

PREDICTING THE IMPACT OF CLIMATE CHANGE ON A WATER SUPPLY RESERVOIR

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ABSTRACT

Climate change is acknowledged to affect hydrological processes and water resources sustainability. Predicting the impact of changing climate on reservoir water quantity and quality is necessary to ensure adequate supply of reasonable quality of raw water. An integrated hydrological and catchment management model is developed for Sg. Terip Reservoir using Infowork Integrated Catchment Model by means of hydrology Probability Distributed Moisture model to simulate the changes of reservoir inflow and capacity, and quality. Rainfall data at three nearby stations are used to calibrate the hydrological model over the period of 2010-2013. Future hydroclimate projection data at the lake catchment based on the downscaled of coarse resolution global climate model projection to 6km grid resolution by means of a regional hydroclimate model over Peninsular Malaysia are used to simulate the climate change impact on the water balance and water quality. The existing water balance of Sg. Terip reservoir is largely impacted by the river water abstraction at the nearby water supply intake and the water source from two water transfer schemes. Inflows from main tributaries are small. Existing water quality assessment showed good water quality throughout the measurement period. Long droughts will have large impact on the reservoir storage capacity. Impact assessment is carried out based on 3 time slices: 2010-2040, 2040-2070, and 2070-2100. Hydroclimate projection under the worst case scenario, IPCC SRES A1FI of the global circulation model - CCSM3 shows that the lake catchment will receive lower rainfall amount in the mid of 21st century (2040-2070) and higher rainfall amount at the end of the 21st century (2070-2100). Simulation results indicate that lake water quality will change only slightly with alteration in these future rainfall events due to low pollution sources. Reservoir water quality may be influenced by the quality of water transferred into the water body.

Keywords: Drought; lake basin; hydrology; hydrodynamic model; water transfer.

1 INTRODUCTION

Water supply reservoir has been continuously created for storage of water to support socio-economic developments. In Malaysia alone, more than 60 reservoirs have been constructed to date for water supply purposes since the first dam was built in 1896 (NAHRIM 2016). The size of the water supply reservoir ranges between 0.05 to 695 km² (NAHRIM 2016). The water availability and storage capacity of these reservoirs are very much shaped by the meteorological conditions and water abstraction. Changes in climate are expected to alter water availability by altering the hydrologic cycle, specifically precipitation and evapotranspiration, and other meteorological parameters such as temperature subsequently affects water balance and quality in the water bodies. A study in the Great Lakes region, for example, showed that a change in climate and land use affects the regional hydrology by increasing the percentage of precipitation resulting in increased surface runoff from 17.1% to 21.4% (Barlage et al., 2002). Similarly, projected climatic changes will lead to significant hydrologic response in the Californian Mono Lake Basin including more frequent droughts that ranges from 15% to 22%, a decrease up to 15% in occurrence of wet hydrologic years and a decrease by 15% of annual stream flows (Ficklin et al., 2013). Such changes in hydrological patterns will eventually affect water quality in the reservoirs including increase in nutrient run-off, alteration in thermal stratification and frequent algal bloom (Sahoo et al., 2013; Trolle et al., 2011). In Peninsular Malaysia, a downscale of the regional hydroclimate model predicted significant changes in rainfall pattern over the Peninsula (Amin et al., 2017; Shaaban et al., 2012). How these hydrologic changes affects water bodies in particular the water quality has not been investigated.

As water supply reservoirs were created based on past hydrology and water resources studies, the impact of climate change may not be incorporated in the original dam design. For example, a low rainfall pattern resulting from climate change may lead to water scarcity in the reservoir while an extreme rainfall event may disrupt the dam ability to store water and lead to excess water release or downstream flooding. Understanding how future climate change affects water quantity and quality in a reservoir is the goal of this study. Sg Terip reservoir in the Linggi Basin is one of the water supply reservoirs in Malaysia that is located within the water stress areas. The reservoir supplies water to 800,000 people in the district of Seremban and Nilai in Negeri Sembilan. The reservoir has recently been affected by frequent droughts induced by El Nino effects which affect its storage capacity. The lake water quality was reported to be in good condition while trophic state was within the mesotrophic to eutrophic in 2012 (Sharip et al., 2014).

The main objective of this study was to investigate the impact of future climate change, specifically rainfall pattern on the water balance and water quality of the water supply reservoir in tropical setting. The work is based on the development of an integrated catchment model comprising hydrological model and water quality model of a lake catchment.

