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A review on Climate change and hydrological models

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Abstract

arious ongoing researches are there on topics like which model will give more compatible results with that of observed discharges. It was argued that even complex modeling does not provide better results. Rainfall-runoff models are classified based on model input and parameters and the extent of physical principles applied in the model. This paper discussed various climate change and Hydrological models. Majorly, there are three types of models such as: Empirical model, conceptual mode and physical model. Empirical model is observation oriented models which take only the information from the existing data without considering the features and processes of hydrological system and hence these models are also called data driven models. Conceptual model (parametric models) describes all of the component hydrological processes. And physical model is a mathematically idealized representation of the real phenomenon. Global Climate Models (GCMs) have grown from the Atmospheric General Circulation Models (AGCMs) broadly used for daily weather prediction. It has been used for a range of applications, including investigating interactions between processes of the climate system, simulating evolution of the climate system, and providing projections of future climate states under scenarios that might vary the evolution of the climate system. Hydrological models are mainly used for predicting system behavior and understanding various hydrological processes. A model consists of various parameters that define the characteristics of the model. SWAT is a semi-empirical and semi-physical model.

Keywords: Climate change, GCM, Hydrology, SWAT

1. Introduction

1.1. Background and justification

Rainfall-runoff models are classified based on model input and parameters and the extent of physical principles applied in the model. It can be classified as lumped and distributed model based on the model parameters as a function of space and time and deterministic and stochastic models based on the other criteria.

Deterministic model will give same output for a single set of input values whereas in stochastic models, different values of output can be produced for a single set of inputs. According to Moradkhani and Sorooshian (2008) in lumped models, the entire river basin is taken as a single unit where spatial variability is disregarded and hence the outputs are generated without considering the spatial processes where as a distributed model can make predictions that are distributed in space by dividing the entire catchment in to small units, usually square cells or triangulated irregular network, so that the parameters, inputs and outputs can vary spatially.

Another classification is static and dynamic models based on time factor. Static model exclude time while dynamic model include time. Sharma et al. (2008) had classified the models as event based and continuous models. The former one produce output only for specific time periods while the latter produces a continuous output. One of the most important classifications is empirical model, conceptual models and physically based models. Various ongoing researches are there on topics like which model will give more compatible results with that of observed discharges. It was argued that even complex modeling does not provide better results. Climate change and soil heterogeneity has got an important role in finding out surface runoff. This paper discussed various climate change and Hydrological models.

2. Types of models

2.1. Empirical models (Metric model)

These are observation oriented models which take only the information from the existing data without considering the features and processes of hydrological system and hence these models are also called data driven models. It involves mathematical equations derived from concurrent input and output time series and not from the physical processes of the catchment. These models are valid only within the boundaries. Unit hydrograph is an example of this method. Statistically based methods use regression and correlation models and are used to find the functional relationship between inputs and outputs. Artificial neural network and fuzzy regression are some of the machine learning techniques used in hydro informatics methods.

Conceptual model (parametric models)

This model describes all of the component hydrological processes. It consists of a number of interconnected reservoirs which represents the physical elements in a catchment in which they are recharged by rainfall, infiltration and percolation and are emptied by evaporation, runoff, drainage etc. Semi empirical equations are used in this method and the model parameters are assessed not only from field data but also through calibration. Large number of meteorological and hydrological records is required for calibration. The calibration involves curve fitting which makes the interpretation difficult and hence the effect of land use change cannot be predicted with much confidence. Many conceptual models have been developed with varying degree of complexity. Stanford Watershed Model IV (SWM) is the first major conceptual model developed by Crawford and Linsley in 1966 with 16 to 20 parameters.

2.2. Physical model

This is a mathematically idealized representation of the real phenomenon. These are also called mechanistic models that include the principles of physical processes. It uses state variables which are measurable and are functions of both time and space. The hydrological processes of water movement are represented by finite difference equations. It does not require extensive hydrological and meteorological data for their calibration but the evaluation of large number of parameters describing the physical characteristics of the catchment are required (Abbott et al. 1986 a). In this method huge amount of data such as soil moisture content, initial water depth, topography, topology, dimensions of river network etc. are required. Physical model can overcome many defects of the other two models because of the use of parameters having physical interpretation. It can provide large amount of information even outside the boundary and can applied for a wide range of situations. SHE/ MIKE SHE model is an example. (Abbott et al. 1986 a, b).

3.Climate change models

3.1. Overview of climate change in general

The rising of fossil fuel burning and land use changes have emitted, and are continuing through time, this leads to increasing quantities of greenhouse gases into the Earth's atmosphere. These greenhouse gases (carbon dioxide (CO_2), methane (CH_4) and nitrogen dioxide (N_2O)), and a rise in these gases has caused a rise in the amount of heat from the sun withheld in the Earth's atmosphere, heat that would normally be released back into space. This rise in heat has led to the greenhouse effect, resulting in climate change. The major characteristics of climate change are increases in average global temperature (global warming), changes in cloud cover and precipitation particularly over land, melting of ice caps and glaciers and reduced snow cover, and increases in ocean temperatures and ocean acidity due to seawater absorbing heat and carbon dioxide from the atmosphere (UNFCC, 2007).

