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Application of Water Quality Simulation for Water Safety Plan at Mahaweli River Basin, Kandy

Koichi Matsubara[1*], Tatsuya Tobe[1], Michihiro Murata[1], Riota adachi[1], Suguru Ishikura[1], Yoshiki Wada[1], S. Weragoda[2], U. Ramawickrama[3] and S. Jinadasa[3]

[1] Nihon Suido Consultants Co., Ltd., Tokyo, Japan
[2] National Water Supply and Drainage Board, Sri Lanka
[3] University of Peradeniya, Sri Lanka
*E-Mail: matubara_k@nissuicon.co.jp, TP: +81-3-5323-6264

Abstract: Water Safety Plan (WSP) is an effective risk assessment framework to elaborate possible risks for water supply systems. However, risk quantification of “severity” and “likelihood” of specific incidents is challenging especially for the risks at water sources. Water quality simulation is an essential tool for predicting the risks and applying effective countermeasures, while data availability and usability for practitioners remains as obstacles for implementation. The objective of this study is to develop appropriate simulation methodology for the risks at water source of all the water supply systems in Sri Lanka. In this report, we focused on the Mahaweli river basin in Kandy. Reviewing the existing WSP at Greater Kandy WTP, the contamination of intake water by the leachate from neighbouring solid waste damping site was considered as a significant risk. We developed dynamic hydraulic model and water quality model which can configure input and output data on Microsoft Excel interface. As a result of the simulation, it was implied that the contaminant from the leachate can flow back to the intake of the WTP due to density flow. Re-risk assessment for possible countermeasures showed the structure modification and leachate treatment are effective to mitigate the risk for water quality hazards.

Keywords: Risk Assessment, Raw Water Quality, Water Quality Simulation, Water Safety Plan

1. Introduction

1.1 Background and Objectives

The Security of water safety for piped water is the important issue in Sri Lanka since the piped water coverage has been dramatically improved recently all over the country. Facing the end year of Millennium Development Goals (MDGs), In 2015, access to piped water on premises is 12% while it has been 34 in 1990, that is to say that the served population has been 3.5 times increased in only 25 year [1]. The water supply expansion also encompassed the change of water sources especially from groundwater to surface water. Population increase, urbanization and groundwater contamination such as fluoride and arsenic accelerated the surface water use as water sources. Thus the water safety of surface water source is increasingly important as the countries drinking water sources.

Surface water contamination is common and historically indigenous in Sri Lanka. The country has been historically doing indirect water reuse as typically described as “Tank Cascade System”. There are many lakes (Wewa) in midst of the rivers to store and diverge water to use for lives and irrigation [2]. The system is efficient in terms of the utilization of limited fresh water resources while it also definitely causes the risk of contamination. It is still common in Sri Lanka that untreated sewage and irrigation drainages inflows at the upstream river from the intake of downstream regions. As a result, algal bloom is reported in Kandy Lake which produces toxic substances which may not properly be dealt with solely by conventional water treatment [3]. Due to high population growth and economic development, this contamination issues are being important all over the country.

There are also increasing concern for contamination from more artificial point sources such as wastewater from factories and leachate from garbage dumping sites. Especially for wastewater from factories, it is of large public concern because of the serious accident at the Kelani River where large volume of oil and greases were discharged and affected 680,000 m3/day of water supply mainly to capital city, Colombo [4].

Facing these problems which could affect water safety of piped water sources, Water Safety Plan (WSP) has been currently introduced at a high speed. WSP is a participatory management approach for water supply systems which includes comprehensive risk assessment and management [5]. WSP has been widely implemented among water utilities all over the world. Despite the importance for practitioners, limited research publications are available. More scientific researches are needed for WSP because risk assessment may contain critical uncertainties without proper scientific approaches are applied.

