Research papers

Application of Climate Assessment Tool (CAT) to estimate climate variability impacts on nutrient loading from local watersheds

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ARTICLE INFO

ABSTRACT

A vast amount of future climate scenario datasets, created by climate models such as general circulation models (GCMs), have been used in conjunction with watershed models to project future climate variability impact on hydrological processes and water quality. However, these low spatial-temporal resolution datasets are often difficult to downscale spatially and disaggregate temporarily, and they may not be accurate for local watersheds (*i.e.*, state level or smaller watersheds). This study applied the US-EPA (Environmental Protection Agency)'s Climate Assessment Tool (CAT) to create future climate variability scenarios based on historical measured data for local watersheds. As a case demonstration, CAT was employed in conjunction with HSPF (Hydrological Simulation Program-FORTRAN) model to assess the impacts of the potential future extreme rainfall events and air temperature increases upon nitrate-nitrogen (NO_3-N) and orthophosphate (PO_4) loads in the Lower Yazoo River Watershed (LYRW), a local watershed in Mississippi, USA. Results showed that the 10 and 20% increases in rainfall rate, respectively, increased NO_3-N load by 9.1 and 18% and PO_4 load by 12 and 24% over a 10-year simulation period. In contrast, simultaneous increases in air temperature by 1.0 °C and rainfall rate by 10% as well as air temperature by 2.0 °C and rainfall rate by 20% increased NO_3-N load by 12% and 20%, and PO_4 load by 14 and 26%, respectively. A summer extreme rainfall scenario was created if a 10% increase in rainfall rate increased the total volume of rainwater for that summer by 10% or more. When this event occurred, it could increase the monthly loads of NO_3-N and PO_4, by 31 and 41%, respectively, for that summer. Therefore, the extreme rainfall events had tremendous impacts on the NO_3-N and PO_4 loads. It is apparent that CAT is a flexible and useful tool to modify historical rainfall and air temperature data to predict climate variability impacts on water quality for local watersheds.

1. Introduction

Since last century, increasing climate variability has resulted in modifications of intensity, frequency, duration, and timing of extreme weather events (IPCC, 2012). In addition to increasing air temperature, such change has caused variations in amount, intensity, and distribution of precipitations along with increasing frequency of extreme events such as floods and droughts (Praskievicz and Chang, 2009; IPCC, 2012; Wasko and Sharma, 2015). This has been observed in many areas around the world (Lecce, 2000; Bates et al., 2008; Labat, 2008; Peterson et al., 2013; Casanueva et al., 2014; Verma et al., 2015; Wasko et al.,

2017). Tank et al. (2009) argued that air temperature is expected to increase 1.1–6.4 °C in 2100 as compared to that in 1900. These authors also speculated that each of the past three decades has been successively warmer than any previous decades based on historical weather records and the decade of the 2000s is the warmest. Bates et al. (2008) stated that very dry land area has been doubled in some parts of the world, while heavy rainfall has been increased in other parts of the world since 1970s. It is a general consensus that increasing climate variability has discernible effects on agricultural, industrial, environmental, and ecological systems at both global and regional scales (IPCC, 2012).

Hydrological processes and surface water quality are vulnerable to climate change through its impact on evapotranspiration, surface runoff, stream flow, water yield, soil erosion, and nutrient loss. Estimate of hydrological processes and surface water quality is central to water resource management, clean water supply, environmental protection, and ecological restoration (Ouyang et al., 2015; Parajuli et al., 2016). To mitigate future climate variability impacts on hydrological processes and water quality, water resource managers and decision makers must be able to assess potential threats and propose practices to adapt the future climatic conditions. Currently, projecting changes in hydrologic cycles and water quality have generally been accomplished by using process-based watershed models in conjunction with future climate scenario datasets created with climate models including the general circulation models (GCMs), regional climate models (RCMs), and CMIP5 (Coupled Model Inter comparison Project Phase 5) (Chang et al., 2001; Verma et al., 2015; Wang et al., 2016; Alamdari, et al., 2017). Chang et al. (2001) assessed the potential impact of climate change on stream flow and nutrient loading in six watersheds of the Susquehanna River Basin, Pennsylvania using the Generalized Watershed Loading Function with future climate datasets, *i.e.*, air temperature and precipitation, from the GCMs. These authors found that mean annual stream flow and nutrient loads increased for most watersheds, but decreased in one watershed that was intensively cultivated, and nutrient load slightly decreased in April and late summer for several watersheds as a result of early snowmelt and increasing evapotranspiration. Shrestha et al. (2012) performed a modeling study on climate-induced changes in hydrologic and nutrient fluxes at the Lake Winnipeg watershed, Canada using SWAT (Soil and Water Assessment Tool) for a 21-year baseline (1980–2000) and a 20-year (2042–2062) future period with climate data derived from the RCMs. These authors found that the simulated nutrient loads closely match the dynamics of the future runoff for both nitrogen and phosphorus. Alamdari et al. (2017) assessed the effects of future climate on water quantity and quality in an urban watershed using storm water management model (SWMM) with future precipitation and air temperature data from the RCMs for the period from 2041 to 2068. These authors learned that annual runoff volume would increase by 6.5%, while total suspended solids, total nitrogen, and total phosphorus would increase by 7.6%, 7.1%, and 8.1%, respectively.

