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Modelling the impact of climate change on hydrological systems in Western Australia to inform managers

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ABSTRACT

Based on climate data from Western Australia, this report assesses future local hydrological responses to land use and climate change impacts through models of two connected lakes and the catchments that support them. It focuses on the potential impact on local hydrology of the significant rainfall reduction trend in Western Australia in recent years. For watershed modeling, the change of daily runoff coefficient due to urbanization is predicted. For lake modeling, runoff, rainfall, and evaporation obtained from upstream catchments are used to simulate changes in lake storage and water levels. The Global climate model (GCM) is used to change rainfall and evaporation data from the basic model to obtain forecast models and observe future changes in lake water storage and water level. In addition, the shortcomings of the existing model are discussed, and the possibility of improving the model and the next steps are proposed. The research will provide important insights into water management in regional Western Australia to address the growing challenge of climate change.

KEYWORDS

Hydrological models; climate prediction; urbanization; future lake ecosystems

1 Introduction

Climate change has a significant impact on water resources, and relevant studies have been carried out around the world. Global warming and other phenomena will lead to changes in climate patterns, which will be increasingly reflected in runoff patterns (Teng J, et al., 2012). Because of the different impacts of climate change on different geographical regions, it is necessary to develop specific water resources management and relevant adaptation strategies for specific regions. The report explores in detail a catchment lake system model that assesses the hydrological response of two connected lakes and the catchments they support, with a focus on the potential impacts of climate change. This assessment is of particular importance given the trend of significant rainfall reductions in Western Australia in recent years. The hydrological model consists of three catchments and a pair of lakes, with the receiving rainfall from the three upstream catchments producing runoff that eventually converges into the downstream lakes. For catchment modeling, the observed numerical model needs to be calibrated to estimate the daily runoff coefficient for each subset of the water, and the resulting urbanization scenario is predicted. For lake modeling, the model is divided into upstream lakes and downstream lakes, with downstream lakes receiving the amount of water spilt from upstream lakes. Runoff, rainfall and evaporation obtained from the upstream catchment are used to model changes in lake storage and water level. For the climate change scenario, the global climate model(GCM) is used to change the rainfall and evaporation data of the basic model to obtain the forecast model, and the changes in the future lake storage and water level of the model are observed. In describing the results of the impacts of climate change, factors contributing to changes in lake storage are assessed, taking into account the differences between basic and forecast models, the relative merits of currently used forecasting tools. In describing the methodology for this climate change assessment, the methodology for obtaining climate change trends from the CSIRO report explains the methods for changing climate forcing in the model. In describing the outcomes of climate change impacts, the difference between the base scenario and the forecast scenario is taken into account, and for the predicted data, the difference between the base scenario and any future scenarios with key catchment and lake outcomes is shown. For the projected results, positive or negative changes in the future lake ecosystem from 2030 to 2033 compared to other climate literature, and any other effects of temperature increases not captured by this model, as well as discussions on how to improve the model, the next steps that future modelers can take.

2 Methods

2.1 Modeling stream flow in the catchment

The model is divided into three sub catchment areas, each with different land type distributions and climates. Firstly, the numerical models of the three catchment areas are calibrated to simulate the flow into the lake. The model uses two key parameters: runoff coefficient (c) and threshold (R_{crit}), and runs at a time step of each day. If the rainfall on a certain day exceeds the threshold, corresponding flow will be generated to flow out of the catchment area. The generated flow is calculated according to the formula Q=c ($R-R_{crit}$) A. If it is less than the threshold, no flow will be generated. It is worth noting that due to the different locations of the three catchment areas, it takes time for the flow to reach the outlet. In this model, based on catchment area 1, it is assumed that catchment area 2 lags behind by one day and catchment area 3 lags behind by two days.

$$Q_i^t = \begin{cases} 0, & R_i^t \le R_i^{crit} \\ c_i\left(R_i^t - R_i^{crit}\right) A_i & R_i^t > R_i^{crit} \end{cases}$$

$$Q_{tot}^t = Q_1^t + Q_2^t + Q_3^t$$

The superscript "t" refers to "time step size", in this example, it is a single day. The subscript "i" refers to the catchment area Index, i=1 represents sub catchment area 1. The total flow rate Q_{tot} is calculated by adding up the time lags of each sub catchment area, A (m^2) is the area of rainfall.