Model studies are one of the possible tools to solve these problems on water safety plan because it gives scientific evaluation to the risk assessment and outputs visual results which could be understandable for the non-technical stakeholders. There is few previous study of water quality simulation for Sri Lankan water environment. One study in Kandy Lake mainly focused on the water environmental improvement for the lake [6]. The issue of previous simulation model was the complexity of the modelling procedure and updating practices. Since the water safety plan needs continuous review and update, it is critical that the model can be easily handled by the practitioners with familiar interfaces. Thus, simple, easy for handling and technically established methodology should be applied to the water quality modelling.

The objective of the study is (i) to review water quality issues in Sri Lanka from actual water safety plan and (ii) to establish appropriate simulation methodology for the risks at water source of all the water supply systems in Sri Lanka. We selected the Mahaweli River basin as a model case to utilize water quality model for WSPs.

1.2 Site Description

Mahaweli River is a longest river (335km) in Sri Lanka which also has the largest drainage basin in the country [7]. The river water is also a major water source of Kandy which is second largest city in the country. There are two major intakes for Water Treatment Plants (Kandy South WTP and Greater Kandy WTP) and two intakes for small WTP (Polgolla WTP and Kandy Municipal WTP). Both major WTPs formulated WSPs for each water supply system under the facilitation of National Water Supply and Drainage Board (NWSDB). Since there is no proper wastewater disposal system, untreated domestic sewage is released directly into the Mid-canal [8] and the Mahaweli River.

Gohagoda dumping site is one of the main dumping site of Kandy Municipal Council (**Photo 1**). The site started to dump waste since 1970s. The waste includes household, commercial, market, healthcare and industrial wastes. According to a previous research, “there are no environmental protections measures taken for solid waste disposal” [9]. The dumping site is located just adjacent to the intake site. There is the discharge point of the leachate from the dumping site at approx. 100 m downstream of the intake station for raw water (Figure 1).

1.3 Review of existing Water Safety Plan

We have reviewed the Water Safety Plan for Greater Kandy Water Supply System to identify the risk for water safety. In the identification of

Figure1: Gohagoda Dumping Site

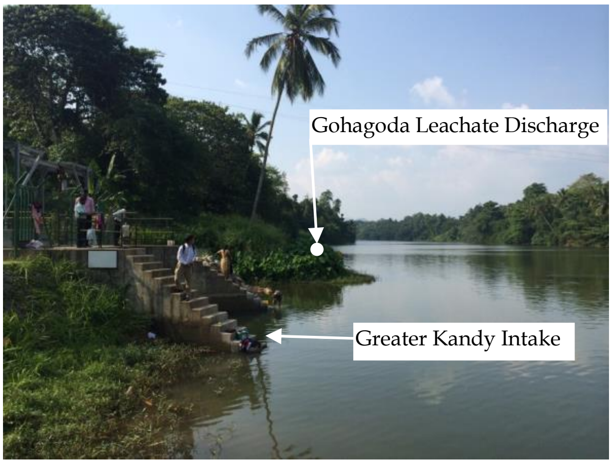

Figure 2: Intake of Greater Kandy Water Treatment Plant and Leachate Discharge Point

Table 1: Hazards of Greater Kandy WTP assessed as "Very High" Risks by assessment of raw risks

Location /Process step	Hazardous event	Hazard type	Residual Risk after Control Measures
Source	Pathogenic contamination from septic tanks and waste from Kandy city through Middle canal (Meda-Ela)	Physical/Chemical/microbiological	Very High
Source	Leachate from Kandy city garbage dumping site entering intake	Physical/Chemical/microbiological	Very High
Source	Pollution by agrochemicals during spraying season	Chemical	Very High
Distribution chamber	Power failure at WTP	Chemical & Microbial	Very High
Service reservoirs	Unauthorized personnel entering premises	Chemical & Microbial	Low
Pipe network	Contamination of treated water	Microbial	Very High

hazards and hazardous events and assessing the risks (module 3), six major risks are rated as "Very High" risks as raw risks (without control measures) (Table 1). Three of six risk incidents are of source problems such as the pollution from contaminated distributaries (Mid-canal), leachate from Kandy city dumping site (Gohagoda dumping site) and possible agrochemical contamination. The risks were evaluated by water quality record or observation. In this study, we focus on the leachate from Gohagoda dumping site, because the problem is likely to be most unknown matter in terms of possibility of incidents.