More recently, Ajami et al. (2017) investigated the nature and frequency of non-stationary hydrological response over 166 anthropogenically unaffected catchments in Australia. These authors found that there are no changes to vegetation in certain type of catchments in a warmer climate, while there are significant changes in other types of catchments that are dominantly dependent on whether the catchments are water limited or nutrient limited. Wang et al. (2017) simulated the influence of sea level rise and warming on circulation and water quality of the Chesapeake Bay with projected climate conditions in 2050. They argued that with a 1.6–1.9 °C increase in monthly air temperatures, water temperature in the Bay is estimated to increase by 0.8–1 °C, and the summer average anoxic volume is estimated to increase by 1.4 percent. Li et al. (2011) predicted effects of temperature change on water discharge and sediment and nutrient loading in the lower Pearl River basin, China using the SWAT model. These authors found that sediment load increases by 13.58% when the air temperature increases by 3 °C and the inorganic N and P inputs into the estuary have an increasing trend when the air temperature increases from −2 °C to +3 °C.

Although the above studies have provided invaluable insights into the direction to project the future hydrologic and water quality trends due to increasing climate variability, the limitations on using the climate scenario datasets created by GCMs, RCMs, and CMIP5 are: (1) They have low spatial resolution and are somewhat difficult to downscale for local watersheds (*i.e.*, state level or smaller watersheds); (2) They are in low temporal resolution (*e.g.*, monthly or annual time intervals) and are difficult to disaggregate into daily or hourly interval required by most watershed models; and (3) They are not flexible to

answer the "what-if" questions for local watersheds. In other words, while a vast amount of future climate datasets have become available in recent years from the GCMs, RCMs, and CMIP5, these datasets are at such a low spatial-temporal resolution that they may not be accurate and flexible to assess climate variability impacts on local watersheds. Wang et al. (2016) reported that these climate scenario datasets have inaccurate spatial information (for example, reported to the nearest minute), which are particularly problematic in steep mountainous terrain, where a medium-resolution grid cell would still span climate environments with several hundred meters difference in elevation. Mohammed et al. (2015) found that most of CMIP5 datasets fail to capture both the trends and variability observed in historical precipitation for a watershed with a drainage area of 360 km^2 in the Winooski Basin (HUC 02010003), which is a multi-state and bi-national basin (Vermont, New York, and Québec). Additionally, these climate datasets do not have flexibility to answer the "what-if" questions for local watersheds, which are fundamental to the state and local water resource managers and stakeholders. For example, state and local water resource managers would like to know what will happen to stream flow and surface water availability for a given local watershed if the extreme precipitation events (*e.g.*, very dry summers and wet winters) occur in the next 10 years so that they can implement practices to adapt for the changing climatic conditions. With the pre-set climate scenario data from the GCMs, RCMs, and CMIP5, these "what-if" questions are difficult to answer. Therefore, an alternative approach is needed to circumvent these obstacles. To this end, the US-EPA Climate Assessment Tool (CAT) is chosen in this study.

CAT was included in the BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) modeling system in 2007 to increase the ability for using BASINS to perform watershed studies as affected by climate change (US-EPA, 2009). CAT can be used to easily create climate change scenarios and to quickly answer a wide range of "what if" questions on how weather and climate could affect hydrological processes and water quality using the HSPF (Hydrological Simulation Program-FORTRAN), SWAT, and SWMM models. More specifically, climate change scenarios can be established with CAT through modifying the historical temperature and precipitation data to reflect the possible future changes (US-EPA, 2009). However, a thorough literature search revealed that very few study has been devoted to using CAT for analyzing climate change impacts on hydrological processes (Zhou et al., 2017), and no effort has been currently made to analyze surface water quality using CAT.

The goal of this study was to apply CAT to project future climate variability impacts on nutrient load for local watersheds. Specific objectives of this study were to: (1) develop a site-specific BASINS-HSPF model using the Lower Yazoo River Watershed (LYRW), a local watershed in Mississippi, USA as a case study; (2) calibrate and validate the model with field measured data; and (3) apply the resulted model in conjunction with CAT to assess stream discharge and nitrate-nitrogen (NO$_3$-N) and orthophosphate (PO$_4$) loads in the LYRW as affected by potential air temperature and rainfall variations due to climate change.

2. Materials and methods

2.1. Study site

The LYRW is located within four Mississippi counties (Sharkey, Issaquena, Yazoo and Warren) south of Yazoo River Basin (YRB), Mississippi with an area of 618 km^2 (Fig. 1a). This watershed consists of 61% forest land and 31% agriculture land with soil types of sand, loam, and clay, and is a highly productive agricultural area known for its cotton, corn, soybeans, rice, and catfish (MDEQ, 2008). Selection of this watershed was based on the following two reasons: (1) there are field measured data available for model calibration and validation, and (2) this watershed is small and is difficult to use the low spatial-temporal resolution climate scenario datasets from the GCMs, RCMs, and CMIP5.
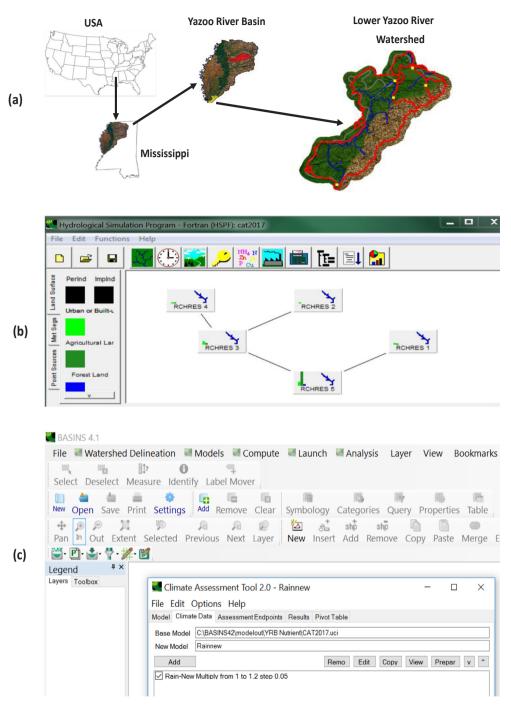
Fig. 1. Location of study site (a), HSPF model map (b), and CAT model map (c).