Estimate the daily runoff coefficient c for each sub basin based on rainfall data and observed outlet Runoff. Firstly, filter the rainfall data through the if statement. Rainfall data greater than R_{crit} will generate runoff, and the obtained model runoff will be compared with the observed runoff. Regarding the estimated value of runoff coefficient, limit the range according to different ground types, and observe the daily Runoff through the lag time of catchment area. Assuming that the time of catchment area 1 is t, then due to the lag time, the corresponding outlet Runoff times for catchment areas 2 and 3 are t+1 and t+2. Adjust the c value in each sub catchment area based on the reference value of outlet Runoff until it matches well with the observed Runoff data. Due to the large amount of data, regression charts are used to evaluate the performance of the model. Next, to visualize the difference in daily flow, choose to create a cumulative mass curve and overlay the flow of the three catchment areas to display the total mass of water transported by runoff.

Now we will further explore the impact of urbanization, assuming that the total urban area of each sub basin expands to 50% . By modifying the model parameters, reduce R_{crit} by 25% to reflect the poor permeability of urban land. To select an appropriate runoff coefficient for urban land use, we usually know that the permeability of urbanization land is poor. Due to the impermeable surface, a portion of the inflow that could have naturally replenished groundwater is now redirected to surface runoff (Pasquier et al., 2022). Therefore, the predicted runoff coefficient c will be higher, and the threshold for generating runoff will also be reduced. The R_{crit} value of each small watershed will be reduced by 25%, and the new c value will be adjusted and increased. The new c value will be calculated based on the average value of the old value and the city value. In order to compare with the basic model, a stacked quality map will still be used to observe the difference between the two model.

2.2 Modeling the lakes

Calculate the lake system based on the simulated runoff from the catchment area above. This includes two main lakes arranged in order. If the water volume of a lake exceeds a certain critical lake height, the overflowing water flows from the initial lake to the downstream lake. We assume that the inflow of groundwater is determined by a relatively stable regional groundwater gradient, and that the lake is steep and the surface area is independent of the water level height, so we can use a constant value. Calculate Lake storage S(m^3) and lake water level h(m) through lake model and corresponding parameters:

$$\frac{dS_{upper}}{dt} = Q_{tot} + \left(R - E - kh_{upper}\right) A_{upper} - Q_{out_{upper}}$$

$$\frac{dS_{lower}}{dt} = Q_{out_{upper}} + kh_{upper} A_{upper} + \left(R - E - kh_{lower}\right) A_{lower} - Q_{out_{lower}}$$

$$h_{upper} = \frac{S_{upper}}{A_{upper}} \& h_{lower} = \frac{S_{lower}}{S_{lower}}$$

Among them, R is the precipitation of the relevant lake (m/day), E is the evaporation rate (m/day), Q_{tot} is the flow rate of the catchment area, Q_{out} is the overflow from the upper lake to the lower lake, and khA reflects groundwater seepage.

Convert all rates to consistent units (e.g. days represent time), To predict the rainfall of the lake, there are currently rainfall data of three catchments, and the location of catchment 2,3 is far away from the lake due to the lag time, so the rainfall data near catchment 1 is selected here. calculate net flow Q_{tot} into the lake (total runoff from catchment areas 1, 2, and 3), and calculate outflow Q_{out} (overflow from lakes 1 and 2),Check whether the overflow condition is met through the if statement. Update the lake storage capacity based on net inflow and outflow, and then update the water level. Repeat these steps for the entire simulation cycle. Based on the calculation results, the water level of two lakes can be obtained, and a line chart can be used to observe the water level changes of the lakes more intuitively.

2.3 Assessing the impacts of climate change

This section will have obtained models to predict the effects of climate change. In Western Australia, a significant reduction in rainfall has been observed. Forecast changes in rainfall and evaporation after 2030 through the CSIRO report. Select the models in this article to get seasonal and annual trend changes to change your climate forcing data. And use your new rainfall and evaporation forcing data to recalculate the water balance from 2030 to 2033 to get a new model that represents future scenarios.