2. Materials and Methods

2.1 Model Framework

1) Overall Model Framework

The study area is Mahaweli River including Mid-canal and Kandy Lake as shown in Figure 3. After the confluence with the Mid-canal in the Mahaweli River, there is the reservoir created by Polgolla Barrage for the purpose of hydropower, irrigation and water supply. In Polgolla Reservoir, there is the intake station for Grater Kandy WTP, which raw water quality may be affected by leachate from Gohagoda dumping site.

Figure 3: Study Area

The overall model framework in this study is shown in Figure 4.

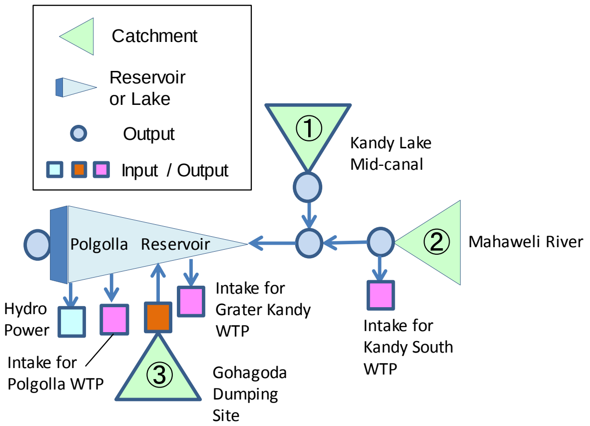

Figure 4: Overall Model Framework

2) Vertical Two Dimension Model for Reservoir

To analyze hydraulic and water quality situation in reservoir, the vertical two dimension model was applied under assumption of hydrostatic pressure distribution (Figure 5). This simulation model can calculate the distribution of water temperature and water quality from hydraulic variables in vertical and flow direction. The vertical two dimension model consists of hydraulic model and water quality model.

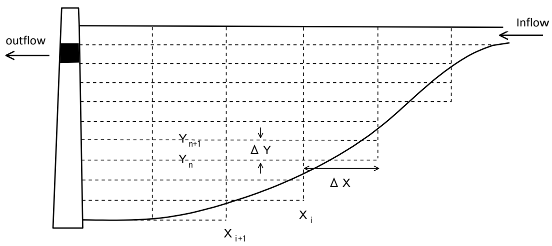

Figure 5: Mesh Division for Reservoir

a. Hydraulic Model

As for hydraulic model, hydraulic variables (e.g. flow velocity) are calculated from equation for continuity and equation for conservation of momentum.

i) Equation for Continuity

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}=0 \qquad (1)$$

ii) Equation for Conservation of Momentum

$$\frac{\partial \bar{u}}{\partial t}+\frac{\partial}{\partial x}\left(\overline{uu}\right)+\frac{\partial}{\partial y}\left(\overline{uv}\right)=-\frac{\partial}{\partial x}\left(\frac{P}{\rho}\right)+\frac{\partial}{\partial x}\left(A_x\frac{\partial \bar{u}}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_y\frac{\partial \bar{u}}{\partial y}\right) \qquad (2)$$

$$\frac{\partial P}{\partial y}=-\rho g \qquad (3)$$

Where x and y: coordinate in flow and vertical direction, u and v: flow velocity in x and y direction, ρ: water density ($\rho = \alpha T^2+\beta T+\gamma$; α, β, γ: constant, T: water temperature), P: pressure, t: time, A_x and A_y: coefficient of eddy viscosity in x and y direction.