Surface water pollution within the LYRW includes excess nutrients and sediments, which are the results of storm water runoff, discharge from ditches and creeks, aquatic weed control, and atmospheric deposition (Nett et al., 2004; Shields et al., 2011; Ouyang et al., 2013). The degradation of water quality has resulted in altered species composition and decreased the overall health of aquatic communities in the LYRW (Ouyang et al., 2015).

2.2. CAT description

Although an elaborate description of the BASINS and HSPF models is not necessary because they are the widely used watershed models in the world, a moderate description of the CAT model is, however, warranted because the model is not yet common in the literature. CAT is basically used to adjust historical precipitation and air temperature time series input data to create climate change scenarios for the HSPF, SWAT, or SWMM model. For precipitation, CAT can be used to modify all values (daily or hourly) by a specified constant or factor, the values within a selected period (month or season) of every year, and all events within a specified event class. Precipitation events can also be randomly added or removed to represent changes in precipitation event frequency. For air temperature, CAT can be employed to modify full historical records and regenerate evapotranspiration (ET) record, add or subtract a constant or factor to a specified season and regenerate ET, and increase or decrease values occurring within a specified time period (years) and within the full record by a specified constant or factor. The standard output files of HSPF, SWAT, or SWMM simulations can be saved for later analysis. Detailed description of the CAT model can be

found in its user's manual (EPA, 2009). It should be pointed out that CAT is a tool for modifying model inputs and saving model outputs and is very similar to a pre- and post-processor. CAT does not perform downscale or disaggregation of input data.

2.3. HSPF model and data acquisition

Procedures in developing a HSPF model within BASINS include: (1) Watershed delineation. This process requires to establish a digital elevation model (DEM), create the stream networks in shape files, and generate watershed inlets or outlets using the BASINS watershed delineation tool. (2) Land use and soil type determination. This was accomplished by using the land use and soil classification tools in BASINS. (3) Mathematical description of the watershed processes and preparation of input meteorological and hydrological time series data (Bicknell et al., 2001).

HSPF model is a lumped parameter model with a modular structure. Three modules are used in this study. The PERLAND modular is for pervious land segments over which an appreciable amount of water infiltrates into the ground. The IMPLND modular is for impervious land segments over which infiltration are negligible, such as paved urban surfaces. The RCHRES modular is for the processes occurring in water bodies like streams and lakes. These modules have several sub-modules dealing with the hydrological processes, biological and chemical reactions, ET, soil water storage, and water quality. Detailed information about the structure and functioning of these modules can be found in Bicknell et al. (2001). Fig. 1b shows the HSPF model for the LYRW developed in this study. We have used the similar approaches previously (Ouyang et al., 2013, 2015).

Major input data used in this study included land use, soil type, topography, precipitation, air temperature, solar radiation, and discharge. They are from the National Hydrography Dataset, US Geologic Survey (USGS) National Water Information System, and the 2001 National Land Cover Data. These data can be downloaded directly from the Metadata Section of BASINS. The resolution of DEM for this model was 30 m and the precipitation, air temperature, solar radiation, and simulation time step were in hourly intervals.

2.4. HSPF calibration and validation

A model calibration is to modify input parameter values within an acceptable range to have a good fit between the field observations and the model simulations, whereas a model validation is to verify the calibrated model by comparing the field observations and the model predictions without changing any input parameter values. In this study, the stream discharge as well as the NO_3-N and PO_4 concentrations from the HSPF model were used for model calibration and validation. The field observed daily discharge and concentration data from 2000 to 2005 were used for model calibration, whereas an independent set of field observed daily discharge and concentration data from 2006 to 2009 were employed for model validation. A similar approach was used previously for the same watershed (Ouyang et al., 2013, 2015; Parajuli and Ouyang, 2013) except that more field measured data and statistical measures were used in this study to calibrate and validate the HSPF model.

Fig. 2 shows the observed and predicted daily stream discharges as well as NO_3-N and PO_4 concentrations (left-hand-side) for the simulation period from January 1, 2000 to December 31, 2005. As the values of R^2 and NSE (Nash-Sutcliffe Efficiency) were, respectively, 0.69 and 0.68 for daily stream discharge, 0.89 and 0.58 for daily NO_3-N concentration, and 0.88 and 0.51 for daily PO_4 concentration, we concluded that good agreements were gained between the model predictions and the field observations during model calibration. The goodness-of-fit was further estimated graphically by comparing the peaks and valleys of daily discharge and concentrations as shown on the right-hand-side of Fig. 2. The daily peaks and valleys from model

predictions matched reasonably well graphically with field observations.

