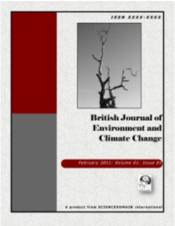

British Journal of Environment & Climate Change
4(4): 355-359, 2014
ISSN: 2231–4784

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Editorial: Climate Change Impacts and Mitigation on Water Quality and Ecological Health in Aquatic Systems

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Guest Editor

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Editorial

Received 28th October 2014
Accepted 28th October 2014
Published 17th November 2014

The increase of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere is projected to cause climate change and global warming. The understanding of climate change impacts on water quality in aquatic systems (lakes, streams, reservoirs, and estuaries) is fundamental in providing better environmental strategies and mitigation methods to protect ecological health of aquatic systems. Water quality is a critical issue due to its direct influence on public health, biological integrity of natural resources, and the economy. The climate change leads to possible changes in local and global weather conditions, such as higher air temperatures and variable precipitation (both intensity and magnitude). Climate conditions affect hydrology in watersheds and then water quality conditions in aquatic systems. To make the projection on future climate, various General Circulation Models (GCMs) of the earth's atmosphere have been developed. These GCM models simulate time series of climate parameters that can be used to create future climate scenarios for hydrological and water quality studies in watersheds and aquatic systems.

Climate variations (seasonal or inter-annual) and climate warming directly affect the heat budget of an aquatic system through the surface heat exchange between the water and the atmosphere, and then influence water quality characteristics. The climate change leads to increase in water temperature and hypolimnetic oxygen depletion during longer periods of summer stratification in lakes and reservoirs. Fish habitat is constrained by water temperature, available dissolved oxygen (DO), food supply, human interference, and other environmental factors. Channel geometry and stream flow are important to fish habitat in streams. In lakes, temperature and DO are the two most significant water quality parameters that affect survival and growth of fishes. Oxygen has implications for the survival of organisms such as fish; in particular the bottom waters of thermally stratified aquatic systems (e.g., relatively deep lakes and reservoirs) can become totally devoid of oxygen due to biochemical oxygen demand and sedimentary oxygen demand. Therefore, projected

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changes in water temperature and DO concentrations are expected to have an effect on indigenous fish populations. One of the mitigation strategies is to identify specific lakes as refuge lakes for different fish species considering effects of climate change. This will allow resource agencies to target conservation efforts to refuge systems. Critical watershed protection efforts will need to be implemented to prevent future degradation of water quality that threatens to reduce the resilience within refuge systems.

Future climate projected by various GCMs includes changes in not only air temperature but also precipitation (both snowfall and rainfall). Projections of future precipitation from different GCMs often disagree, even in the direction of change. Projected spatial and temporal variations and changes in precipitation ultimately affect hydrology and water quality in watersheds, which are in turn expected to have an effect on water quality and ecological health in aquatic systems that receive stream flow from surrounding watersheds. This is because runoff washes nutrients such as phosphorus and nitrogen from watersheds into streams and then lakes and reservoirs and eventually to oceans. Water quality in aquatic systems then controls aquatic habitat and biodiversity such as algal communities in rivers and distribution of seaweeds in coastal areas. Climate change and human activities affect future land use that affects runoff generation and associated water quality.

Climate change impacts are often investigated using various hydrological and stream/lake/reservoir water quality models. These models with different complexities in model theory and structure are often calibrated and validated using historical observed data before they are applied to project hydrology and water quality in the future. Field data of water quality and algal communities collected in rivers and lakes under different climate conditions can be analyzed using various statistical methods to reveal climate impacts on them. Remote sensing technology is useful to identify spatial and temporal distributions of algae, water quality such as suspended solids and chlorophyll-*a* concentrations, and seaweeds over large areas with adequate ground truth, which allows image data to be related to real features and materials on the ground.

In paper 1 of this special issue, Shrestha et al. studied impacts of climate change on both hydrology and water quality in the Saugahatchee Creek watershed in Alabama, USA. The watershed model WARMF (Watershed Analysis Risk Management Framework) was developed and applied to the Saugahatchee Creek watershed which includes two stream branches that were listed on State of Alabama’s 303(d) list of impaired water for nutrients and organic enrichment/dissolved oxygen. The WARMF model for the Saugahatchee Creek watershed was calibrated using observed data in 2000–2005 and validated in 2006–2009 with satisfactory model performance. The calibrated model was then used to investigate hydrologic and water quality response to two different land use scenarios (LU 2009 and LU 2030) and four statistically downscaled future climate scenarios derived from Couple GCMs from Canadian Climate Centre Modeling and Analysis (CCCma) and Hadley Centre Couples Climate Model (HadCM) developed in the United Kingdom under A1B, A2, and B2 scenario families. For example, the A2 scenario family represents a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other scenarios.