2 STUDY AREA

This research was carried out in Sg Terip Reservoir, Negeri Sembilan ($102^{\circ} 00' 17''$ E, $2^{\circ} 45' 30''$ N). The reservoir was selected as research site due to the 2014 state water crisis where water level drops to the critical level. Sg Terip reservoir was created in 1987 for water supply purposes. It has a total surface area of 2.43 km^2 and catchment area of 25.9 km^2 . The dam has a full supply level at 103 m above sea level corresponding to 47.7 MCM while the minimum operating level is 79.9 m above sea level contributing to an active storage of 44 MCM (SAINS 2010). The reservoir received water from three tributaries namely Sg Anak Buaya, Sg Terip and Sg Gantor. Two water transfer schemes provide source of water to Sg. Terip reservoir namely the Kelinchi-Talang Reservoirs (98 MCM) and Triang water supply scheme. The existing water balance of Sg. Terip reservoir is largely impacted by the river water abstraction by the nearby water supply intake (Sg. Terip Water Treatment Plant, 136 Mld) and the water source from the transfer schemes.

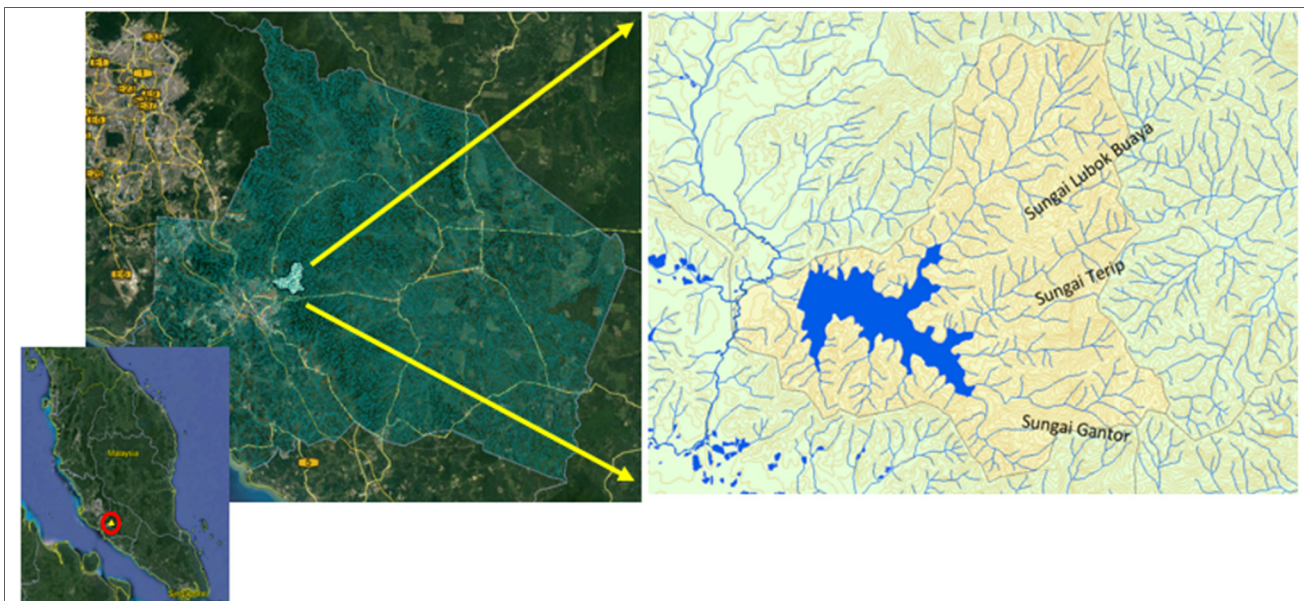


Figure 1. Sg Terip reservoir and its catchment. Inset the study location.

3 MATERIALS AND METHODS

3.1 Data collection

Water quality sampling was carried out in 2014 and 2016 involving measurement of physico-chemical parameters such as temperature, dissolved oxygen (DO), pH and turbidity using multi-parameter probe (YSI 6600) and water sampling. Sampling in 2014 was carried out once while sampling in 2016 was performed about 3-4 times. All sampling was done during the dry period. Water samples were analyzed for nitrate, ammonium suspended solids and phosphorus.

Bathymetric survey was carried out in September 2014 using a single-beam Reson-210 model of echo sounder unit. Depth soundings were acquired along 2.5 km^2 spaced at 100m intervals. In addition, a cross-lane was also established perpendicular to the main survey lines with symmetry with the survey lines to provide the cross-check comparison data needed to evaluate the consistency of the bathymetric data.

Temporary tide level observation station was established near to the over-section Sg Terip Dam. All the measured tidal data corrected with the TBM value that lied from the Department of Survey and Mapping Malaysia's Temporary Bench Mark (TBM) to the tidal monitoring site. Rainfall and water level data were obtained from the Drainage and Irrigation Department of Malaysia and Syarikat Air Negeri Sembilan (SAINS). Rainfall data at three nearby stations (Kg Baru Pantai, Setor JPS and Ulu Bendul) were checked with rainfall data measured near the Sg Terip dam. Rainfall data were processed and analyzed for missing values and areal estimates. Water level data between 2003 and 2009 were assessed to understand trend and pattern of existing water balance.

