Climate Change Impact on Water Quality of Phewa lake, Nepal

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Acknowledgements

I wish to acknowledge the invaluable direction, support and advice were provided by the ministry of environment science and technology, Government of Nepal. I would like thank to Portland State University to provide CE-QUAL-W2 model software for the analysis of data of this research. I also give thanks to Aquatic Ecology Lab(AEC) of Kathmandu University to provide lab for analysis of physio chemical parameter of water. It is not an easy task to be compressive in acknowledge the help received from different persons from different field. With no experience in interdisciplinary writing, I personally gained a lot from this opportunity to pursue this research.

My depth thanks go to Pro. Chirinjebi prased Upadhya, Institute of Forestry Pokhara, who enabled me to think scientifically and come up with the scientific way of presenting my dissertation. His friendly, cooperative attitude and sense of humor will always be remembered. In spite of this busy and tight work schedule, he managed to give the sufficient time and relevant comments. I specially thanks to my research assistants Mrs Pramila K.C for her outstanding assistance during the field work and report preparation.

I am extremely thankful to Dr. Subodh Sharma Professor of Kathmandu University for his helpful assistance during my research period. I am thanking full to Mrs Rosa Rawut for her assistance in chemical analysis of water parameter in ENPHO laboratory.

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Abstract:

Water quality of Phewa lake has been identified as potentially vulnerable to climate change. In a sub-temperate climate like western region of Nepal, there will be changed in the spatial and temporal distribution of temperature and precipitation due to climate change which in turn will increase both the intensity and frequency of extreme events like droughts and floods. Climate change has several impact on water quality of Phewa lake because of depletion of oxygen level and thermal stratification. The prime objective of this research is to analyze impact of climate change on water quality Phewa lake through CE-QUAL-W2 simulation model. The model parameters were calibrated by field data collected during 2002–2007, and verified against observations made during 2007–2011. The projected temperature and precipitation data for the near- and long-term future were downscaled to regional and daily scales, and used to simulate the projected changes in water quality through the validated model. This lake is tectonic nature so the stratified random sampling technique was adopted at sampling time. The results indicate that rising temperatures will significantly lower the water quality in sub-tropical climate region through greater thermal stability and dissolve oxygen stratification, resulting in reduced dissolve oxygen concentrations in deeper layers of the lake and increased release of phosphorus and nitrate nitrite from sediments. Dissolve oxygen is decreasing from 9.5mg/l to 6mg/l in mean annual in summer season. Average annual surface water temperature is going up by 2.2 percentage. This flux in phosphorus in the hypolimnion may not support algal growth in the epilimnion during summer. However, nutrients are projected to increase throughout the lake, since it is well-mixed in late fall/winter. If the presence of nutrients is high, the prolonged growing season will increase the expected frequency of algal blooms. Phewa lake is mesotrophic to eutrophic status. Most of the chemical parameters shows negative result. The ecosystem of Phewa lake was worst if depletion rate of dissolved oxygen would be continued.

Key words: Climate change, lake, water quality, dissolve oxygen

1. Introduction

Nepal is renounced in the world on account of her natural beauty, geographical / biological diversity and culture heritage. In adequate management and unwise utilization of these resources, despite there high potential has been undergoing several environment degradations. As a result, they may reach to a critically threatening point if adequate measures are not taken. One of such important natural area is Phewa lake in Pokhara valley. The Phewa Lake is one of the most beautiful place in Nepal and attracts a large number of tourists from all over the world. By the virtue of its natural beauty, the lake contributes significantly in local and national economy through tourist industry.

The analysis of water is the major subject in the modern environmental chemistry. Lakes are one of the most important resources of water for the mountainous country like Nepal.

Climate provides fundamental limits on and opportunities for human activities and ecosystem functioning within the lakes region. A changing climate could lead to alterations in the frequency and severity of droughts and floods; water supply; air, soil, and water quality; ecosystem health; human health; and resource use and the economy. Climate change may act through multiple pathways; interactions in and impacts on the Great Lakes ecosystem can be dynamic and non-linear. Within the Great Lakes watershed, there are already numerous stressors that cause ecosystem change including land use change, pollution, eutrophication, invasion of exotic species, and acid precipitation. A changing climate should be considered as another agent of change acting in concert with other ecosystem stresses (Easterling and Karl, 2001; Magnuson *et al.,* 1996).

Rather than simply focusing on the physical, chemical, and biological changes in water quality due to a changing climate, this paper has taken an ecosystem approach as outlined in the Lakes Water Quality Agreement. This approach recognizes that all components of the ecosystem are interdependent, including the water, biota, surrounding watershed, and atmosphere; humans are considered an integral part of this system (Lake Erie LAMP, 2000). Then, climate change can be considered from a broader, sustainability perspective. Identifying risks and opportunities of a changing climate on human activities and ecosystems of the Phewa Lakes watershed facilitates decision-making and planning on how to respond to the problem.

One effective way to evaluate the effects of climate change on ecosystems and water quality is to use numerical models. Several simulation models have been widely used to study freshwater ecosystems. This study focused on Phewa lake and used the CE-QUAL-W2 model to study the impacts of climate change on risks to water quality under A1B and A2 scenarios for the near- (2020–2039) and long-term future (2080–2099). Compared with other reservoir/climate studies, the research in this work focuses on three particular aspects. First, we assess the impacts of climate change on the water quality for an artificial dam reservoir, which differs from natural lakes in geometric shape and the method of water recharge. Second, this work performs in a vulnerable region where the site- and climate-specific information is limited and hence needed. Third, the climate-reservoir modeling results utilize probability-based cumulative distribution functions, which are different from common statistical approaches, such as averages and correlations. Specifically, the intent was to (1) calibrate and validate the CE-QUAL-W2 model; (2) investigate the risks to water quality under A1B and A2 scenarios for the near- and long-term future; and (3) put forward risk-based adaptation and planning strategies for improving water quality and ensuring the safety of drinking water

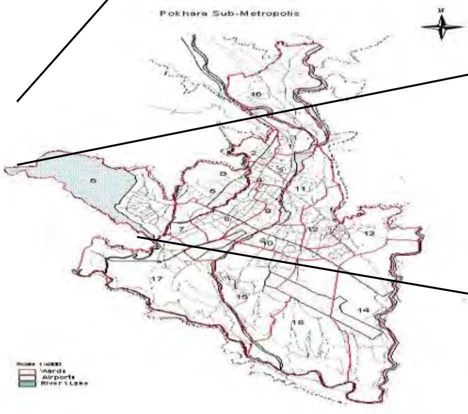
2. **Objective of the study:**

- To analyze climate change impact on water quality of Phewa lake through CE-QUAL-W2 model.
- To predict long term climate change impact on Phewa lake.