The CSIRO report(Charles SP, et al,2010) has used 15 global climate models (GCMs) to project rainfall for 2030 relative to 1990, with the general trend of climate in the future being water limited. Two GCMs, GFDL 2.0 and MIROC-M, ranking at the top rung in performance consistency, were chosen, but after comparing the two in seasonal and annual change in rainfall and APET, each was found to have its own merits and demerits. It seems logical that climate change results from a GCM must be a credible representation of the present day climate, so, instead choosing one of them, an average of percent change in seasonal rainfall and APET of the two models were used. The projected annual percent change used for climate forcing data for 2030 to 2033were as following: rainfall at summer 2.5% decrease, autumn 7.5% decrease, winter 7.5% decrease, spring 5% decrease. APET 2.5% increase was used. This projected change is similar to the 9 better performing GCMs showing annual 8 percent median decrease in rainfall and APET increase of 2 percent.

After the changes of rainfall and evaporation are obtained, the rainfall and evaporation data of the catchment area from 2007 to 2010 are selected, and the changed values are substituted according to different seasons for accuracy. In this way, a new forecast rainfall and evaporation data can be obtained, and the outlet runoff of the catchment area in the future can be calculated through the new rainfall data.

3 Results

3.1 Modeling stream flow in the catchment

By calibrating the catchment model, the daily runoff coefficient of each subarea was adjusted. In order to verify the obtained model data, regression is used to combine the model data with the observed data, and the resulting graph is shown below.

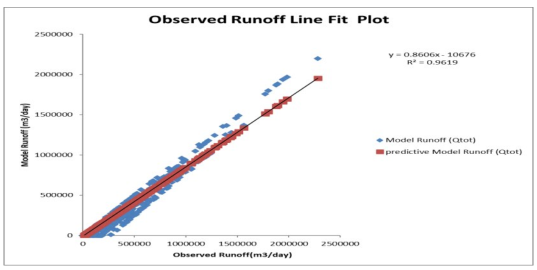


Figure 1 Regression plot between observed Runoff and model Runoff

Through the regression graph, we can observe that the R^2 value reaches about 0.96, which means that the model data has a good similarity with the observed data, which indicates that the results calculated by the current model can be accepted.

Next, to visualize the difference in daily flow, choose to create a cumulative mass curve and overlay the flow of the three catchment areas to display the total mass of water transported by runoff. The following chart helps to reveal trends and changes.

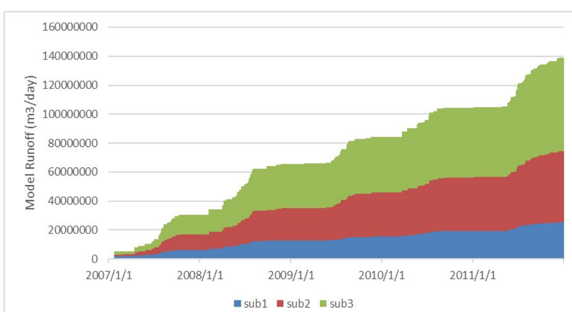


Figure 2 A stacked area chart, displays the cumulative flow of each sub catchment

This graph illustrates how the contributions of different sub watersheds increase over time. We can see that due to factors such as catchment area, rainfall, and land use, there are significant differences in the contributions that different catchment areas can make.

Assuming that the total urban area of each sub-basin expands to 50%, the impact of urbanization is explored by modifying the model parameters and comparing with the base model, the difference between the two will still be observed using the stack quality map, as shown in the figure below:

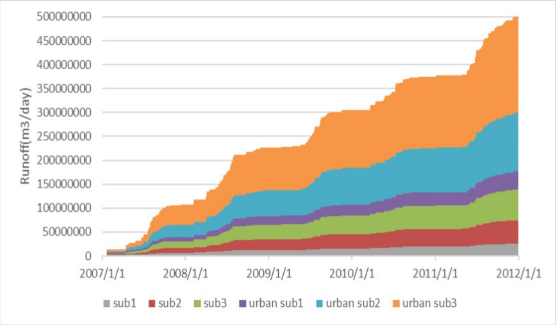


Figure 3 Comparison of runoff time series between basic models and urbanization scenario models