3.2 Model development

The model platform utilized for this research is the Infowork two-dimensional Integrated Catchment Model (ICM) together with of the hydrology Probability Distributed Moisture (PDM) model, developed by HR Wallingford-CEH. ICM simulated the hydrodynamic flow and water quality pattern in the reservoir while the PDM model simulated the hydrology of the catchment taking into consideration the continuous rainfall and soil moisture (Moore, 2007). The 2-D ICM model is based on the shallow water equations known as the depth-average version of the Navier-Stokes equations, Eq. [1-3] assuming that the flow is predominantly horizontal while the variation of the velocity over the vertical coordinate is negligible (Innovyze 2015).

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = q_{1D} \quad [1]$$

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x} \left(hu^2 + \frac{gh^2}{2} \right) + \frac{\partial(huv)}{\partial y} = S_{0,x} - S_{f,x} + q_{1D}u_{1d} \quad [2]$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial}{\partial y} \left(hv^2 + \frac{gh^2}{2} \right) + \frac{\partial(huv)}{\partial x} = S_{0,y} - S_{f,y} + q_{1D}v_{1d} \quad [3]$$

where,

h is the water depth; u and v are the velocities in the x and y directions;

$S_{0,x}$ and $S_{0,y}$ are the bed slopes in the x and y directions;

$S_{f,x}$ and $S_{f,y}$ are the friction slopes in the x and y directions;

q_{1D} is the source discharge per unit area; U_{1D} and V_{1D} are the velocity components of the source discharge q_{1D} in the x and y directions, respectively

Long duration continuous rainfall runoff model using PDM, which is available in InfoWorks was used for hydrological analysis. The hydrological analysis aimed at determining the rainfall-run off within the catchment which flows into the lake. The runoff from the sub-catchment will then be used as input to the 2D lake model. The catchment was divided into 29 sub-catchments to provide inflow from various tributaries (Figure 2). The water flowing directly to Sg Terip reservoir from Kelinchi through tunnel was included as inflow into the lake while the water abstracted to Sg Terip water treatment plant was included as outflow from the lake. Inflow from Triang Dam which was piped to Sg Terip reservoir since middle of 2016 was not included for model calibration. The survey data were imported into the ICM as ground model and interpolated using mesh technologies to capture the variation of the lake shape.

The water quality model process as described in Toriman et al. (2011) is simulated in 2-dimensional setting in ICM. Water quality determinants configured includes temperature, dissolved oxygen, pH, and nutrients such as nitrate, ammonium and total phosphorus.

3.3 Model calibration and future climate projection

The model was calibrated based on rainfall data at three nearby stations and water level data for the period of 2010-2013. This calibration period was chosen due to availability of reasonably quality rainfall data. We used future hydroclimate projection data at the Sg. Terip catchment based on the downscaled of coarse resolution global climate model projection to 6km grid resolution to simulate the climate change impact on the water balance and water quality. The downscaled model was based on a regional hydroclimate model over Peninsular Malaysia developed by the National Hydraulic Research Institute of Malaysia (NAHRIM 2014a). Impact assessment was carried out using the hydroclimate projection under the worst-case scenario, IPCC SRES A1FI scenario of the global circulation model - CCSM3 and was based on 3 slices period: 2010-2040, 2040-2070, and 2070-2100.

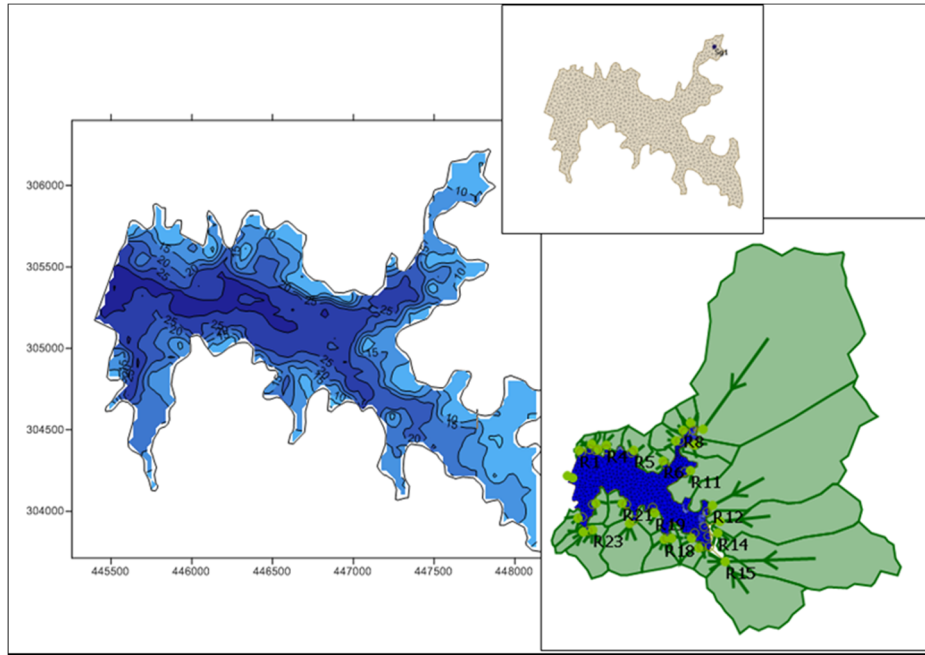


Figure 2. Bathymetry and two dimensional hydrodynamic and catchment model set up for Sg Terip reservoir.