3. Material and Method:

3.1 Study area

Fig 1a Nepal



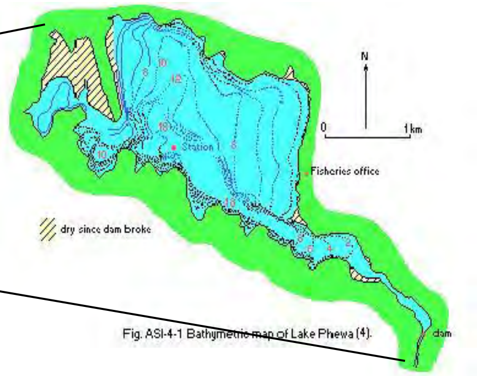


Fig 1b: Pokhara valley

Fig1c: Phewa lake

The research area is situated around 900 m, Pokhara lies 200 km west from Kathmandu, the capital city of Nepal. The most important lake of Nepal is a stream fed dam regulated, semi- natural freshwater subtropical mountain lake (maximum depth 24m and mean depth 7.5 m), lying at an altitude of 742m in Pokhara valley (28º 11’37” to 28º 17’ 26” North and longitude of 83º 48’ 2” to 85º 59’18” East). It occupies an area of 5.23 km2, watershed area of 110km2 (Rai et al., 1995). The lake has multiple uses such as hydroelectricity, irrigation, fishery and a boating facility. By land use pattern the lake features contrast in terms of forested with sparse rural settlement on southern side, agricultural land with dense urban areas on northern side, silt trap zone in western side and river channel zone in eastern side of the lakeshore. The watershed of the lake constitute forest (44%), agricultural land (39%), urban and wetland area (5%), pasture and barren land (5%), lake area (4%) and shrub land (3%) (DSC, 1994).

The watershed area lies in a fragile physiographic region, which experiences intense monsoon rainfall events probably, it is the one of the highest rainfall –receiving watershed of Nepal (IWMP, 1991b**)**. Intensive land use primarily in response to meeting their basic needs for food, fodder, fuel wood, fiber and shelter and development construction especially road without due consideration of the conservation measures integrated with high rainfall have been the major cause of the erosion process in the watershed, which has transported an enormous amount of sediment to the lake reducing its capacity. Sedimentation monitoring of the lake became utmost for the formulation of strategies for the soil conservation and watershed management and also for the management of the lake water for tourism, irrigation and hydropower production.

3.2 CE-QUAL-W2 Model:

The CE-QUAL-W2 (W2) is a two-dimensional, hydrodynamic, and water quality simulation model, which was developed by the Environmental and Hydraulics Laboratory of the US Army Engineer Water-ways Experiment Station. The W2 model uses finite-difference method to approximate the solution for laterally averaged equations of fluid motion. The model has the capabilities of simulating free surface elevation, pressure, density, vertical and horizontal velocities, and constituent concentration and transport. W2 has been under continuous development since 1975, and was particularly popular in simulating basic eutrophication processes in stratified water systems, such as the relationships between temperature, dissolved oxygen and algae in a natural lake; and the association between organic matter and sediment in a man-made reservoir. In recent years, this model has been used to evaluate the impacts of climate change on reservoir water quality to make adaptation and planning decisions for optimized water treatment plant operations. The W2 model version 3.6 released in 2012 was used in this work, which is currently maintained and continually updated by the Water Quality Research Group (WQRG) at Portland State University, USA. Because the model assumes lateral homogeneity, it is most suited to narrow and deep-water bodies where lateral variations in both hydrodynamic and water quality variables are minimal.

In this study, the long, deep and narrow shape of the Phewa lake justifies the choice of the W2 model to predict the hydrodynamic and water quality variables. According to the physical layout of Phewa lake (Figure 1), there is only one tributaries in the catchment; it is assumed that one computational branch grid is sufficient to represent the entire waterbody. The horizontal and vertical spacing of 100–10,000 m and 0.2–5 m was respectively to define the geometry of the single branch grid in W2 for capturing the water quality gradients efficiently and maintaining the numerical stability. Based on manual of CE-QUAL-W2, I divided 10 longitudinal the main *Water* having the length of 50-50 m and one-meter thick vertical layers. All 10 segments were divided on topographic map of Phewa lake. Note that the nine divided segments were identified from the topographic map. The size of each segment has same length and width but random sampling method was adopted for fix of segments on map. As the result, the *x*–*z* computational grids representing the waterbody of Phewa lake are shown in Figure 1.2 The water quality sampling station (Station 1) and the water inlet/outlet of Phewa Lake are located in segments 1 and 10, respectively.

The validated model was then employed to evaluate the impacts of climate change (*i.e.*, changes in temperature and direct precipitation) on the direct inflow quantity and reservoir water quality in the near- and long-term future scenarios. It is assumed that the quality of catchment runoff, rainwater and recharged water, as well as the patterns of water recharge and outflow, remain unchanged in the future and hence these are set to the same conditions as those of 2002–2011.

3.3 Climate Change Data

The climate change dataset used in this study was provided by department of Hydrology and meteorology, Government of Nepal. The study was considered two alternative approaches for producing downscaled data - empirical (statistical) downscaling and Regional Climate Model (RCM) outputs. An analysis of statistically downscaled data (derived from using station meteorological data) was presented below, (A2 scenario for the 1980-2010-time period, UCT, 2012). This considers around 9 models, downscaled to individual met stations (Figure 4). The climate change projections for Pokhara shown in the box below (for 2040-2060 period for the A2 scenario). These show broadly consistent trends for temperature, but very complex and uncertain projections for precipitation. The downscaled data showed even greater variation when the wide range of climatic zones in Nepal was considered.

In addition, the A1B and A2 emission scenarios were chosen as they were the most commonly used scenarios for planning climate adaptation strategies in Nepal. The A1B scenario assumes a balanced mix of technologies and supply sources, with technology improvements and resource assumptions such that no single source of energy is overly dominant. The A2 scenario assumes relatively slow demographic transition and slow convergence in regional fertility patterns, with slow end-use and supply-side energy efficiency improvements, such that there is delayed development of renewable energy and no barriers to the use of nuclear energy. As a result of PRECIS-RCM outputs, two emission scenarios and two time projected periods evaluated in this study, 30 sets of future climate data that will be produced for the assessment of the impacts of climate change on water quality using the W2 model. Because of the similarity in trends and distribution patterns between climate outputs from PRECIS-RCM, it is impractical to run each of the 30 sets of climate data.