Future climate projected using GCMs have coarser spatial resolutions than what is required for a watershed scale study. For hydrologic and water quality impact studies, local or station scale meteorological variables are required, which can be derived using large-scale atmospheric variables available from GCM outputs. There are many methods available for downscaling GCM outputs to the specific region of interest. The method ranges from complex procedures such as dynamical (regional climate model) and statistical downscaling to simple approaches like bias correction methods. In this study, future climate change scenarios were downscaled using the Statistical DownScaling Model (SDSM) for the Saugahatchee Creek Watershed at daily time scales, using four GCM outputs (CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2) and daily NCEP/NCAR reanalysis data.

The impact study was performed on the Saugahatchee Creek Watershed to evaluate the effects on hydrology and water quality under three categories: impact due to land use change only, impact due to climate change only, and impact due to combined land use (LU) and climate change. Flow and water quality parameters were reported at the watershed outlet (Yates Reservoir Embayment) and their monthly average of daily values for baseline and various land use and climate change scenarios were calculated and compared for impact analysis. Land use change scenario for 2030 projects forest areas will be reduced to 71.4% from 83.3% in 2009 and urban areas will be increased to 17.5% from 3.4% in 2009 in the Saugahatchee Creek watershed. The results demonstrate that land use change has major impact on nutrient concentration but less significant impact on flow. Combined effect due to land use change and climate change adds more to increases in nutrient concentrations under HadCM3 A2 and B2 scenarios as both land use change and climate change cause nutrient concentration to increase.

In paper 2, Wambura studied stream flow projections in the Wami River sub-basin, Tanzania, using a physically based and semi distributed rainfall runoff model, SWAT (Soil and Water Assessment Tool). In particular, a total of 24 GCMs from CMIP3 database representing twentieth century precipitation were interpolated into 45 sub-catchments in the sub-basin and evaluated for their skills. The non-linear bias correction method was applied to GCM-scale projects. In this study, the inverse distance weighting method was used to interpolate the GCM grids to the point of interest (sub-catchments). Wambura claimed that the reliability of stream flow projection under changing climate cannot be guaranteed if the GCM projections for future climate does not predict well its past climate. In skill score test of GCM precipitation projections, probability distribution functions (PDFs) were derived for observed and the 24 GCMs precipitation for all 45 sub-catchments. The test compares the similarity between two PDFs (observed and from GCM); it allows a comparison across the entire PDF. The skill score is the cumulative minimum value of two distributions of each binned value, thereby measuring the common area between GCM and observed precipitation. The skill score is equal to zero with negligible overlap between the observed and GCM precipitation PDFs, but if the PDF for observed and GCM precipitation is exactly the same, the skill score becomes unity. HadCM3 with the highest average sub-basin skill score of 79.0% and an uncertainty range of 7.3% in different sub-catchments was selected from 24 GCMs to simulate future precipitation in the Wami River sub-basin.

Using skilled and non-linear corrected HadCM3precipitation, stream flow in the Wami River sub-basin is projected to have an overall increase for the near term climatology (2010 – 2039). For the upstream of the sub-basin, HadCM3 projects a high increase (+392 m^3/s) in flow from February to August as the result of March-April-May rainfalls, but a decrease (-39%) in flow is projected from October to December. However, a sudden drop of flow (-99%) is projected in October in the upstream of Wami River sub-basin. Climate change impacts on water quality in the watershed were not studied using SWAT in Wambura's study.

In paper 3, Shoubaky and Kaiser studied spatial and temporal seaweeds variations using remote sensing technology in Al Shoaiba Coast, Red Sea, Saudi Arabia, from summer 2011 to spring 2012. The study area was divided into four sites extending about 10 km. Four sets of remote sensing data, i.e., the Enhanced Landsat Thematic Mapper (ETM+) images, were used to assess seaweed abundance and distribution. Seaweed species (a total of 46 seaweed taxa) were collected in the field for ground truth. The assessment of seaweeds abundance and distribution were performed using quadrate method, quantitatively measuring percentage cover of each species inside the quadrate. They found that seaweeds varied significantly not only between seasons but also between sitesalong Al Shoaiba Coast. Sea surface temperature is the most significant seasonal and climatic parameter controlling seaweed niche distributions. High evaporation of sea surface water in summer and autumn contributed to the large visual appearance of seaweeds. Climate change in the future will then possibly affect spatial and temporal seaweed distributions.