4 RESULTS AND DISCUSSIONS

4.1 Measurement and calibration

Measurement over the period of July to October 2016 showed mean total inflows from main tributaries were small ranging between 0.8 – 2.8 m³/s. These low inflows were very much influenced by small catchment and long drought. Mean annual rainfall in 2016 was 1876.5 mm compared to mean rainfall in 2015 (1911.1 mm). Figure 3 shows the variation of annual rainfall in all four stations. Average rainfall is about 2000 mm/year.

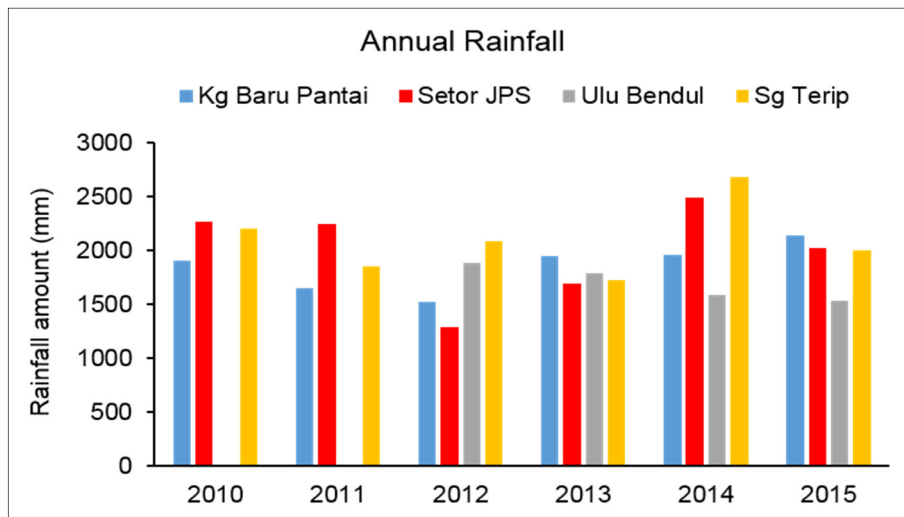


Figure 3. Annual rainfall at few stations near Sg Terip reservoir.

The calibration process for the PDM uses similar approaches as described in Azad et al. (2016) which include analysis of rainfall data, correlation between rainfall data and water level and rainfall factor. In this study, the calibrated parameter consists of rainfall factor, moisture storage distribution and time constant for surface flow. Model calibration showed reasonable match to the measured water level (Figure 4). However, it under-estimated the water level during the dry season likely due to differences in areal rainfall pattern, surface water evaporation and varying amount of water abstraction.

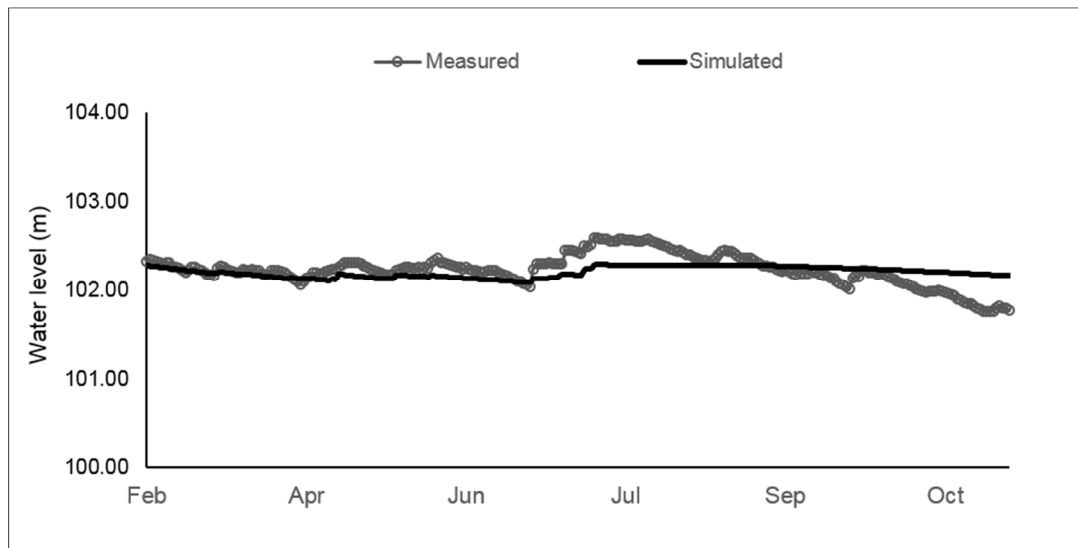


Figure 4. Measured and simulated water level in 2010.