The density flow is analyzed through calculating of density depending on water temperature.

b. Water Quality Model

As for water quality model, water temperature and water quality are calculated from equation for concentration balance including advection and diffusion.

i) Equation for Temperature Balance

$$\frac{\partial T}{\partial t}+\bar{u}\frac{\partial T}{\partial x}+\bar{v}\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{H}{\rho C_w} \qquad (4)$$

ii) Equation for Water Quality Balance

$$\frac{\partial C}{\partial t}+\bar{u}\frac{\partial C}{\partial x}+\bar{v}\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+S \qquad (5)$$

Where T: water temperature, H: unit volume, C_w: absorbed heat by solar insolation, t: time, K_x, and K_y: diffusion coefficient for temperature in x and y direction, D_x and D_y: diffusion coefficient for water quality in x and y direction, S: term for water quality variation in ecological model.

Term for water quality variation is calculated from the ecological model as shown in Figure 6 including growth of phytoplankton by intake of nutrient (nitrogen and phosphorus).

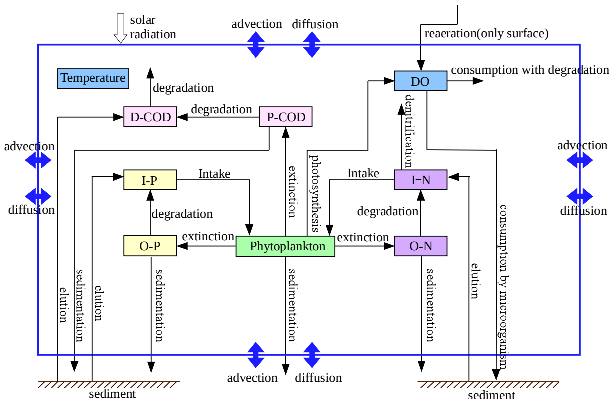

Figure 6: Ecological Model

3) Catchment Model

The discharged water quality (COD, nitrogen and phosphorus) from catchment is calculated from the annual pollution load from nom-point and point sources (Figure 7). The annual pollution load is calculated from residential and tourist population, and land use. The daily discharged water quality is calculated through L-Q (Load-Quantity of flow) equation which parameters are identified by annual pollution load and observed water quality. The impact of load reduction measures in catchment including installation of sewerage system can be evaluated by this catchment model.

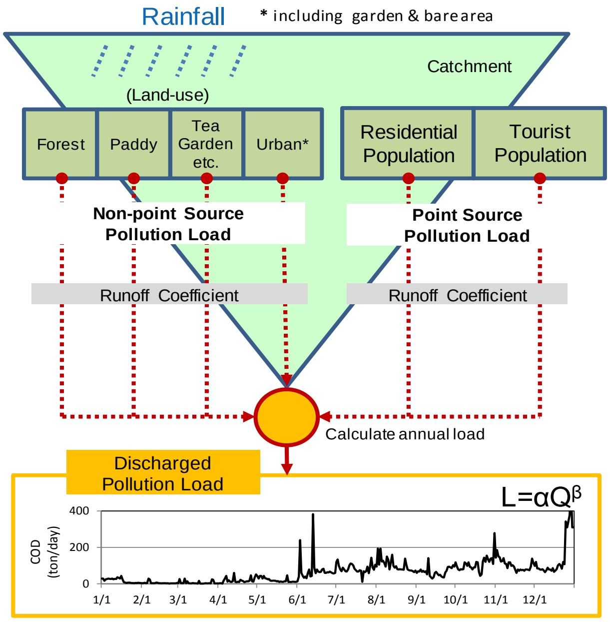

Figure 7: Catchment Model

(2) Datasets

The calculation conditions for Polgolla Reservoir are shown as follows. All the datasets were provided by courtesy of the water environment laboratory of the Department of Civil Engineering, University of Peradeniya.

1) Topographical Condition

Polgolla Reservoir which length is 7.5 km was divided into meshes at intervals of 0.5 km in flow direction and 1.0 m in vertical direction (Figure 8).