Looking at how urbanization affects total runoff, it can be observed that urbanization scenarios lead to significant increases in runoff. In highly urbanized watersheds, impervious surfaces alter the balance between surface runoff and infiltration, with runoff running out of control across the region, for example, a study conducted in the Ethiopian city of Adama found that urbanization led to a significant increase in runoff. The study found that urban built-up area increased by about 22% per year from 1995 to 2019, which was associated with an increase in runoff depth (Pasquier et al., 2022). The results are consistent with the literature, suggesting that urbanization does affect runoff, and in this model, increased runoff may result in flooding, which was found to be exacerbated by urbanization, overexploitation of groundwater, increased impervious surfaces from construction, water pollution, and deterioration of water quality (Bilgic et al., 2023). This illustrates the vital role that natural land replaced by urban development plays in absorbing and mitigating runoff, underscoring the importance of sustainable urban planning and development.

3.2 Modeling the lakes

Calculation of lake system based on simulated runoff of catchment area. The upstream and downstream lakes are designated as lakes 1 and 2, and the changes of the lake system after the inflow of runoff are observed by observing the lake storage capacity and lake water level. The storage capacity and water level of two lake water models are shown in the following figure.

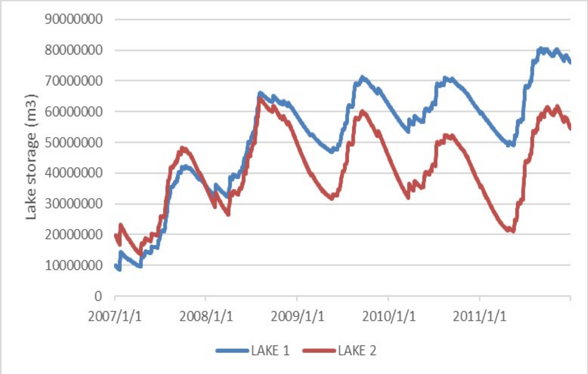


Figure 4 Storage capacity diagram of lake water model

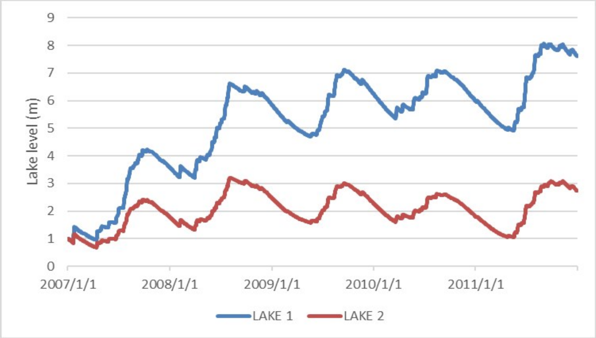


Figure 5 Lake level of lake water model

It can be seen from the charts of the two lakes that the water storage capacity and lake water level increase significantly after runoff enters the lake and fluctuate during the growth period, which is speculated to be related to the change of rainfall caused by seasonal changes. The amount of water stored in the upstream lake has been increasing, although it fluctuates, and its water level also reached its highest level in late November. It is speculated that the runoff in the catchment area is higher than the evaporation and outflow capacity of the lake. Although the water storage capacity of the downstream lake has been increasing, its water level growth has tended to balance out. Under the influence of seasonal changes, rainfall and evaporation rates can change, which is responsible for the fluctuation of water levels in upstream and downstream lakes. Normally, when there is more seasonal rainfall, the water level of the upstream lake rises, resulting in an increase in water storage. However, the water level of the downstream lake may not reach the maximum height due to some factors, such as terrain, hydrological characteristics, etc., but will reach a dynamic equilibrium. If environmental conditions do not change, the existing water level is maintained and only seasonal variations are preserved.

3.3 Assessing the impacts of climate change

This section forecasts the model changes between 2030 and 2033 by considering the climate change trends in the model, and recalculates precipitation, evaporation, runoff and other factors to simulate the lake model. First, the new runoff data obtained are compared with the basic model, as shown in the figure below.