3.4 Data Collection

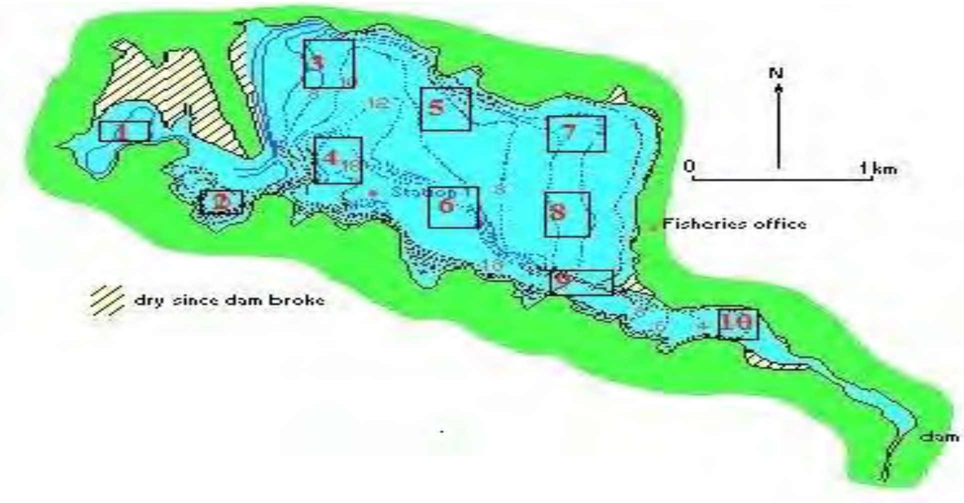


Fig: Ten Sampling site of Phewa Lake

Water samples were taken once in a month, i.e first day of week, from 10 stations located in different part of lake namely Anadu, Khapaudi, Hallan Chowk, Inlet and Outlet. Water samples from Anadu were collected from 0m, 2.5m, 5.0m, 7.5m, and 10m. Only water temperature, pH and dissolved oxygen (DO) were measured *in situ*; other water quality parameters were measured in the laboratory. The analytical methods used for determining water quality parameters included: (1) water temp determined by thermometer; (2) DO measured using the ion-selective-electrode method; (3) nitrate–N (NO_3–N) measured with the cadmium reduction flow injection method; (4) ammonia–N (NH_3–N) measured with the indophenol flow injection method; (5) the total phosphorous concentrations were determined by the ascorbic acid method; and (6) the chlorophyll extraction method (in 90% acetone) was applied to measure Chl-*a*. For further details on analytical methods used in this study,

3.5 Model Calibration and Validation Procedure

The occurrence of thermal stratification can be the most important cause of water quality problems in Phewa Lake, which not only causes a DO deficit and nutrient-enriched hypolimnion water, but also leads to the overgrowth of blue-green algae when the water column overturns and becomes warmer during spring. First, observations of monthly water level, monthly surface temperature and temperature profile were used to calibrate hydrological parameters governing the simulation of hydrodynamic variables, as well as to ensure the water budgets are consistent with grid settings. The hydrological parameters governing horizontal dispersion and bottom friction were set to default values for the Chezy friction model. Second, based on the number of water quality parameters that have been observed and are available for model calibration, six major water quality state variables associated with stratification were simulated, including DO, Chl-*a*, PO_4^{3-}, NH_3–N, NO_3–N, and TP. The default settings of the W2 model (version 3.6) were applied for the other related coefficients. These calibration and simulation results were statistically evaluated to measure for deviations between simulated and observed data, e.g., the absolute mean error (AME) and root mean square error (RMSE); and the goodness-of-fit of model, e.g., the coefficient of determination (R^2).

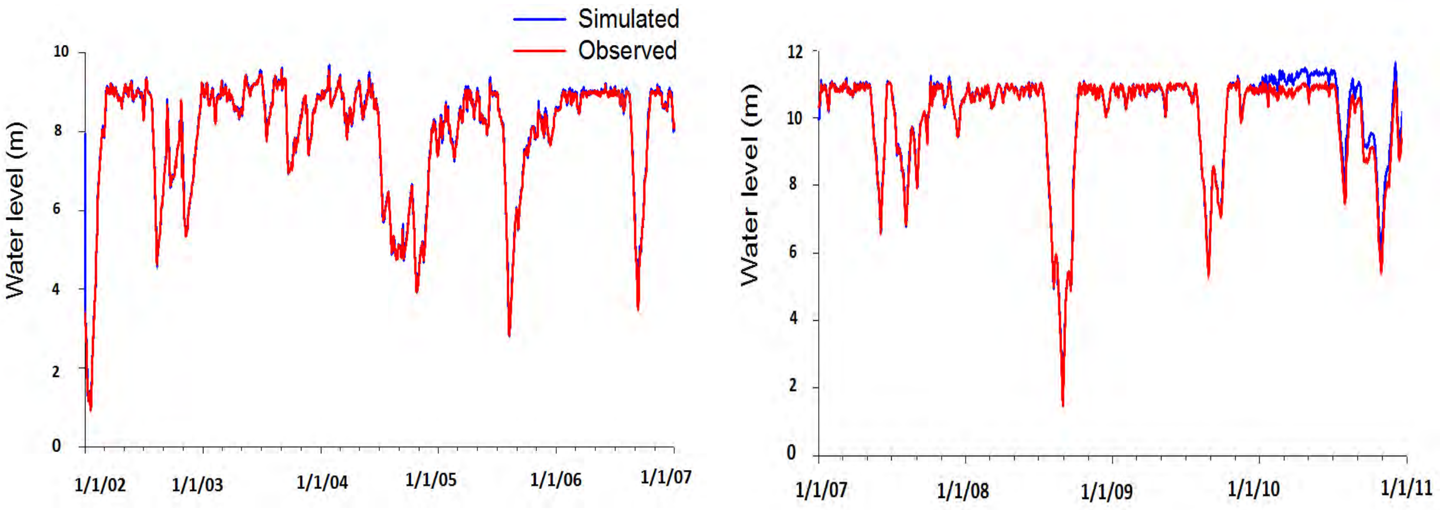
3.6 Risk Analysis

The simulation results for the projected water quality concentrations are organized as probability-based CDFs to identify the risks of the various impacts of climate change on water quality, *i.e.*, the probability exceeding a specific threshold value. The thresholds (low, medium, and high) represent different levels of a water quality variable that, if attained or exceeded, indicate a problem with the water quality. For example, a threshold of 25 °C water surface temperature was used to denote the possible occurrence of algal bloom events in Phewa lake based on historical observations, and 10 μg/L of Chl-*a* was used to indicate the threshold of eutrophication. The risk exceedance probability is defined by: Risk of exceedance for $x = 1 - \mathrm{CDF}(x)$ (1) where x is the threshold value of a water quality variable.

