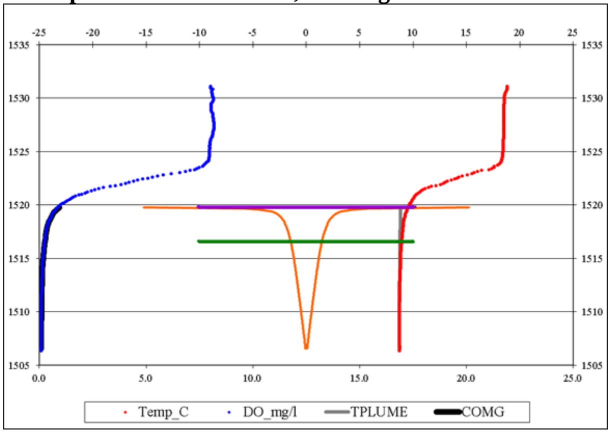

Figure 8. Prediction the plum rise of Yamchi reservoir:green line: the elevation of equal density, violetline:depth of maximum plume rise, orangeline: the predicted width of the plume

The cost of the system is estimated 100 million Rials for oxygen generator and pump, 3600 million Rials for piping and its joints. That is a total of 3700million Rials. The cost of electricity (including 7 kWh for oxygenation and pumping system, and 12 hr. per day) is estimated 20million Rial per month.As a result, the overall costis estimated about 3720 million Rialsfor one month. The big advantage of this system compared to other systems,is its lower cost as well as the ease of installation and operation.

4. CONCLUSIONS

Due to variations in air temperatures, thermal stratification occurs over time for the reservoirs. This process can cause oxygen depletion inthe lower layer of water or hypolimnion, and adverse effect on water quality, including smell, color, taste, and so on. The study of Yamchi dam revealed that this reservoir, because of obtaining various pollutants, is subjected to anaerobic conditioninhypolimnion during summer months. In this paper, a hypolimnetic oxygenation system is proposed and its details are discussed. Beside of non-structural solution, this system can be an effective solution for Yamchi reservoir. To date, no oxygenation system have been publishedfor Iranian's dams.

5. ACKNOWLEDGMENT

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