4.2 Existing conditions

4.2.1 Water quantity assessment

Based on the annual dam water level, the water level during 2016 was the lowest compared to the water level between 2010 to 2015 but showed similar trend of water level pattern for 2015 (Figure 5a). The water level in 2016 was about 2 m lower than the water level in 2015. Lower water level in 2016 could also be related to the small increase in dam level in 2015 which was likely to be related to longer dry season. Low water level in 2015-2016 were similar to the low water level in 2003-2006 (Figure 5b). Three-year water level of 2011-2014 showed similar pattern with three-year water level of 2007-2010 with no significant monthly variations.

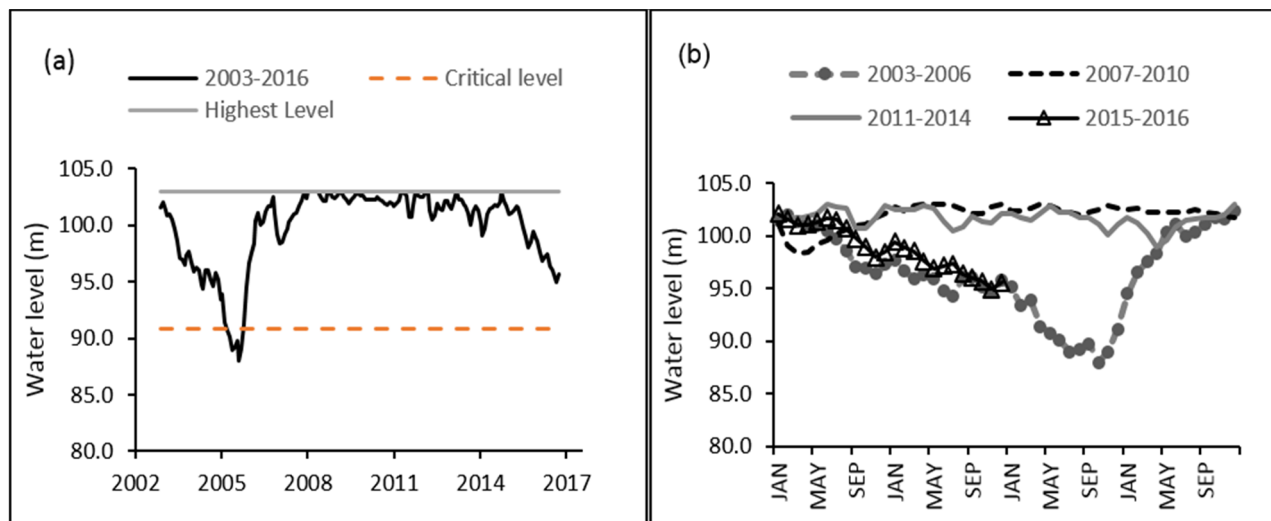


Figure 5. Pattern of reservoir water level over the period of 2003 – 2016 (a) long-term annual (b) three-year.

4.2.2 Water quality assessment

Existing water quality assessment showed good water quality condition throughout the measurement period. Mean values for temperature, DO, pH and turbidity were 30.5 °C, 7.8 mg/L, 6.8 and 5.1 NTU respectively. Based on the Department of Environment Water Quality Index (WQI), the overall water quality in Sg Terip Reservoir was at Class II or clean with WQI ranging between 90 and 93. Water in the lake was observed to be clear and good transparency. Chlorophyll concentrations were generally low in this reservoir (<10 µg/L), with mean value of 3.72 µg/L and higher value >5 µg/L occurred at around 5 m depth. This is consistent with transparency of about 1.5m where photosynthetic active radiation may be penetrated to deeper water column to provide the light environment for plankton growth. However, low nutrient levels may limit growth of plankton communities. TP concentration fluctuated from 0.01 to 0.24 mg/L. Chlorophyll-a and TP values reported in this study are consistent with prior findings (Sharip et al., 2014). However, transparency level was much lower compared to the transparency value of 2.7 m reported in 2012 (Sharip et al., 2014).

Vertical temperature profile in 2016 showed isothermic conditions indicating the non-existence of thermal stratification likely due to the artificial de-stratification system. DO remained above 4 mg/L in the surface layer until depth ~20m. Depth below 20 m has low DO nearing hypoxic conditions. Horizontal and vertical variation of water quality is shown in Figure 6.

The water quality of the incoming water is mostly clean. The stream temperature is colder < 29°C and transparent indicating undisturbed catchment. The estimation of sediment loading based on measurement of three main tributaries namely Gantor, Anak Buaya and Terip rivers in 2016 showed TSS load ranging between 0.13 to 2600 kg/d while TP and nitrate load ranged between 0.04 to 31.4 kg/d. Higher turbidity was recorded in water from Triang river that transferred into the reservoir (unpublished data SAINS). However, water quality in nearby areas measured between the period of September – November 2016, after the pipe is in operation, showed mild increase in nutrient and TSS.