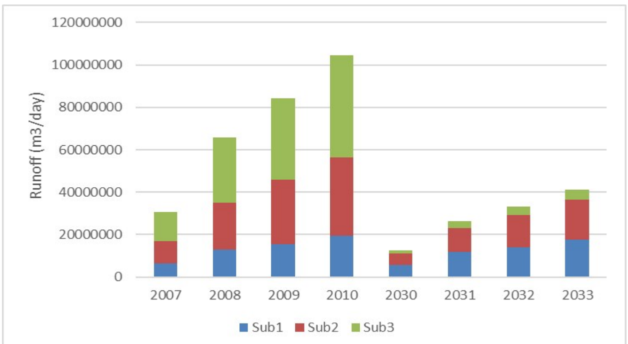
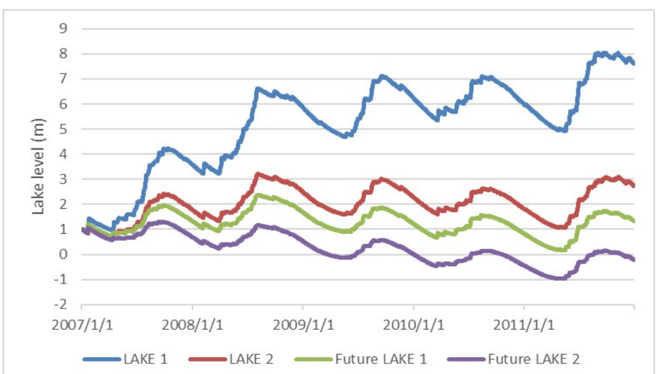


Figure 6 Runoff accumulation bar graphs from catchment outlet models between 2007 and 2010 and 2030 to 2033, showing current and future inflow lake runoff

By observing the comparison between the two scenarios, we found that due to the decrease of rainfall and the increase of evaporation in the future, the runoff from the catchment area will decrease significantly, and it is speculated that a relatively large decrease in rainfall is the key factor leading to the decrease of runoff. The study on the Baikal basin found that there is a significant correlation between precipitation and runoff. The decrease in rainfall explained more than 60% of the decrease in runoff, and although rainfall resulted in an increase in potential evaporation, precipitation was the main cause of the decrease in runoff (Grigore et al., 2023). These findings suggest that reduced rainfall and increased evaporation do lead to significant reductions in runoff in catchment areas, which could lead to declines in lake levels and water storage.

The decrease of runoff from the catchment area will certainly affect the lake model. If the runoff from the catchment area reaches the outlet, it is speculated that the storage capacity and water level of the upstream lake will decrease, while the downstream lake will also decrease due to the influence of the upstream lake. Coupled with the decrease of precipitation and the increase of evaporation, the lake water will suffer a large decrease. Comparing the lake model forecast after 2030 with the lake model data from 2007 to 2011, the results are shown in the figure below.



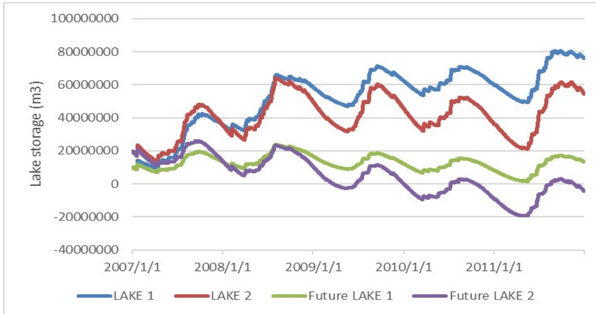


Figure 7,8 Projected lake storage and water level curves after 2030 based on data from 2007 to 2011, indicating changes in lake water and water levels now and in the future