Daily stream discharge and NO_3-N and PO_4 concentrations between the field observations and the model predictions during model validation from January 1, 2006 to December 31, 2009 is shown on the left-hand-side of Fig. 3. With reasonable values of R^2 and NSE, we showed that good agreements were achieved between the model predictions and the field observations during the model validation. A visual estimate of the peaks and valleys of daily discharge and NO_3-N and PO_4 concentrations, shown on the right-hand-side of Fig. 3, further confirmed that the model was reasonably validated.

2.5. Simulation scenarios

To estimate the impacts of potential future rainfall and air temperature variations on NO_3-N and PO_4 loads in the LYRW, four simulation scenarios were chosen in this study. Comparison of simulation results among these four scenarios allowed us to evaluate the potential impacts of future air temperature and rainfall variations due to climate change upon the daily and annual stream discharge and NO_3-N and PO_4 loads.

The first scenario (base scenario) was chosen to predict daily and annual NO_3-N and PO_4 loads with historical air temperature and rainfall data over a 10-year simulation period from 2000 to 2009 with an hourly time step. The input data used in this scenario were the same as those used for model validation above. More specifically, the meteorological data such as rainfall rate, air temperature, relative humidity, and solar radiation are the measured hourly data at the LYRW. CAT was not used for this base scenario because we did not modify the meteorological data.

The second scenario was the same as the first scenario except that the rainfall rates during the 10-year simulation period were increased by 20% from the historical data at an increment of 5% for each run (*i.e.*, a total of four simulation runs). This was accomplished through the following steps (Fig. 1c): (1) open the CAT from "Analysis" toolbar in the BASINS program, (2) open the Based Model file "CAT2017.uci" for HSPF model and type the New Model file "Rainnew", (3) click "Add" to create the new rainfall input data. The phrase "Rain-new multiple from 1 to 1.2 step 0.05" means that the original historical rainfall data for the entire simulation period were increased to 20% at the interval of 5%. Detailed instructions on how to set up a CAT modeling scenario are beyond the scope of this study but can be found in the CAT user manual (EPA, 2009). This second scenario was chosen to somewhat reflect the future rainfall trend because the amount of rainfall in Mississippi tended to increase over the past 100 years based on weather records.

The third scenario was the same as the first scenario except that the air temperature and rainfall rate were increased simultaneously. More specifically, when the air temperature increased by 1.0 °C from the historical data, the rainfall rate was assumed to increase by 10% from its historical data, whereas when the air temperature increased by 2.0 °C from the historical data, the rainfall rate was presumed to increase by 20% from its historical data. Although it is a general consensus that an increase in air temperature would couple with an increase in rainfall rate in sub-tropical and tropical regions (IPCC, 2012), we do not know exactly how much the rainfall rate would increase when the air temperature increases by 1 or 2 °C for this local watershed. Therefore, this scenario was chosen to estimate the "what-if" conditions regarding the potential air temperature increase.

The fourth scenario was somewhat complicated, and was the same as the first scenario except that the extreme rainfall events were added to the historical data in summer months (*i.e.*, June, July, and August). In Mississippi, summer is the crop growth and harvesting season, and extreme rainfall events are harmful to crop productions and stream water quality. Understand these "what-if" conditions would provide useful information to farmers and water resources managers. The extreme rainfall events were established using the CAT as follows:
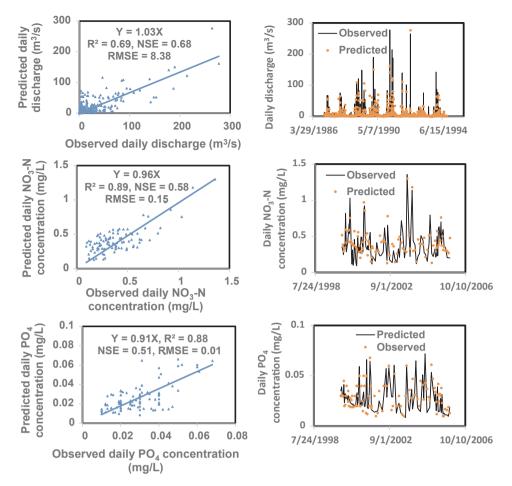
Fig. 2. Comparison of the observed and predicted daily discharge and NO₃-N and PO₄ concentrations during model calibration.

increased the rainfall rate by 10% from the historical rainfall data in summer of each year and checked to see if the total volume of the rain water (after increase) for that summer exceeded 10% of the total volume of historical rain water. If this is true, then the rainfall rate for that summer was increased to 20% and was used as an extreme rainfall event for simulations. Similar set up can be found in the CAT user manual and interested readers are recommended to consult the manual for details.