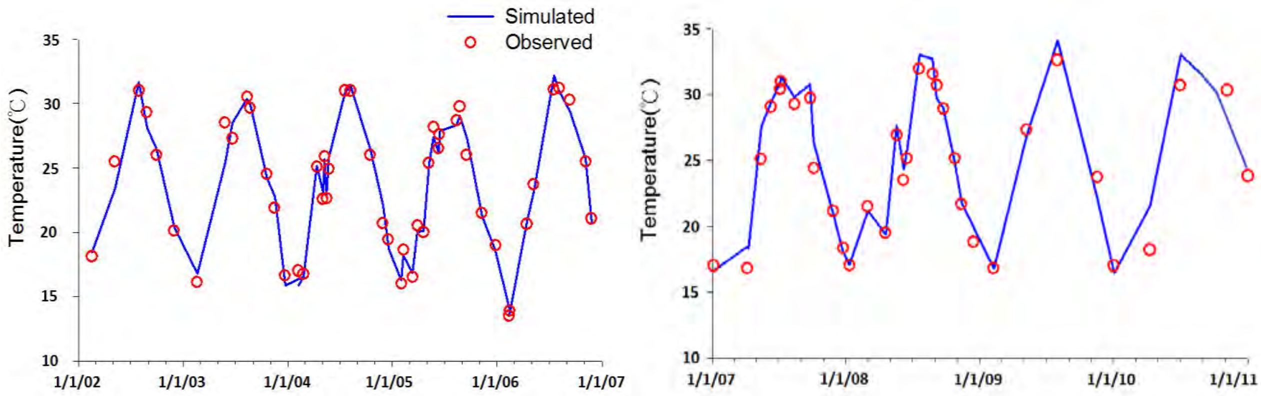
4. Results and Discussion

4.1 Calibration and Validation

A comparison between the observed and simulated hydrodynamic variables, e.g., water level and surface temperature, at the calibration and verification periods, is shown in Figure. The related model performance indicators, *i.e.*$R2$, for simulation of hydrodynamic variables were calculated before model run. Generally, the calibrated hydrological parameters resulted in good agreement between the observations and W2 simulations. The simulation results of hydrodynamic variables in Phewa lake using W2 model, e.g., water level and temperature, showed lower errors and much higher $R2$ values than the simulation of water quality parameters. Hydrodynamic modeling in this study was successful because of proper development of a best-fitting computational grid. The grid was developed because of the availability of both sizable amounts of Phewa lake inflow and outflow measurements and a measured volume-area-elevation table. Hence, the accurate simulation of water levels shows that the water temperature and temperature profile can be well simulated without additional effort for model calibration.



2.a. Calibration of water level (2002-2007) **2.b. Validation of water level (2007-2011)**



2c. Calibration of water temperature (2002-2007) **2d. Validation of water temperature (2007-2011)**

Figure 2. The calibration and validation results of W2 simulated hydrodynamic parameters at surface layer of segment 3. Sub-figures show the comparisons between W2 simulation results to: measured water level during (**a**) calibration and (**b**) validation periods; and measured water temperature during (**c**) calibration and (**d**) validation periods.

The water budget simulation shows that the water level decreased rapidly and reached its lowest level in summer due to lower precipitation and higher demand, when Phewa lake was commonly thermal stratified. During the period of early winter to spring, the water level gradually increased and reached a relatively stable level because of abundant precipitation and recharge water from Harpan river.

As shown in Figure c,d, the surface water temperature is governed directly by the variation of atmospheric temperature, and hence its simulation is straightforward when the given air temperature is representative of the reservoir area. Although a successful simulation of surface water temperature is not difficult, it plays an essential role in accurately deriving the thermal stratification and determining the vertical distribution of water quality variables in the lake.

The comparison between model-derived and observed temperature profiles shows that the thermal structure of the water column can also be well reproduced by the calibrated hydrological parameters. The simulated temperature profiles show that the thermal stratification in Phewa lake developed gradually from April and became the strongest during August and September, with a 2 to 8 °C temperature difference between the surface and bottom layers. Generally, no significant thermal stratification was found with either the observations or the modeling results during October to March. Overall, the hydrodynamics simulation successfully captured the periodic process of thermal stratification and turnover in Phewa Lake.

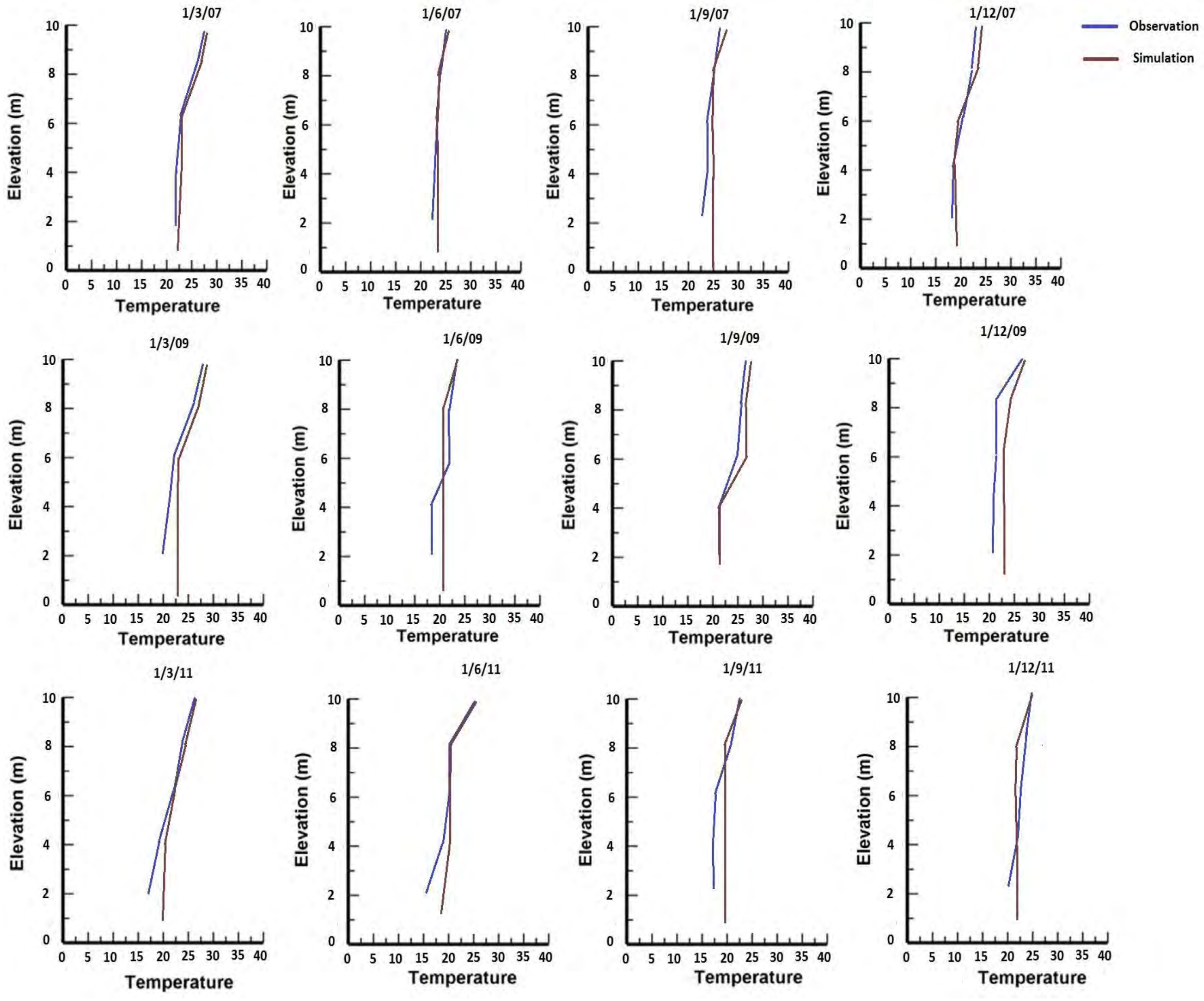
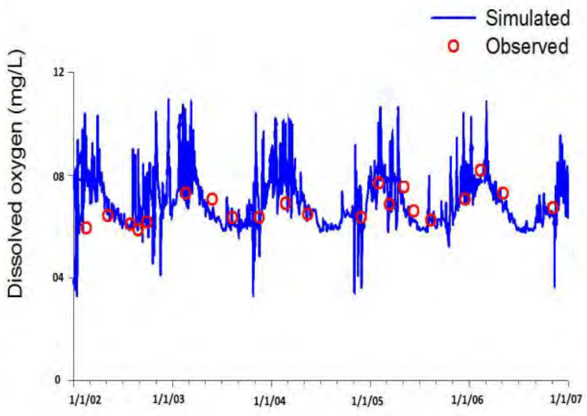