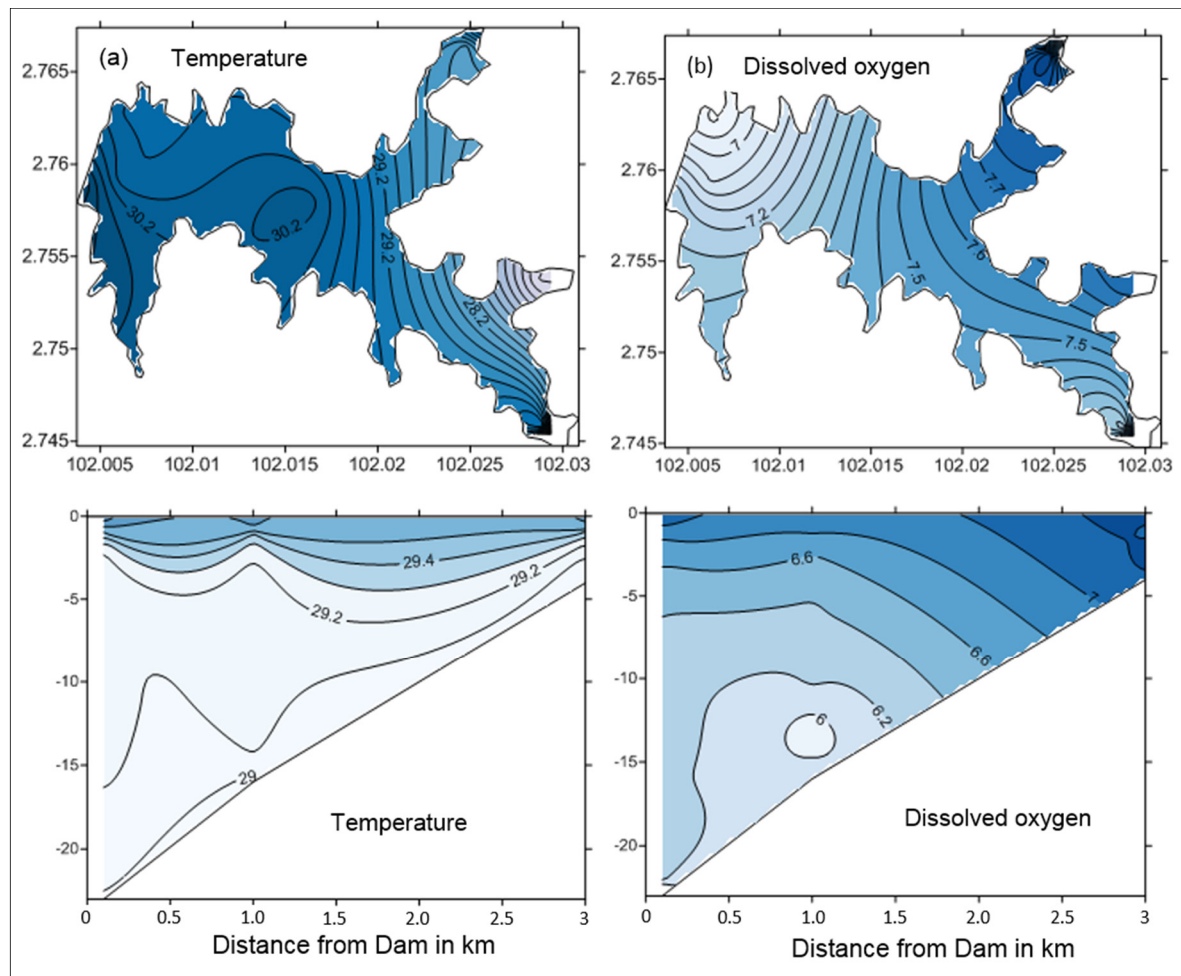


Figure 6. Horizontal and spatial variation of water quality.

4.3 Conditions under future climate projection

4.3.1 Water quantity assessment

Rainfall pattern during future hydroclimate period using IPCC SRES A1FI scenario is shown in Figure 7. Based on hydroclimate projection under the worst case scenario of the global circulation model - CCSM3, Sg Terip lake catchment will receive lower rainfall amount in the mid of 21st century (2040-2070) and higher rainfall amount at the end of 21st century (2070-2100). The mean and maximum rainfall amount during the mid 21st century was 2.8 mm and 225 mm per day, while the mean and maximum rainfall amount during the end of 21st century was estimated at 6.6 mm and 689 mm per day respectively.