3. Results and discussion

3.1. Rainfall impact

Daily changes in rainfall rate, stream discharge, and NO₃-N and PO₄ concentrations at the rainfall rates increased by 0 (base), 10, and 20% over a simulation period from 2000 to 2009 in the LYRW are shown in Fig. 4 (noted that simulation results at 5 and 15% increases in rainfall rate are not shown for better graphical clarity). Overall, the peaks of the stream discharge (Fig. 4b) related very well to those of rainfall (Fig. 4a) despite the increase in stream discharge was not proportional to the increase in rainfall rate. For instance, the daily discharge on May 14, 2008 was 77,000 m³/s when the rainfall rate was unchanged (base scenario) but was 88,700 m³/s when the rainfall rate increased by 10% (Fig. 4b). In other words, an increase in rainfall rate by 10% increased the stream discharge by 15.2%. This occurred because the daily stream discharge depended not only on rainfall rate but also on watershed hydrogeological conditions. Generally, the steeper slope, narrower stream channel, larger drainage area, and lesser tree and grass covered land would generate higher stream discharge.

In contrast, the daily NO₃-N concentration in general decreased as

the rainfall rate increased (Fig. 4c). For example, the daily NO₃-N concentrations were 0.49, 0.43, and 0.37 mg/L, respectively, as the rainfall rate increased by 0 (base), 10, and 20% on May 14, 2008. It was assumed that no additional sources of N were added to the watershed during the entire period of simulation from 2000 to 2009 in this study. Therefore, the decrease in daily NO₃-N concentration as the rainfall rate increases could be attributed to the dilution effect. The more rainwater was added, the lower the NO₃-N concentration was in the stream.

Mixed results were obtained for the PO₄ concentration in the stream as the rainfall rate increased. That is, as the rainfall rate increased, the PO₄ concentrations in the stream increased for some dates, decreased for other dates, and were unchanged for the rest of the dates (Fig. 4d). For instance, the daily PO₄ concentrations were 0.0594, 0.0694, and 0.0822 mg/L, respectively, as the rainfall rate increased by 0 (base), 10, and 20% on August 20, 2003 but were 0.025, 0.0245, and 0.0241 mg/L, respectively, as the rainfall rate increased by the same percentage levels on October 19, 2007. The daily PO₄ concentration was unchanged (0.012 mg/L) when the rainfall rate increased by 0 (base), 10, and 20% on June 28, 2005. These mixed results occurred likely due to dilution and desorption of PO₄ as the rainfall rate increased. Unlike the case of NO₃-N which has little adsorption in the soil because of its negative charge, desorption of PO₄ from the soil happens when the rainwater wets the soil. Overall, the dilution reduced while desorption released PO₄ into the stream.

Annual stream discharge and NO₃-N and PO₄ loads from the LYRW at the rainfall rates increased by 0 (base), 10, and 20% are shown in Fig. 5. It is apparent that an increase in rainfall rate increased the annual stream discharge. As an example, the 10 and 20% increases in rainfall rate from the historical data increased, respectively, the annual stream discharge by 12.2 and 24.7% in 2000 (Fig. 5a). This was so
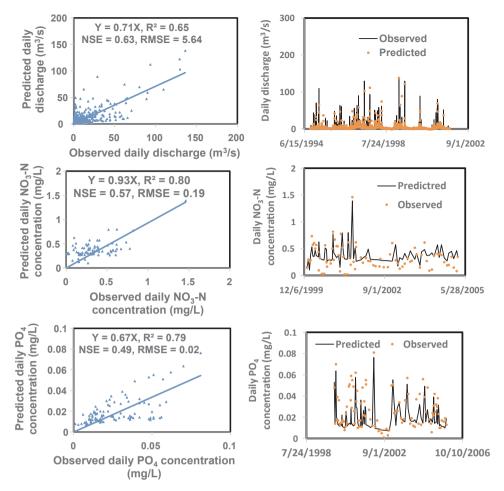
Fig. 3. Comparison of the observed and predicted daily discharge and NO₃-N and PO₄ concentrations during model validation.

because the increase in rainfall rate enhanced surface runoff and added more water for stream discharge. Analogous to the case of stream discharge, the annual NO₃-N and PO₄ loads increased as the rainfall rate increased (Fig. 5b and c). A 10% increase in rainfall rate increased the NO₃-N and PO₄ loads in 2000 by 9.1 and 12.2%, respectively. This occurred because more volume of water containing the NO₃-N and PO₄ masses discharged out of watershed outlet as the rainfall rate increased. Over a 10-year simulation period, the 10 and 20% increases in rainfall rate, respectively, increased stream discharge by 11 and 22%, NO₃-N load by 9.1% and 18%, and PO₄ load by 12% and 24%. Therefore, a potential future wet climate could have discernable impacts on stream discharge and NO₃-N and PO₄ loads at the LYRW watershed. Efforts should be given to mitigate discharge and nutrient loads in the streams at this watershed.

3.2. Impacts of coupled air temperature and rainfall

Annual changes in stream discharge and NO₃-N and PO₄ loads for the following three conditions, (1) the base case, (2) increased air temperature by 1.0 °C and rainfall rate by 10%, and (3) increased air temperature by 2.0 °C and rainfall rate by 20% (Scenario 3), over a simulation period from 2000 to 2009 in the LYRW are shown in Fig. 6. An 11% increase in annual stream discharge was found when the air temperature increased by 1.0 °C and the rainfall rate increased by 10% (Fig. 6a) as compared to a 12.2% increase in annual stream discharge when only the rainfall rate increased by 10% (Scenario 2 and Fig. 5a). This occurred because of more evapotranspiration (ET) loss of water in the LYRW due to an increase in air temperature, which reduced surface water runoff and soil water seepage into the streams. Simulation results

further revealed that there was 19% increases in annual stream discharge when the air temperature increased by 2.0 °C and the rainfall rate increased by 20%. Results suggested that a two-fold increase in air temperature and rainfall rate did not increase the annual stream discharge by two times (rather than 19%/11% = 1.7 times). This was because a two-fold increase in air temperature would enhance ET loss of water.