Figure 3: Comparison between W2 simulated and observed water temperature profile in Phewa Lake

4.2 Water Quality State Variables

To assess the reliability and validity of this water quality model, multiple statistical analyses were used; these included *R*2, mean prediction errors, and Pearson's coefficient of correlation (*r*). The calibration and simulation results for water quality state variables are shown in Figures 3 and 4.



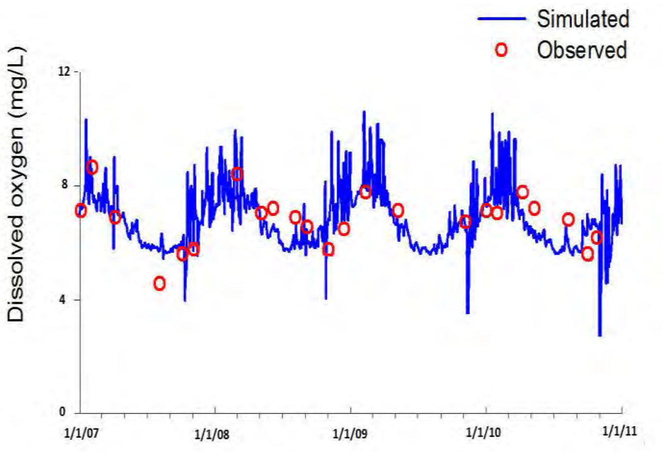
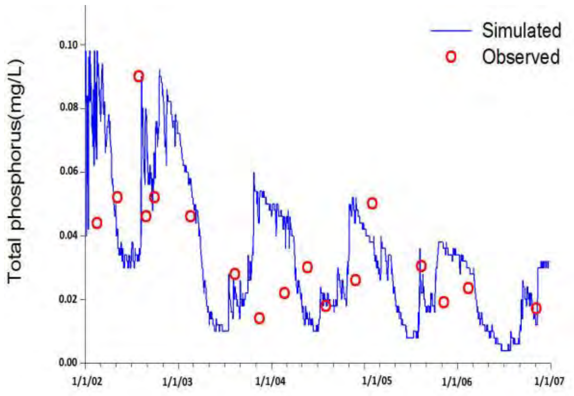


Figure: 3a. Calibration of DO (2002-2007)

Figure: 3b. Validation of DO (2007-2011)



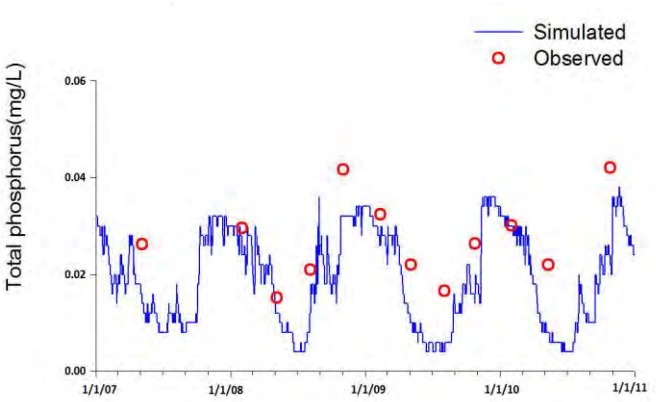


Figure: 3c. Calibration of TP (2002-2007)

Figure: 3d. Validation of TP (2007-2011)

Figure 3. The calibration and validation results of W2 simulated water quality parameters at surface layer of segment 3. Sub-figures show the comparisons between W2 simulation results to: observed DO concentrations during (**a**) calibration and (**b**) validation periods; and observed TP concentrations during (**c**) calibration and (**d**) validation periods.

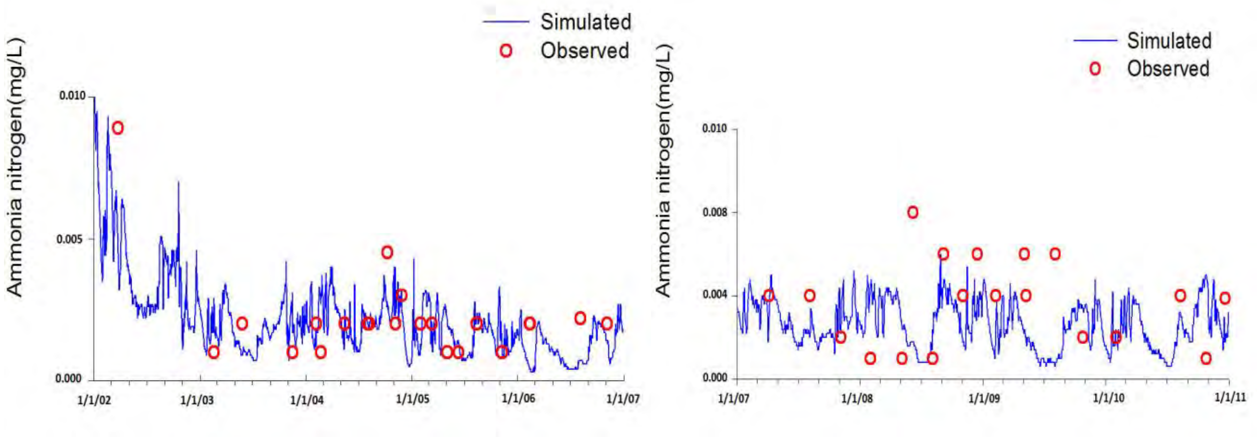


Figure:4a Calibration of AN (2002-2007) **Figure:4b Validation of AN (2007-2011)**