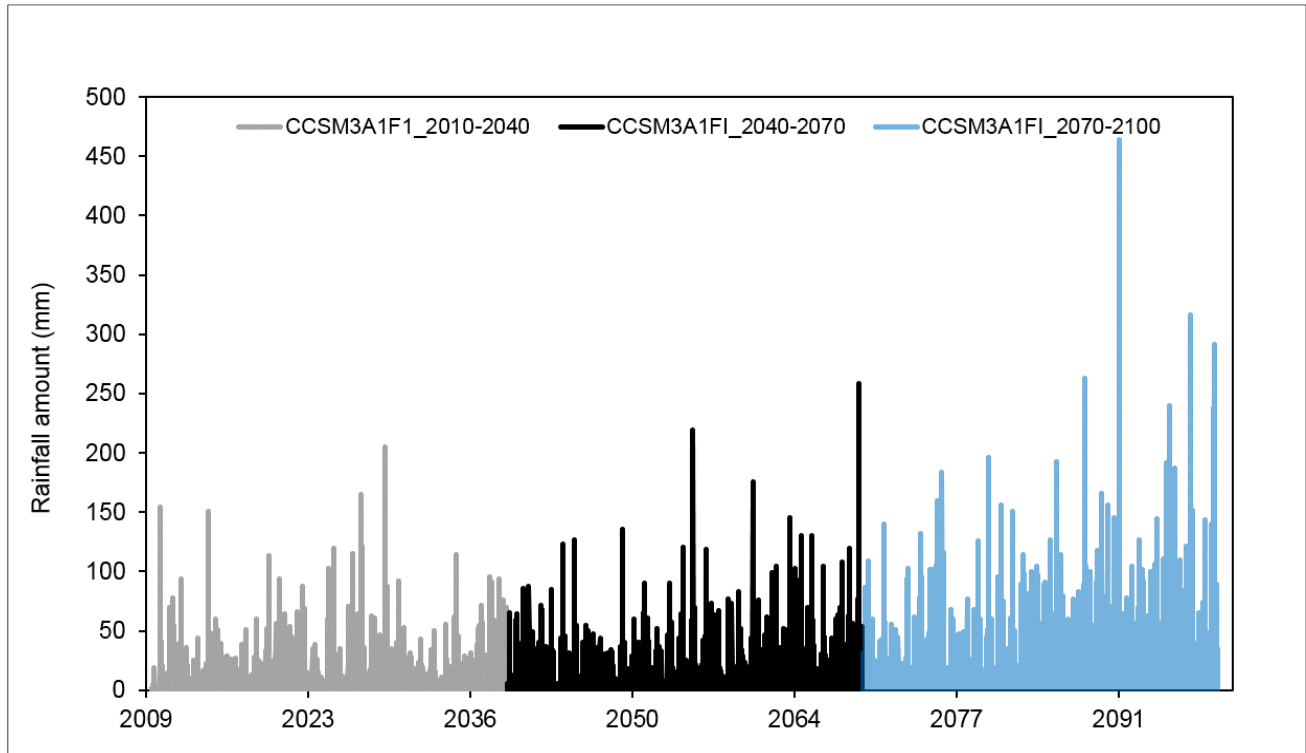


Figure 7. Daily rainfall pattern during future hydro-climate period.

Under the present inflow, future climate projection during 2040-2070 will lead to a decrease in water level below the 100 m above sea level while future climate projection during 2070-2100 will lead to increase in water level exceeding 104.9 m. The simulated water level pattern during 2040-2050 and 2090-2100 is shown in Figure 8. The drop in water level to 98 m above sea level which is equivalent to 80.7% of storage capacity. This value is still high compared to the lowest dam level recorded at 87.64m which was registered on 6 October 2005 (unpublished data, SAINS). Lower water level such as observed in 2005 and 2016 could be associated to lower rainfall within the catchment, higher evaporation rate in the lake and higher water abstraction. The varying changes in evaporation rate, which is associated to temperature, and changes in the amount of water transfer and intake need to be included to improve further the model.

Future climate change projection 2070-2100 suggest that frequent flood will occur especially during 2092-2100 resulting from simulated water level exceeding the spillway level of 103 m above sea level. The excess water can be tapped for future use, and is recommended to be stored in bunded storage to avoid flood to downstream areas. This is consistent to an earlier study that predicts flooding as a major problem for the Sg Terip reservoir (NAHRIM 2014b). The earlier study which simulation was based on HEC-RESSIM model also reported that the reservoir will be free of drought, defined as the simulated water level exceeding the dead storage level (NAHRIM 2014b). This work assume no changes in reservoir storage and catchment land use. The reservoir storage will change with time and land use due to deposition of sediments from eroded catchment areas. However, this effect was not consider in the analysis.