Analogous to the case of the annual stream discharge, changes in annual NO₃-N and PO₄ loads were significant as the air temperature and rainfall rate increased (Fig. 6b and c). More specifically, there were 12 and 14% increases in annual NO₃-N and PO₄ loads, respectively, when increasing the air temperature by 1.0 °C and rainfall rate by 10%, while there were 15 and 18% increases in annual NO₃-N and PO₄ loads, respectively, when increasing the air temperature by 2.0 °C and rainfall rate by 20%. Apparently, the increases in both air temperature and rainfall rate had discernable impacts on NO₃-N and PO₄ loads.

The 10-year stream discharge and NO₃-N and PO₄ loads are shown in Fig. 7. Overall, the decadal stream discharge and NO₃-N and PO₄ loads increased as the air temperature and rainfall rate increased. There were 8, 12, and 14% increases in annual discharge, NO₃-N load, and PO₄ load, respectively, when increasing the air temperature by 1.0 °C and rainfall rate by 10%, while there were 15, 20, and 26% increases in annual discharge, NO₃-N load, and PO₄ load, respectively, when increasing the air temperature by 2.0 °C and rainfall rate by 20%.

3.3. Extreme event impact

Monthly changes in stream discharge and NO₃-N and PO₄ loads for extreme rainfall events over the 10-year simulation period from 2000 to
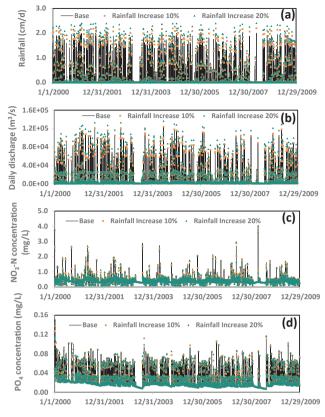
Fig. 4. Simulated daily rainfall rate (a), stream discharge (b), and NO$_3$-N (c) and PO$_4$ (d) concentrations as the rainfall rate increased by 0, 10, and 20%.

Fig. 5. Simulated annual stream discharge (a) and NO$_3$-N (b) and PO$_4$ (d) loads as the rainfall rate increased by 0, 10, and 20%.

2009 at the LYRW are shown in Fig. 8. The extreme rainfall events were added by modifying the historical data in summer months (i.e., June, July, and August) each year if the rainwater volume to be added exceeded 10% of rainwater volume for that summer. If this condition was true, the rainfall rate for that summer was modified to increase by 20% from the historical data at an increment of 10% for each run. These extreme rainfall events were calculated and created using the CAT.

Simulation results showed that there were four times, namely the summers of 2001, 2004, 2008 and 2009, when the extreme rainfall events occurred with dramatic changes in monthly stream discharge and NO$_3$-N and PO$_4$ loads (Fig. 8). There were, respectively, 36 and 72% increases in monthly stream discharge, 31 and 63% increases in monthly NO$_3$-N load, and 41 and 86% increases in monthly PO$_4$ load as the rainfall rate increased by 10 and 20% when the extreme rainfall events occurred in June 2004 (Fig. 8a). It is apparent that extreme rainfall events had tremendous impacts on stream discharge and nutrient load. This information is very important for local water resource managers, stakeholders, and farmers for adapting management practices to account for potential climate variability. With the help of CAT, such what-if questions can be easily answered. Results suggest that CAT is a useful tool for estimating climate change impacts on watershed hydrology and water quality.

It should be pointed out that the future climate scenario datasets created by GCMs and RCMs are not only in low spatial resolution but also in low temporal resolution. That is, these datasets are normally in monthly or annual interval. For most watershed models, a daily time step (e.g., SWAT) or hourly time step (e.g., HSPF) is required. To meet this time step requirement, the monthly precipitation and air temperature data are disaggregated and downscaled into daily or hourly data with great uncertainty and inaccuracy. For a local watershed, simulations using these downscale and disaggregate data as inputs may not be appropriate. Therefore, it would be a good idea to use the GCMs and RCMs climate scenario datasets to assess future climate change
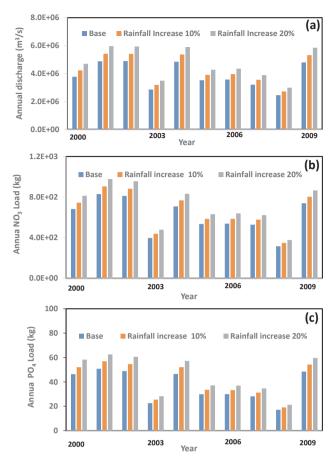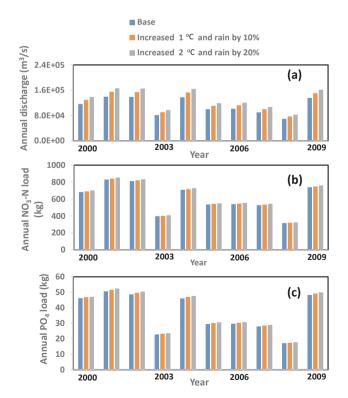