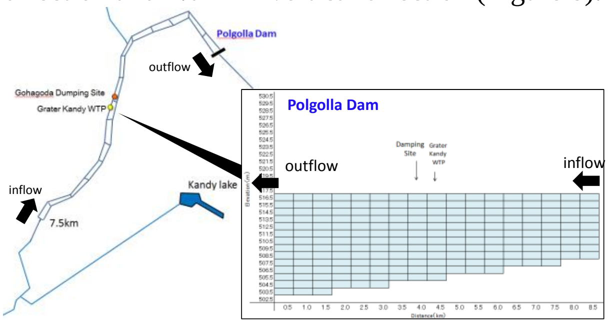

Figure 6: Mesh Distribution

2) Meteorological condition

The average meteorological condition (e.g. temperature, solar insolation, relative humidity, wind velocity and cloudiness) was set according to monthly meteorological data observed in Kandy and nearby cities.

3) Hydrological Condition

The inflow condition for Polgolla Reservoir was set according to the actual record of inflow volume in year 2014. The hydrological condition in 2014 corresponds to dry year in recent 7 years.

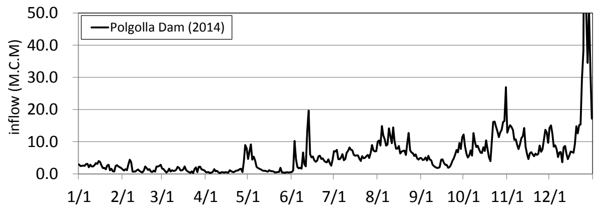

Figure 9: Inflow Condition

4) Water Quality Condition

The target items for water quality simulation are water quality items calculated by ecological model shown in Figure 6 (COD, nitrogen, phosphorus, DO and etc.) and heavy metals (lead (Pb) and zinc (Zn)). The water quality condition was set according to discharged water quality calculated through the catchment model. The concentration of Pb and Zn was set according to the observed data of Mahaweli River and leachate water of Gohagoda dumping site. It is necessary to set more accurate and detailed water quality condition through water quality monitoring and data accumulation.

Table 2: Water Quality Condition

	①Inflow from Kandy Lake	②Inflow from Mahaweli River	③Leachate from Gohagoda Damping Site
Catchment Area (km^2)	255	1063	0.06
Discharge Volume (m^3/s)	13.1	54.6	0.006
COD (mg/L)	22.4	8.0	700
T-N (mg/L)	5.9	1.9	700
T-P (mg/L)	1.1	0.4	8.0
Pb (mg/L)	0.005	0.005	12.9
Zn (mg/L)	0.145	0.145	700

2.3 Interface of Simulation Model

We developed hydraulic model and water quality model for Polgolla Reservoir, which can configure input and output data on Microsoft Excel interface. Users can easy to handle the simulation model (e.g. change of input data and evaluation of simulation results).

3. Results and Discussion

3.1 Simulation Results for Water Intake Quality

The current water intake quality in 2014 was calculated through the water quality simulation model developed by this study. Figure 10(A) and (B) show the simulation results in Polgolla Reservoir. The simulation result shows that substances in leachate discharged from dumping site can flow back to upstream by approx. 2 km.

The phenomena can be explained by the density flow due to water temperature differences in the reservoir. The water temperature between surface and bottom layer in the reservoir is different due to sunshine and low flow volume especially in the dry season. Then the difference in temperature makes density flow including following flow in middle layer and backflow in surface and bottom layer. As a result, the contaminated substances discharged from dumping site can flow back to upstream mainly by density flow.

Figure 11 shows the annual variation result of Pb for water intake quality at Grater Kandy WTP. The result shows Pb concentration at water intake is higher than background value in the Mahaweli River throughout the year. The concentration in the dry season (January to April) is especially higher than that in the rainy season. The result also shows that seasonal variability of the contamination level results from the backflow of contaminated substances in leachate from dumping site.