In paper 4, Barinova et al. studied climate impact on freshwater biodiversity in Siberia, Russia. They studied the response of high latitude riverine planktonic algal communities in northeastern Siberia to extreme climatic conditions of its habitats by implementing diverse statistical methods. A total of 303 water samples and 800 phytoplankton samples were collected for hydrochemical and algological analyses in 12 rivers. Statistical analysis of correlation between species diversity and major climatic condition variables was calculated by distance-weighted least squares. Multiple regression stepwise statistical analysis on phytoplankton, including chemical and climatic variables, was performed in order to determine which variables have strongest influence on the algal communities in studied rivers.

The studied rivers are mostly alkaline, ice-covered about half of the year with an average water temperature in summer ranging from 3.8 to 23ºC and have no limitation for algal biomass development. Statistical analyses of phytoplankton in 12 large rivers revealed an increase in species richness to the north with community structure changing under stimulation of air temperature, ice-free periods, and humidity. Environmental stress in high altitude and high latitude climatic conditions affect algal distributions, for example, diatoms in both cases are replaced by green and red algae in high mountains or by green and chrysophyta algae and cyanobacteria in the Arctic.

In paper 5, Fang et al. studied fish survival in lakes, specifically for a cold-water fish speciescisco *Coregnous artedi* in Minnesota, which is strongly influenced by water temperature and DO concentration. Cisco is the most common cold-water stenothermal fish in northern Minnesota lakes. Cisco physiologically require cold, well-oxygenated water to survive, grow, and reproduce. A one-dimensional (vertical) lake water quality model MINLAKE2012 was calibrated in 23 Minnesota lakes and used to simulate daily water temperature and DO concentrations in 36 representative lake types under past (1992–2008) climate conditions and a future climate scenario (MIROC 3.2). Because it is infeasible to simulate more than 600 cisco lakes in Minnesota using MINLAKE2012, the 36 representative Minnesota lake types were developed based on three maximum depths (H_{max} = 4, 13, and 24 m), three surface areas (A_s = 0.2, 1.7, 10 km^2), and four Secchi depths (SD = 1.2, 2.5, 4.5, and 7 m, from eutrophic to oligotrophic lake). The generic approach using representative lakes provides a good picture of how different lake types may behave (e.g., water quality conditions and corresponding fish habitat), especially under future climate scenarios for which there are no lake data.

A fish habitat model using the lethal-niche-boundary curve of adult cisco was then developed to evaluate cisco oxythermal habitat and survival in Minnesota lakes. In this study, the required DO concentration limit (DO_{lethal}) was computed from the simulated water temperature in each water layer of a lake for each simulated day using the lethal-niche-boundary equation. Lethal conditions for cisco were assumed to occur if the simulated DO was less than the DO_{lethal} value in all water layers (from the lake water surface to the lake bottom) on that day. The fish habitat model was validated in the 23 Minnesota lakes of which 18 had cisco mortality while 5 had no cisco mortality in the unusually warm summer of 2006. Cisco lethal and habitable conditions in the 23 lakes simulated by the model had an overall good agreement with observations in 2006.

Using validated fish habitat model, cisco lethal days in the 36 lake types were modeled using simulated daily temperature and DO profiles under past and future climate. The monthly climate parameter differences or ratios predicted by MIROC 3.2 were applied to measured daily climate conditions (1961–2008) month by month to produce the projected daily future climate scenario. The monthly GCM output was not downscaled as the paper 1 and 2 did. Polymictic shallow lakes with lake geometry ratio $A_s^{0.25}/H_{max} > 5.2\ m^{-0.5}$ were simulated to typically not support cisco oxythermal habitat under past climate conditions and the future climate scenario MIROC 3.2. Medium-depth lakes ($H_{max} = 13$ m) are projected to be most vulnerable to climate warming with most increase in the number of years with cisco kill (average increase 13 years out of 17 simulation years). Strongly stratified mesotrophic and oligotrophic deep lakes ($H_{max} > 20$ m) are possible to support cisco habitat under both past and future climate conditions, and these deep lakes are good candidates for cisco refuge lakes that should be protected against water quality deteriorations. A ‘refuge lake’ is a cisco lake that is projected to provide suitable cold-water habitat under future climate scenarios. Asingle oxythermal habitat variable TDO3, temperature at 3 mg/L of DO, was previously used by authors to divide 620 cisco lakes in Minnesota into Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes. The paper 5 did not classify 620 cisco lakes into different tiered refuge lakes, but it recommends that in the future, fish habitat projections in medium-depth lakes should be studied separately from deep lakes.