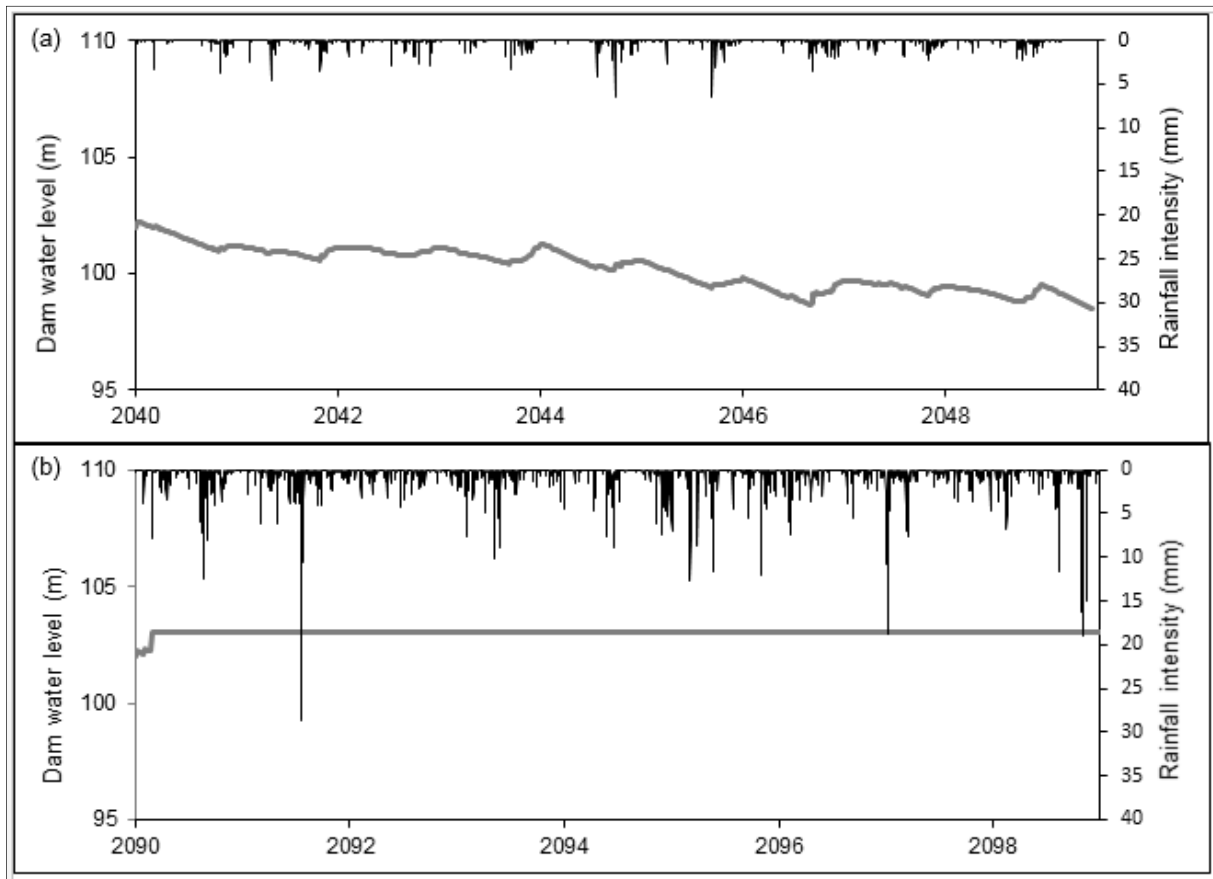


Figure 8. Rainfall pattern and dam water level during future hydro-climate (a) period 2040-2050 (b) period 2090-2100.

4.3.2 Water quality assessment

Simulation results indicated that lake water quality will change only slightly with alteration in these future rainfall events due to low pollution sources. The water quality simulation shows small changes in water quality and pollutant transport due to very slow water movement and flow within the lake, and low pollution levels. Surface DO concentration remains above 7 mg/L under the future climate projection during 2040-2070 and 2070-2090. High DO is probably associated to the atmospheric flux and low oxygen demand due to moderate biological productivity. Higher rainfall amount under the climate projection during 2070-2100 may weaken potential intermittent stratification and improve the water quality through frequent flushing effects. Stratification dynamic, however, was not modelled in this study. Under the assumption of intact catchment, deterioration in water quality will remain small for this reservoir. Some studies reported that increased rainfall associated with climate change will result in increase in suspended and nutrient loadings (Riverson et al., 2013; Mooij et al., 2007). In this reservoir, water quality, however may be influenced by the quality of water that transfer into the waterbody.

5 CONCLUSIONS

Simulation results indicated that flood will occur resulting from excess in rainfall during the end of 21st century while drought will occur resulting from low rainfall amount during the mid of 21st century. Water quality simulation indicated slight change with alteration in these future rainfall events due to low pollution sources. Reservoir water quality may be impacted by the quality of water transferred into the waterbody. This study explores the prediction of the impact of extreme future hydroclimate projection on the condition of a water supply reservoir. However, the results of the study need to be verified further with flood rule curve and probable maximum precipitation/flood in order to enhance the model findings. Further testing of the model with other hydroclimate projection scenarios is also necessary and currently been undertaken to improve the model results and enhance the usefulness of the model for determining alternate management options.

ACKNOWLEDGEMENTS

This project was funded by the Ministry of Natural Resources and Environment Malaysia through vote of Kajian Lanjutan Impak Perubahan Iklim Ke atas Sumber Air (vote No. P23170000190001). The first author would like to thank M. Azril Hilmi Shapiai and Mohd Hafiz Zulkifli for their technical support at field.

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