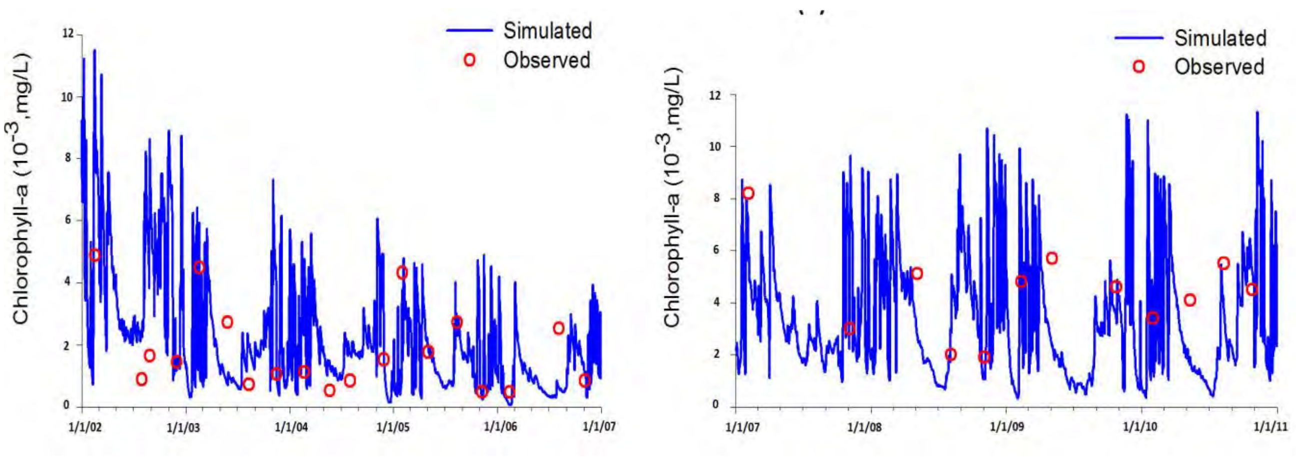


Figure:4c Calibration of chlorophyll-a (2002-2007) **Fugure:4d Validation of Chlorophyll-a (2007-2011)**

Figure 4. The calibration and validation results of W2 simulated water quality parameters at surface layer of segment 3. Sub-figures show the comparisons between W2 simulation results to: observed NH3–N concentrations during (**a**) calibration and (**b**) validation periods; and observed Chl-*a* concentrations during (**c**) calibration and (**d**) validation periods.

Dissolved oxygen is the most important water quality variable determining the health status of an aquatic ecosystem. In Phewa lake, the DO concentrations in the surface layer were commonly at a saturation level, and this can then become supersaturated and undergo higher day and night fluctuations during March and April, because of elevated photosynthetic activity of algae. The phenomenon of DO supersaturation was insignificant during summer, when the reservoir was experiencing thermal stratification. Significant fluctuations in surface DO were again simulated during October to

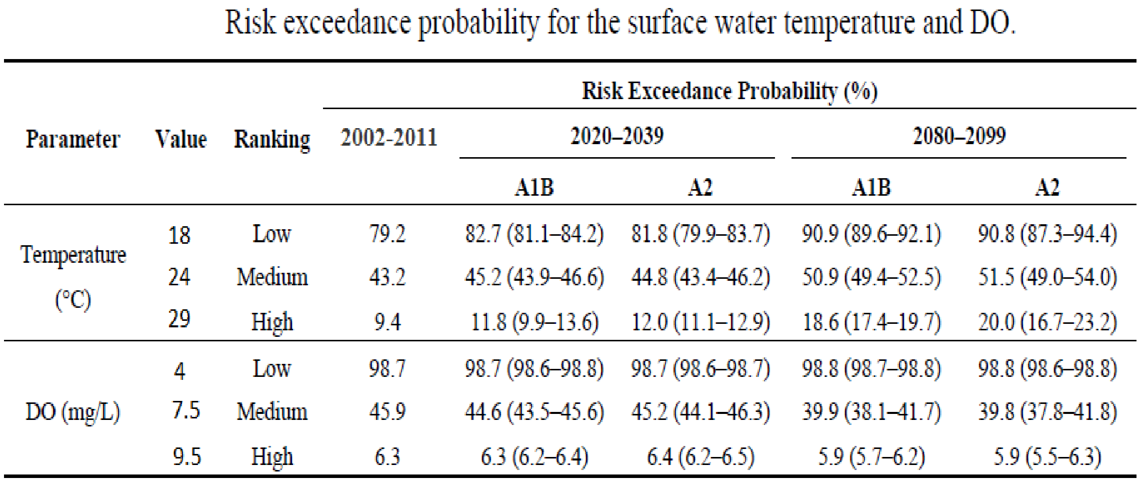
November, due to two simultaneous processes occurring: (1) low-DO from the hypolimnion was upwelling towards the reservoir surface; (2) cooler weather tended to raise the solubility of DO. Consequently, the surface DO was generally increasing during this “turnover” period, but some “oxygen deficit” points were found in the simulation results.

Low-DO at the hypolimnion would significantly accelerate the release of phosphorus from sediment, and thus promote the growth of algae through “turnover” (October to May). Evidence for this “turnover” or the upwelling of nutrient-rich water originating from the hypolimnion is also shown in the time series plots of TP (Figure 3c–d)). It is speculated that phosphorus is one of indicative factors causing eutrophication. However, the increased TP did not immediately trigger a significant growth of algae, because of the lower water temperatures from October to December. As shown in Figures 4c-d the overgrowth of algae was significant during February to May following the winter overturn, due to the combination of nutrient-rich water and warmer weather. Therefore, “oxygen oversaturation” was simulated only in spring and early summer, when algal bloom events were also most frequently observed.