As a result of the simulation, it was implied that the contaminant from the leachate can flow back to the intake of the WTP due to density flow. The simulation results of Pb and Zn don’t exceed the WHO guideline values. However, there is a possibility that the actual contaminant concentration of intake water is higher than simulation results, because the water quality conditions in this study were set by constant values due to lack of detailed monitoring data.

It is necessary to conduct detailed water quality monitoring in reservoir and leachate of dumping site for not only contaminated substances but also water temperature in vertical direction for evaluation of density flow. Through the water quality monitoring, accuracy of simulation model can be improved and more detailed impact on intake water quality can be evaluated.

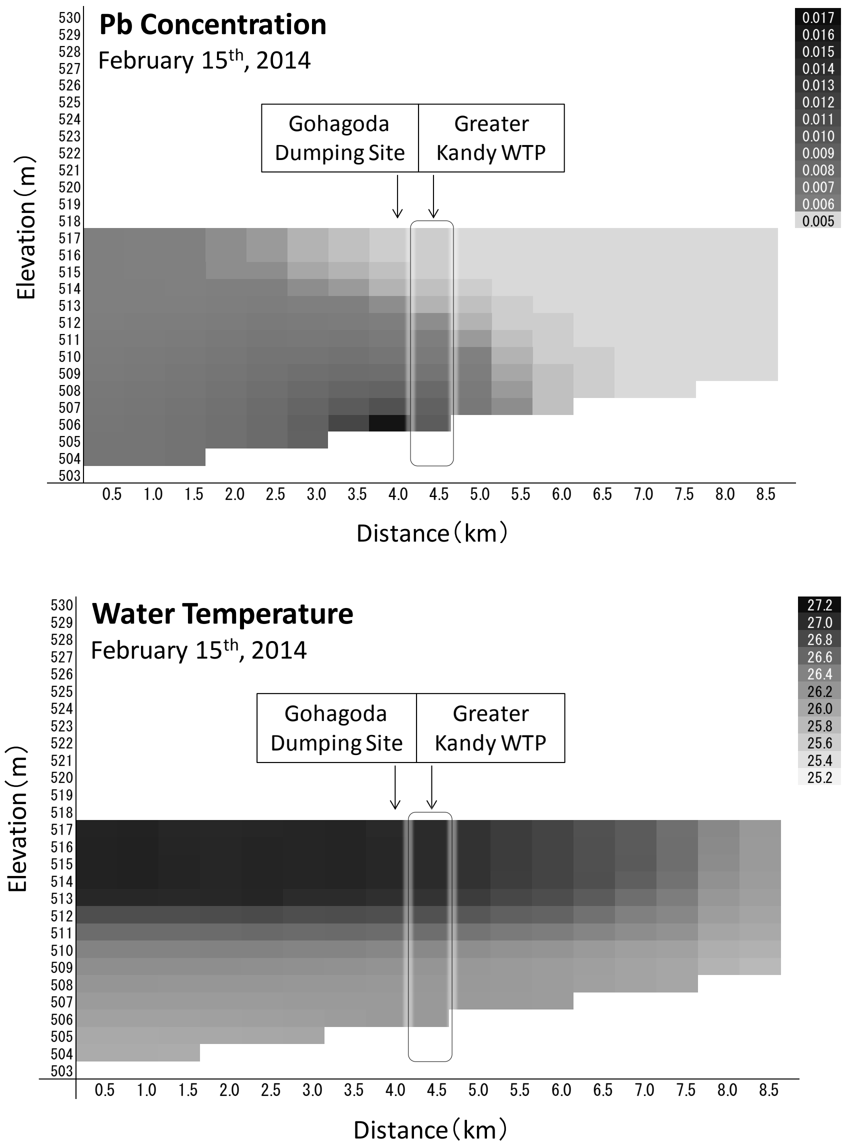

Figure 10: (A) Simulation Result of Water Quality Distribution,
(B) Simulation Result of Water Temperature Distribution