Fig. 6. Simulated annual stream discharge (a) and NO$_3$-N (b) and PO$_4$ (c) loads as the air temperature and rainfall rate increased by 1.0 °C and 10% as well as 2.0 °C and 20%, respectively.
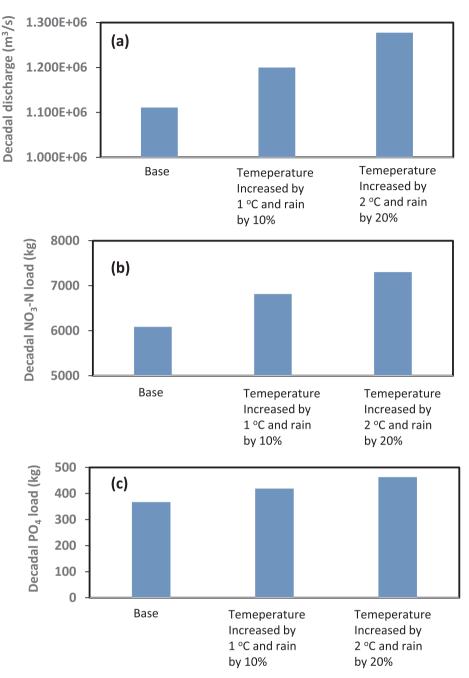
Fig. 7. Simulated 10-year stream discharge (a) and NO$_3$-N (b) and PO$_4$ (c) loads as the air temperature and rainfall rate increased by 1.0 °C and 10% as well as 2.0 °C and 20%, respectively.

impacts on hydrological processes and water quality for global and regional river basins, and to use CAT to create climate scenario datasets for the same assessment for local watersheds.

4. Summary and conclusions

The Climate Assessment Tool (CAT) along with HSPF model in the BASINS modeling system was applied to assess the impact of potential rainfall and air temperature variations due to climate change upon hydrological processes and water quality in the LYRW, Mississippi. In addition to the base simulation scenario, three more simulation scenarios were chosen to investigate impacts of increasing air temperature and increasing rainfall rate and/or extreme events upon NO$_3$-N and PO$_4$ loads in the LYRW.

In general, the daily NO$_3$-N concentration decreased as the rainfall

rate increased when no additional source of N was added to the watershed. Such a decrease was attributed to the dilution effect as the rainfall rate increased. In contrast, the daily PO$_4$ concentration could increase or decrease as the rainfall rate increased, and this occurred because of the dilution and desorption of PO$_4$. The dilution reduced while desorption released PO$_4$ into the stream. A potential future wet climate could have discernable impacts on stream discharge and NO$_3$-N and PO$_4$ loads in the LYRW watershed. The increases in both air temperature and rainfall rate had very significant impacts on NO$_3$-N and PO$_4$ loads.

Extreme rainfall events had tremendous impacts on stream discharge and NO$_3$-N and PO$_4$ loads. This information is very important for local water resource managers, stakeholders, and farmers for adapting management practices to account for potential climate variability.

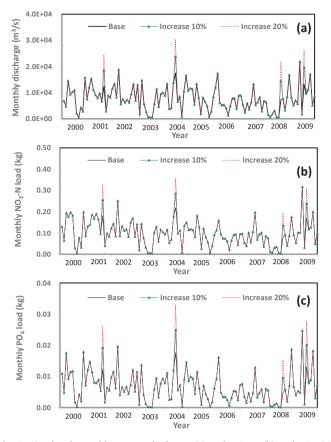For local watersheds, simulations using the GCMs and RCMs climate

Fig. 8. Simulated monthly stream discharge (a) and NO$_3$-N (b) and PO$_4$ (c) loads as the rainfall rate increased by 0, 10, and 20% under extreme summer rainfall events.

scenario datasets as inputs may not be appropriate because they have low spatiotemporal resolution and are not flexible. With the help of CAT, such obstacles could be circumvented. Results suggest that CAT is a useful tool for estimating climate change impacts on local watersheds, which can be extended to other watersheds in the larger scale based on availability of data.

Acknowledgements

References

Alamdari, N., Sample, D.J., Steinberg, P., Ross, A.C., Zachary, M., Easton, Z.M., 2017. Assessing the effects of climate change on water quantity and quality in an urban watershed using a calibrated stormwater model. Water 9, 464.

Ajami, H., Sharma, A., Band, L.E., Evans, J.P., Tuteja, N.K., Amirthanathan, G.E., Bari, M.A., 2017. On the non-stationary of hydrological response in anthropogenically unaffected catchments: an Australian perspective. Hydrol. Earth Syst. Sci. 21, 281–294.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P., 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, pp. 210.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jobes, T.H., Donigian, A.S., 2001. Hydrological Simulation Program – FORTRAN, HSPF, Version 12, User's Manual. National

Exposure Research Laboratory, Office Of Research and Development. U.S. Environmental Protection Agency, Athens, Georgia 30605.

Casanueva, A., Frías, M.D., Herrera, S., San-Martín, D., Zaninovic, K., Gutiérrez, J.M., 2014. Statistical downscaling of climate impact indices: testing the direct approach. Climate Change 127, 547–560.