5. Evaluating the Risks to Water Quality due to Climate Change

Although the uncertainty analysis for W2 model is not provided in this work, the W2 model structure and its parameter settings have been tested to be sensitive to climate drivers, and is a suitable tool for the prediction of climate change impacts on reservoir/lake hydrodynamic and water quality parameters. In actuality, there are many sources of uncertainty in evaluating climate change impacts on freshwater resources, including parametric uncertainty, model structure uncertainty and the selected climate data. Generally, a consensus has been reached among researchers that the climate change data and its associated decision procedures, such as the choice of global climate models (GCM-PRECIS), emissions scenario, and downscaling methodology, are commonly the largest source of uncertainty when the projected climate data and hydrodynamic/water quality model are integrated for the evaluation of climate change impacts. Furthermore, uncertainties due to the model

parameters and structure are concluded to be relatively less important if variation for the climate outputs from different GCMs is considered. Therefore, the possible variation for the future prediction of water quality parameters are estimated in this study by evaluating the uncertainty induced by the selection of climate outputs from PRECIS4.0 outputs (as described in Section 2). The uncertainty ranges can represent the possible variations of hydrodynamic and water quality state variables for future predictions.



Risk exceedance probability for the surface water temperature and DO.

Parameter	Value	Ranking	Risk Exceedance Probability (%)				
			2002-2011	2020–2039		2080–2099	
				A1B	A2	A1B	A2
Temperature (°C)	18	Low	79.2	82.7 (81.1–84.2)	81.8 (79.9–83.7)	90.9 (89.6–92.1)	90.8 (87.3–94.4)
	24	Medium	43.2	45.2 (43.9–46.6)	44.8 (43.4–46.2)	50.9 (49.4–52.5)	51.5 (49.0–54.0)
	29	High	9.4	11.8 (9.9–13.6)	12.0 (11.1–12.9)	18.6 (17.4–19.7)	20.0 (16.7–23.2)
DO (mg/L)	4	Low	98.7	98.7 (98.6–98.8)	98.7 (98.6–98.7)	98.8 (98.7–98.8)	98.8 (98.6–98.8)
	7.5	Medium	45.9	44.6 (43.5–45.6)	45.2 (44.1–46.3)	39.9 (38.1–41.7)	39.8 (37.8–41.8)
	9.5	High	6.3	6.3 (6.2–6.4)	6.4 (6.2–6.5)	5.9 (5.7–6.2)	5.9 (5.5–6.3)

Table 1: Projection of water temperature and DO

5.1 Water Temperature

Temperature is regarded as an important factor that can induce algal blooms. There will thus be a higher risk of algal blooms if the projected surface water exceeds a temperature threshold. In this study, temperature thresholds of 16, 24, and 29 °C were used to assess the risk to water quality. The results indicate that the projected changes in climate will significantly raise the water temperature (relative to the 2002–2011 period), and increase the risk of developing associated water quality problems in Phewa lake.

The probability that surface water temperature would exceed 29 °C is projected to increase by 2.2% and 8.6% for the short- and long-term future under the A2 scenario respectively. Compared with the water temperature in the 2002–2007 period, the increased exceedance probabilities in extremes (low and high) are greater than that seen in a medium temperature range (24 °C).

5.2 Dissolve Oxygen:

Dissolve Oxygen is a temperature-associated parameter. Increased temperature will reduce DO saturation levels and increase the risk of oxygen depletion. The projected risks for DO at the surface layer exceeding thresholds of 4.5, 7.5 and 9.5 mg/L are listed in table. Compared to the significant change in water temperature, the change in surface DO is relatively minor. However, the level of surface DO is expected to decrease significantly in the long-term future (2080–2099), due to a stronger increase in surface water temperature (likely ranging from 1.6 to 1.8 °C). For example, under the A1B scenario, the risk exceedance probability for surface DO at a threshold of 7.5 mg/L is projected to decrease by 1.3% (95% confidence interval (CI), 0.3 to 2.4) and 6.0% (95% CI, 4.2 to 7.8) for the short- and long-term future, respectively. Although the increased temperature decreases the DO content of water, the results indicate that the surface DO will still commonly be kept at a saturation level under the projected changes in climate.

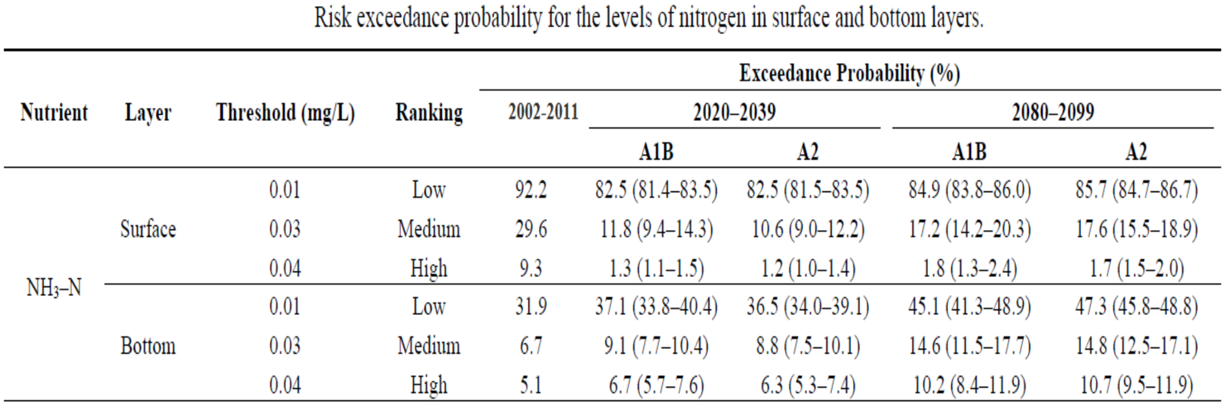
The projected divergence between surface- and bottom-layer DO for each season is shown in Table. The difference between surface- and bottom-layer DO is expected to be stronger during the stratification season under the projected changes in climate, which will increase by between 0.1 and 0.3 mg/L for the near future, and 0.3 to 0.9 mg/L for the long-term future. As a result, the projected increase in thermal stratification will lead to a stronger DO stratification in Phewa lake.

5.3 Nutrients:

The results show that climate change has an obvious impact on risk to Total Phosphate, the limiting nutrient of algal growth in Phewa Lake. Relative to the 2002–2011time period, the probability that TP in the surface layer would exceed the medium threshold is projected to increase by 6.8% and 13.8% for the short- and long-term future under the A1B scenario. The exceedance probabilities for bottom layer TP at the same threshold value are much greater than that within surface layer. For example, the projected changes in the level of TP in the bottom layer are approximately five times greater than those in surface layer under the A1B scenario, because of the increased oxygen stratification and depletion in Phewa lake.