It can be observed that with the diminishing rainfall, increase of evaporation, and corresponding decrease of runoff, both the water level and water storage capacity of the lake decreased. According to the curve, the lake initially reaches a new dynamic equilibrium at a lower water level. It can still be observed that the lake's water volume changes correspond to seasonal variations due to seasonal variations in rainfall and evaporation rates. When the water level was below the water table, groundwater will flow into surface stream channels, aiding in sustaining streamflow when surface runoff is low or nonexistent. Under natural conditions, the travel time of groundwater can range from a less than a day to many years. Interaction of surface water systems with groundwater systems depend on many factors, including positions of the surface water system relative to the groundwater systems: characteristics of the surface water systems and their underlying materials; and the climate setting(Mays LW,2012). However, as the input continues to be lower than the output over time, the recharge of the groundwater system could not maintain the minimum water level, the lake will eventually dry up, which is a negative change for the lake system. The drop in lake level means that the decrease in rainfall and the increase in evaporation are the two key drivers upsetting the surface water balance. The earth ' s temperature is affected by numerous causes, among which the greenhouse effect plays a significant role. On a global scale the warming would result in increased evaporation and increased precipitation. In general, its hydrologic effects are likely to influence water storage patterns throughout the hydrologic cycle and impact the exchange among aquifers, streams, rivers and lakes (Mays LW, 2012). Relevant research results show that the increase in temperature caused by global warming will correspondingly increase the evaporation, although it will not cause the loss of most lakes at present, and even increase the lake water through the melting of glaciers. However, lakes in arid regions still experience significant water loss (Huang et al., 2023). For the current lake model, even with runoff replenishment from the catchment area, the backup of the groundwater system, the lake will dry up in the future trend, indicating that the current water balance is short-lived without ecosystem protection. Once rainfall and evaporation reach the critical point, the water volume of the lake will continue to lose, and the loss of the upstream lake will continue to affect the water storage of the downstream lake, leading to a chain reaction. This will have a significant impact on the local water environment and water resources management.

4 Discussion

This model aims to adapt to global change, and the current global climate has witnessed significant changes in the past. Current water management practices may not be sufficient to cope with the impact of climate change. By simulating catchment runoff models and lake models, we can predict the adaptability of local hydrological systems to climate change and the trend of future water resources management, which will provide guidance for managers. However, the applicability of the model is worth discussing, so the calculation process of the model needs to be evaluated.

First of all, the weather forecast applied in this model is a global climate model, which predicts the hydrological model obtained from the temperature change of the global warming scenario and the historical rainfall evaporation data. The model considers the weather factors on a global scale and provides long-term forecasts for the next few decades. However, when screening the models, it is found that the weather data provided by the model may not be consistent with local characteristics. In recent decades, alpine glaciers in the high mountains of Asia will melt due to global warming, and the long-term reduction of glacier cover will reduce the water supply in the upstream basin, putting the basin at risk of severe water shortage, but the corresponding precipitation will increase (Huang et al., 2023). This seriously interferes with the calculation process of the lake model and does not accord with the predictable results of the normal model. But in coastal areas, global models can better account for ocean, land and other factors. This model is a small regional lake, and the global climate model may not be able to reflect the terrain and local climate characteristics around the lake, but the regional model can capture the local temperature and rainfall characteristics more satisfactorily, and can consider the relevant terrain, land use, and local unique seasonal characteristics. Taken together, regional models can be used to obtain more accurate data for calculations, and the use of global climate models as a reference for the general direction can make the obtained models more convincing.

The paper does not take into account some other effects of temperature change that could interfere with the lake model, and related studies show that rising temperatures in climate models will intensify the Earth's water cycle and increase evaporation. Increased evaporation will lead to more rainfall, but will also lead to drought in some areas (Trenberth, K. E., 2011). The current model does not take this factor into account. Temperature rise may change the evaporation mode and rate of water bodies, thus affecting the parameters of evaporation process in the model. Increased evaporation will also lead to changes in precipitation distribution, so it is necessary to consider the spatial changes of rainfall and the size of rainfall, and the changes in evaporation and precipitation need to be verified and calibrated through actual conditions, to ensure that the simulated model agrees with the observed results. In addition, the hydrological model used in this model is a global climate model, which provides some references for the current hydrological model calculation. However, global climate models have certain limitations. The study of Risley and Zammit (2023) found that global climate models rely on large-scale observational data sets, which causes data measurement errors in temperature, precipitation and some key climate variables. A large range of data is more intuitive, but if there is less local hydrological observation and monitoring, there will be a large measurement error, affecting the results of the hydrological model. When selecting the climate model, this model also encountered that the climate predictions of different climate models for different seasons showed completely opposite trends, which seriously interfered with the results of the forecast data. Moreover, global climate models can only roughly distinguish the local topography, which will have a bias, and the topography of a specific region will affect the climate prediction. Baker et al. (2021) found that global climate models simplify many physical processes, such as the interaction between land and atmosphere, which cannot accurately reflect the local hydrological behavior. This model consists of three catchment areas and a pair of upstream and downstream lakes. The rough model cannot accurately reflect how the climate interacts with local characteristic factors, resulting in inaccurate results. Local observation data need to be calibrated to improve data accuracy.