Chang, H., Evans, B.M., Easterling, D.R., 2001. The effects of climate change on stream flow and nutrient loading. J. Am. Water Resour. Res. Assoc. 37, 973–985.

IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation, in Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Labat, D., 2008. Wavelet analysis of the annual discharge records of the world's largest rivers. Adv. Water Resourc. 31, 109–117.

Lecce, S.A., 2000. Spatial variations in the timing of annual floods in the southeastern United States. J. Hydrol. 235, 151–169.

Li, Y., Chen, B.M., Wang, Z.G., Peng, S.L., 2011. Effects of temperature change on water discharge, and sediment and nutrient loading in the lower Pearl River basin based on SWAT modelling. Hydrol. Sci. J. 56, 68–83.

Mohammed, I.N., Bombliesa, A., Wemplea, B.C., 2015. The use of CMIP5 data to simulate climate change impacts on flow regime within the Lake Champlain Basin. J. Hydrol. Regional Stud. 3, 160–186.

MDEQ (Mississippi Department of Environmental Quality). 2008. State of Mississippi water quality criteria for intrastate, interstate, and coastal waters. Mississippi Department of Environmental Quality, Office of Pollution Control, P. O. Box 10385, Jackson, Mississippi 39289.

Nett, M., Locke, M.A., Pennington D.A. 2004. Water quality assessments in the Mississippi Delta. Washington, DC; 30-42pp.

Ouyang, Y., Leininger, T.D., Moran, M., 2013. Impacts of reforestation upon sediment load and water outflow in the Lower Yazoo River Watershed, Mississippi. Ecol. Eng. 61, 394–406.

Ouyang, Y., Leininger, T.D., Moran, M., 2015. Estimating effects of reforestation on nitrogen and phosphorus load reductions in the Lower Yazoo River Watershed, Mississippi. Ecol. Eng. 75, 449–456.

Parajuli, P.B., Jayakody, P., Sassenrath, G.F., Ouyang, Y., 2016. Assessing the impacts of climate change and tillage practices on stream flow, crop and sediment yields from the Mississippi River Basin. Agric. Water Manage. 168, 112–124.

Parajuli, P. B. Ouyang Y. 2013. Chapter 3: Watershed-Scale Water Quality Modeling Methods and Applications. In "Current Perspectives in Contaminant Hydrology and Water Resources Sustainability", book edited by Paul M. Bradley, Hydrology, ISBN 980-953-307-926-9. Page 57-80.

Praskievicz, S., Chang, H., 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. Progr. Phys. Geogr. 33, 650–667.

Peterson, T.C., Heim, R., Hirsch, R., Kaiser, D., Brooks, H., Diffenbaugh, N., Dole, R., Giovannettone, J., Guirguis, K., Karl, T., Katz, R., Kunkel, K., Lettenmaier, D., McCabe, G., Paciorek, C., Ryberg, K., Schubert, S., Silva, V., Stewart, B., Vecchia, A., Villarini, G., Vose, R., Walsh, J., Wehner, M., Wolock, D., Wolter, K., Woodhouse, C., Wuebbles, D., 2013. Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the united states: state of knowledge. B. Am. Meteorol. Soc. 94, 821–834.

Shrestha, R.R., Dibike, Y.B., Prowse, T.D., 2012. Modeling climate change impacts on hydrology and nutrient loading in the upper Assiniboine catchment. J. Am. Water Resour. Assoc. 48, 74–98.

Shields, F., Douglas, Jr, Knight, S.S., 2011. Significance of riverine hypoxia for fish: the case of the big sunflower River. Mississippi. J. Am. Water Resour. Assoc. 48, 170–186.

Tank, A.M.G., Zwiers, F.W., Zhang, X. 2009. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. Climate Data and Monitoring, WCDMP-No. 72, World Meteorological Organization, WMO-TD No. 1500.

US-EPA. 2009. BASINS 4.0 Climate Assessment Tool (CAT): Supporting Documentation and User's Manual. Global Change Research Program National Center for Environmental Assessment Office of Research and Development U.S. Environmental Protection Agency Washington, DC 20460. EPA/600/R-08/088F.

Verma, S., Bhattarai, R., Bosch, N.S., Cooke, R.C., Kalita, P.K., Markus, M., 2015. Climate change impacts on flow, sediment and nutrient export in a Great Lakes watershed Using SWAT. Clean – Soil Air Water 43, 1464–1474.

Wang, P., Linker, L., Wang, H., Bhatt, G., Yactayo, G., Hinson, K., Tian, R., 2017. Assessing water quality of the Chesapeake Bay by the impact of sea level rise and warming. IOP Conf. Series: Earth Environ. Sci. 82, 012001.

Wang, T.L., Hamann, A., Spittlehouse, D., Carroll, C., 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One. http://dx.doi.org/10.1371/journal.pone.0156720.

Wasko, C., Sharma, A., 2015. Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. Nat. Geosci. 8, 527–529.

Wasko, C., Sharma, A., 2017., 2017. Global assessment of flood and storm extremes with increased temperatures. Sci. Rep. 7, 7945.

Zhou, Z., Ouyang, Y., Li, Y.D., Qiu, Z.J., Moran, M., 2017. Estimating impact of rainfall change on hydrological processes in jianfengling rainforest watershed, China using BASINS-HSPF-CAT modeling system. Ecol. Eng. 105, 87–94.