The simulation results of water quality state variables during the base-period (2002–2011) indicate that TP at the water surface decreased while the temperature and DO were stratified in Phewa lake during summer. The peak TP concentrations in surface layer have often been simulated during the turnover periods (winter and spring), due to the upwelling of nutrient-rich hypolimnion water. Therefore, this suggests that the key source of phosphorus in Phewa lake is in fact its release from sediment

5.3.1 Ammonium Nitrate



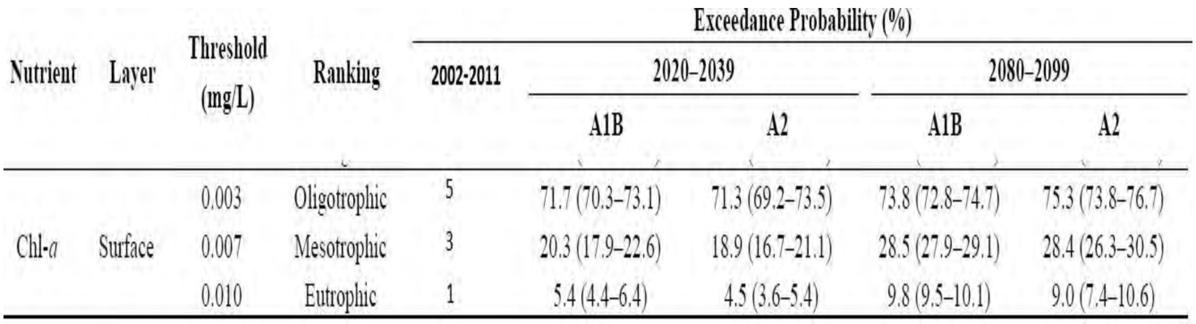
Risk exceedance probability for the levels of nitrogen in surface and bottom layers.

Nutrient	Layer	Threshold (mg/L)	Ranking	Exceedance Probability (%)				
				2002-2011	2020–2039		2080–2099	
					A1B	A2	A1B	A2
NH_3–N	Surface	0.01	Low	92.2	82.5 (81.4–83.5)	82.5 (81.5–83.5)	84.9 (83.8–86.0)	85.7 (84.7–86.7)
		0.03	Medium	29.6	11.8 (9.4–14.3)	10.6 (9.0–12.2)	17.2 (14.2–20.3)	17.6 (15.5–18.9)
		0.04	High	9.3	1.3 (1.1–1.5)	1.2 (1.0–1.4)	1.8 (1.3–2.4)	1.7 (1.5–2.0)
	Bottom	0.01	Low	31.9	37.1 (33.8–40.4)	36.5 (34.0–39.1)	45.1 (41.3–48.9)	47.3 (45.8–48.8)
		0.03	Medium	6.7	9.1 (7.7–10.4)	8.8 (7.5–10.1)	14.6 (11.5–17.7)	14.8 (12.5–17.1)
		0.04	High	5.1	6.7 (5.7–7.6)	6.3 (5.3–7.4)	10.2 (8.4–11.9)	10.7 (9.5–11.9)

Table 2: Projection of Nitrogen

The result shows the projected risks of NH3–N and in surface and bottom layers exceeding the threshold values due to changes in climate. The results indicate that NH3–N in the bottom layer is expected to increase, but the projected level of NH3–N in the surface layer in the entire water column both show a decreasing trend in the future. The lower estimated nitrate concentrations might be attributed to the increased rates of algal growth and bacteria denitrification, as well as the extended growing period of aquatic plants under the warmer climate. In Phewa lake, the increased consumption of phosphorus can be compensated or even exceeded by the projected increase in phosphorus flux from sediment. However, according to the decreasing trend of nitrogen, it is evident that the supply of nitrogen from different sources is less than the increased consumption due to the warmer climate.

5.3.2. Chlorophyll-a



Nutrient	Layer	Threshold (mg/L)	Ranking	Exceedance Probability (%)				
				2002-2011	2020–2039		2080–2099	
					A1B	A2	A1B	A2
Chl-*a*	Surface	0.003	Oligotrophic	5	71.7 (70.3–73.1)	71.3 (69.2–73.5)	73.8 (72.8–74.7)	75.3 (73.8–76.7)
		0.007	Mesotrophic	3	20.3 (17.9–22.6)	18.9 (16.7–21.1)	28.5 (27.9–29.1)	28.4 (26.3–30.5)
		0.010	Eutrophic	1	5.4 (4.4–6.4)	4.5 (3.6–5.4)	9.8 (9.5–10.1)	9.0 (7.4–10.6)

Table4: Projection of Chlorophyll

The probability that Chl-*a* will exceed 7.2 µg/L, the threshold of eutrophication in outlet is only 14.2% during the base-period (2002–2011) in Phewa lake, indicating that lake is generally in a mesotrophic state. However, changes in climate will significantly increase the concentrations of Chl-*a*. As shown on Table4 , the risks of Chl-*a* exceeding 7.2 µg/L in the near- and long-term future are estimated to increase by 6.1% (95% CI, 3.7 to 8.4) and 14.3% (95% CI, 13.7 to 14.9) under the A1B scenario, respectively. The occurrences of extreme temperature (>29 °C) and high phosphorus concentrations in the surface layer (>0.025 mg/L) are both predicted to increase, resulting in a higher risk of eutrophication and algal events in Phewa lake. For example, the risk of Chl-*a* exceeding 10.0 µg/L in the long-term future will increase by 7.1% (95% CI, 6.8 to 7.4) under the A1B scenario.

6. Conclusions

This study assessed the impacts of climate change on the risks to water quality of phewa lake in a subtropical climatic region under the greenhouse gas emission scenarios of A1B and A2. The projected changes in water quality for the near (2020–2039) and long-term (2080–2099) future are estimated by CE-QUAL-W2 model with downscaled future climate data. The results indicate that rising temperatures will significantly lower the water quality in Phewa lake through greater thermal stability and DO stratification, resulting in reduced DO concentrations in deeper layers of the lake and increased release of phosphorus from sediments. This flux in phosphorus in the hypolimnion may not support algal growth in the epilimnion during summer. However, nutrients are projected to increase throughout the reservoir, since it is well-mixed in late fall/winter. However, even more critical for reservoir managers is the projected earlier arrival of spring. If the presence of nutrients is high, the prolonged growing season will increase the expected frequency of algal blooms.

In Phewa lake it would be advantageous to inhibit the upwelling of nutrients available to algae during the growing season, therefore conventional aeration approaches which involve the breaking up of thermal stratification may actually have negative impacts on water quality. Two adaptation strategies are thus suggested. First, management strategies that apply hypolimnetic aeration are recommended so as to increase bottom-layer DO without de-stratification. The second suggested strategy involves lowering the height of the inlet to the depth of the hypolimnion layer formed during the stratification period. This will prevent the overgrowth of algae from the direct supply of nutrient-rich recharge water, and so can be used to address to the issue of anoxia in deeper layers

It should be noted, however, that this study did not consider the projected changes in the quantity and quality of the recharged water Harpen and Pherke river and the modeling results do not reflect the impacts of climate change on the Harpen river catchment. Future work that links the outputs of catchment hydrology and the water quality model with W2 is thus required to comprehensively assess the impacts of climate change on the risks to water quality in Phewa lake.

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