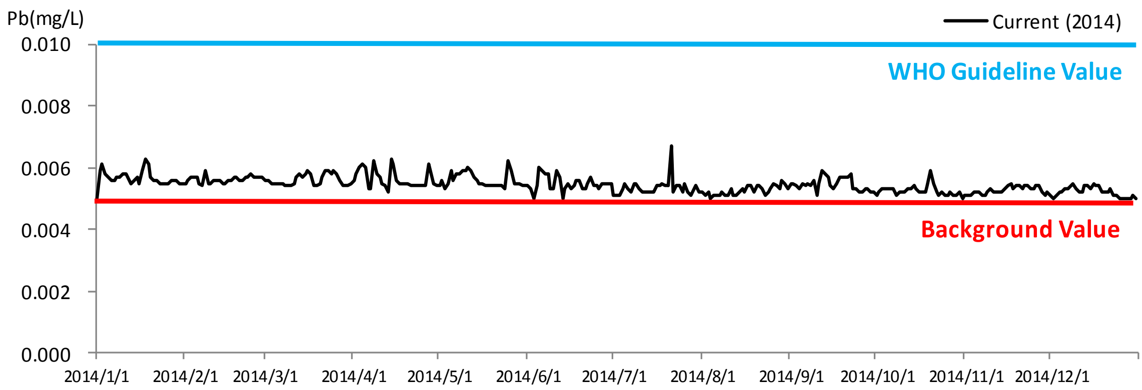

Figure 11: Simulation Result of Pb Annual Variation

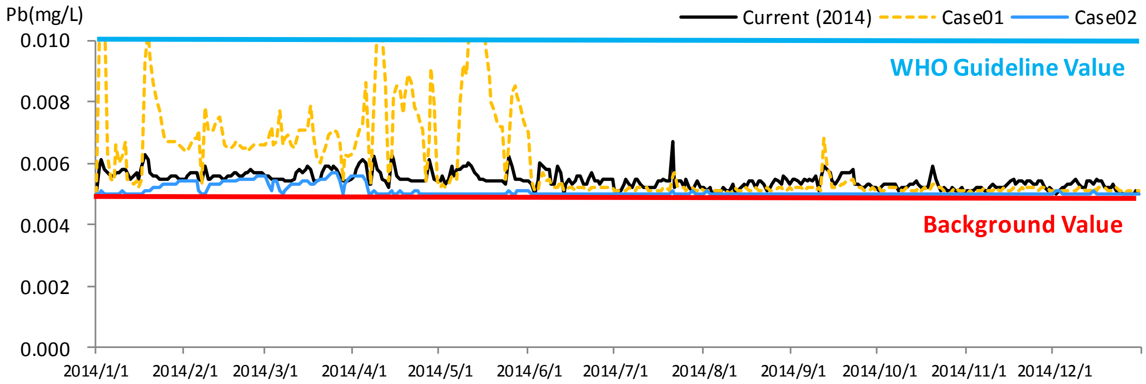

Figure 10: Simulation Result of Pb for Control Measures

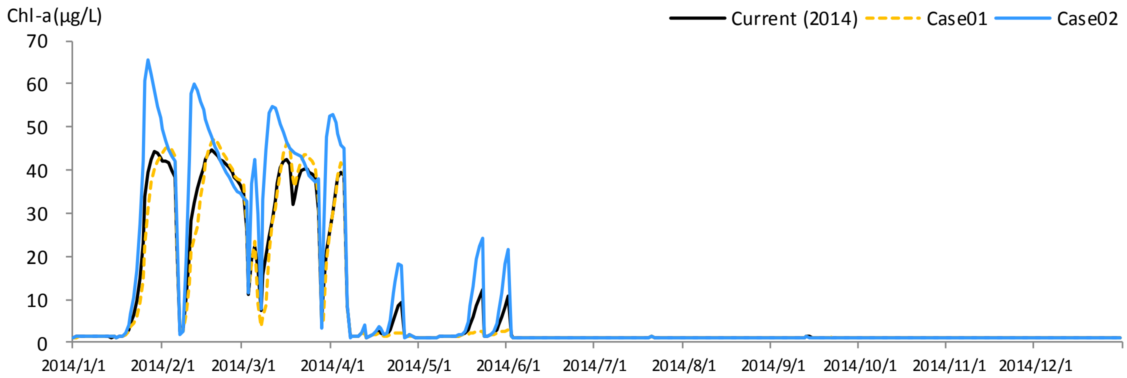

Figure 13: Simulation Result of Chl-a for Control Measures

3.2 Control Measure Identification and Re-risk Assessment

To assess possible control measures for mitigation of the risk for intake water quality hazards, the impact on improvement of intake water quality by the following 2 control measures was calculated through the developed simulation model.

Table 3: Control Measures

Case	Control Measure
Case 01	Installation of fence in bottom layer
Case 02	Intake of raw water from surface layer

As for Case 01 (installation of fence), the intake water quality of Pb goes over 0.01 mg/L while the maximum concentration of the baseline case (without any countermeasure) is about 0.006 mg/L (Figure 12). The results shows the water quality could be worsen by the countermeasure in terms of heavy metals. The possible explanation is that the backflow in surface layer increases and contaminated substances in surface stay longer in bottom layer at intake location.

As for Case 02 (intake from surface), the intake water quality of Pb is lower than that of baseline case throughout the year. Thus it is implied that intake of raw water from surface is effective control measures to mitigate the risk for intake water quality hazards. The improvement can be explained by the fact that the contaminant concentration in surface layer is lower than that in bottom layer due to density difference. However, the intake water quality of Chl-a (chlorophyll-a) in Case 2 was increased in the dry season (Figure 13) due to growth of phytoplankton. Thus it is necessary to care the impact on water treatment by increase of phytoplankton.