General circulation models or global climate models include land, air, and ocean domains, making predictions on an innumerable environmental variables, showing us how climate changes on a regional scale, which is of utmost importance for our daily life as well as in planning our future. However, knowing their limits in the uncertainty of their predictions is essential to our rational use of these models. The models predict better on a monthly- or annually-averaged basis rather than daily event. The simple bucket model has the merits of using simple mathematical models pragmatically for the real world, but it does not take into account of industrial, agricultural and community usage of water. Anyhow our model has predicted that urbanization increase will lead to significant increases in runoff(Fig. 3). Based upon the predictions of the GCM model, our model predicted the runoff from the catchment area in 2030 to 2033 will decrease significantly(Fig, 6), lake storage and water level curves will decline till the lakes dry out(Fig, 7, 8). This leads to a contradictory result, which is caused by the fact that the predicted climate change reveals a serious decrease trend in local precipitation. Despite the uncertainty of future climate change, the significant decrease in runoff caused by the decrease in precipitation will change the local water balance. Lakes are usually one of the sources of groundwater recharge. If the lake level is lowered, it will affect the rate at which lake water seeps into groundwater, which will affect the rivers and streams fed by groundwater. In addition, as the water level of the lake falls, the surface area of the lake may decrease, changing local evaporation rates and possibly affecting local climate patterns, which may become more unpredictable.

Before the scarcity of water issue arises, our water policy should be modified in advance. Rationing is one way to reallocate water resources. Even trading water with one another can be encouraged. Models are in a constant state of improvement with the rapid advances in computational power and the understanding of the climate forces.

Finally, as for model improvement and future suggestions, this model is an idealized model, and the goal is achieved through relatively rough calculation and prediction. The accuracy improvement of this model is as follows:

1. For the parameters of the catchment model, it is necessary to obtain a more accurate runoff coefficient c value according to the proportion of land use, so as to obtain a more accurate runoff calculation.

2. There are deviations between the model runoff and observed runoff in different days, and it is presumed that the runoff is caused by other factors on the surface, which should be taken into account when calculating the results.

3. For lake models, accurate rainfall data for lake areas should be used instead of rainfall data for catchment areas.

4. For the prediction of future climate change trends, it is necessary to combine regional climate models and global climate models to obtain more accurate changes, and it is recommended to use climate models that conform to local seasonal characteristics.

5. For forecasting rainfall and evaporation due to future weather changes, it is necessary to use data closer to the current time to reduce the error caused by long-term forecasts.

For modelers, the following steps can be taken to further refine the lake model in the future:

1. This model only discusses the effect of catchment runoff on upstream and downstream lakes. For further research,

the spatial location of catchment and lakes can be simulated according to the actual local topography, and parameters can be improved to obtain more topographic lake models.

2. Refer to more parameters, such as the exchange of surface water and groundwater caused by the surrounding rivers, or whether the sea level rise will affect the lake model.

3. This model does not explore the impact of water quality factors on the lake system, but introduces water quality parameters into the lake model to simulate the impact of rising temperature on lake water quality and assess the impact of water quality changes on the lake ecosystem.

4. Based on the results of the model, explore the impacts of different management strategies on the lake system, such as the positive or negative impacts caused by possible future urban construction, afforestation and even terrain changes, and guide the lake management and protection work through the obtained data.

5. Conduct model uncertainty analysis, idealized simulation results have unreliability and uncertainty, and evaluate and explain the uncertainty of model parameters, data input and assumptions, which can improve the credibility and applicability of simulation results.

Through these measures, modelers can more comprehensively understand the dynamic balance mechanism of lake system and cope with environmental changes, and provide more accurate scientific basis and decision support for lake management and protection.

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