In these two assessments of countermeasures, Case 02 was implied to be effective in terms of improving heavy metals water quality while it may affect the risk of toxic substances formulated by phytoplankton in raw water. We could not attain the conclusion that some realistic countermeasures can surely reduce the risk. Possible other effective alternative for the countermeasures is the installation of leachate treatment facility in the dumping site. The method is more direct and effective control measure while there are many stakeholders and complicated process for implementation. The flashing discharge from lower gate at Polgolla Barrage is also effective control measure. In that case, it is necessary to prepare the proper operation rules for gates in the barrage.

In this research, we could not reach quantitative re-risk assessment utilizing the results because the concentration of modelled substances (Pb) did not go beyond the WHO guideline level and thus it is less likely harmful for human body. More research is needed for identifying the possible harmful substances such as agro-chemicals, carcinogenic substances and other unknown substances. Re-risk assessment for possible countermeasures through water quality simulation could show the structure modification and leachate treatment might be effective to mitigate the risk for water quality hazards.

4. Conclusions

The challenge for water safety was reviewed and some practical tools to assess the risks of water safety were developed. We have attained following conclusions in this study:

1) From a review of Water Safety Plan of a water supply system (Greater Kandy WTP), water source issues are evaluated as "Very High" because of the unavailability of observed data. Contamination backflow of the leachate from the adjoining solid waste dumping site was identified one of the critical and unknown risks.

2) Water Quality Simulation model for Pollgolla Reservoir was developed to evaluate the risks to water safety. The simulation model was proven to be effective to show the result visually and logically. It was implied that;

- Leachate contamination can flow back by 2km due to density flow.
- Fences at Intake (Case 01) have implied to have adverse impact on water quality and Intake at surface (Case 02) found to be effective while it has the concern to be more affected by toxic phytoplankton.

Acknowledgement

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