Over the last century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million to 379 parts per million in 2005, this indicates the average global temperature rose by 0.74^0C. This is mostly due to man-made emissions of greenhouse gases (mostly CO2). An increasing rate of global warming has particularly taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the past 12 years (IPCC, 2007). The report gives detailed projections for the 21st century and these show that global warming will continue and accelerate. The best estimates indicate that the Earth could warm by 3^0C by 2100. Even though countries reduce their greenhouse gas emissions, the Earth will continue to warm. Predictions by 2100 range from a minimum of 1.8^0C to as much as 4^0 C rise in global average.

3.2. Climate change on water availability

Vörösmarty *et al*. (2010) report that about 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability, water demand, and pollution. UNESCO (2011); Mohammed *et al*. (2020) warns for World population climate change can alter the availability of water and therefore threaten water security.

Schewe et al. (2013) projected that about 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1^0C rise in global mean temperature (compared to the 1990s), rising to 14% at 2^0C and 17% at 3^0C; the spread across climate and hydrological models were, however, large.According to Mohammed *et al*. (2020), Maximum temperature increase up to $+1.9^0$C in the month of October at TikurWuha watershed. The projection is based on RCP8.5 scenario.

According to Kundzewicz and Döll, (2009) due to climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to increased precipitation variability and decreased snow and ice storage. Under these conditions, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals. However, this option is sustainable only where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Labat *et al*. (2004) claimed a 4% increase in worldwide total runoff per 1^0C rise in temperature during the 20th century.As indicate by Mekonnen et al. (2018) Smallholder and subsistence farmers, pastoralists and forest-dependent households are the most hit by climate-related hazards.

3.3. GCMs

Global climate models (GCMs) Global Climate Models (GCMs) have grown from the Atmospheric General Circulation Models (AGCMs) broadly used for daily weather prediction. It has been used for a range of applications, including investigating interactions between processes of the climate system, simulating evolution of the climate system, and providing projections of future climate states under scenarios that might vary the evolution of the climate system. The most widely known application is the projection of future climate states under various scenarios of increasing atmospheric carbon dioxide (CO_2). Global Climate Models (GCMs) must incorporate all the many physical, chemical, and biological processes that influence climate over different spatial and temporal scales. Although the models have evolved much in recent years, limitations and deficiencies remain (Lupo, 2006).

Dynamically simulates the circulation of the atmosphere, including many processes that regulate energy transport and exchange by and within the atmospheric flow. The main atmospheric flow is represented by fundamental equations that link the mass distribution and the wind field. These equations are represented on a spherically spatial grid field that has many levels characterizing the depth of the atmosphere. The flow equations are modified by the representation of processes that occur on a scale beneath that of the grid; including such processes as turbulence, latent heat of condensation in cloud formation, and dynamic heating as solar and infrared radiation cooperate with atmospheric gases, aerosols, and clouds. The oceans are at small as important as the atmosphere for the transport of energy. For that reason, the GCM also includes an Ocean General Circulation Model (OGCM) to simulates the circulation of the oceans. The OGCM is important for climate simulations because the oceans represent a dynamic thermal reservoir that, through energy exchange with the atmosphere, dominates the evolution of the climate system. The specification of the processes that regulate heat, moisture, and momentum exchanges between the ocean and atmosphere is vital to the integrity of a GCM (Lupo, 2006).

3.4. Statistical downscaling Model (SDSM)

The Statistical downscaling Model is a freely available tool that produces high resolution climate change scenarios. SDSM is intended to bridge the divide between accessibility and sophistication. This software enables the production of climate change time series at sites for which there are sufficient daily data for model calibration, as well as archived General Circulation Model (GCM) output to generate scenarios of the 21st century. SDSM can also be used as a stochastic weather generator or to fill gaps in meteorological data. (Wilby and Dawson, 2013).

Statistical downscaling has an advantage over RCMs because it can produce site specific climate projections (USAID., 2014). It is computationally inexpensive and efficient (Fowler *et al*., 2007).

3.5. Historical development of IPCC emission scenarios

There are many Climate modeling teams around the world. If those teams used different metrics, made different assumptions about baselines and starting points, then it would be very difficult to compare one study to another. In the same way, models could not be validated against other different, independent models, and communication between climate modeling groups would be made more complex and time-consuming. There is also another difficulty with the cost of running models. The higher processing speed computers required are in short supply and great demand. Scenarios provide a framework by which the process of building experiments can be streamlined (Wayne, 2013).

In order to address these problems, the Intergovernmental Panel on Climate Change (IPCC) published the first set of climate change scenarios in 1992, called IS92. In the year 2000, the IPCC released the second generation of projections, collectively referred to as the Special

Report on Emissions Scenarios (SRES). SRES were used in two subsequent reports; the Third Assessment Report (TAR) and Assessment Report Four (AR4) and have provided common reference points for a great deal of climate science research in the last decade. In 2007, the IPCC responded to calls for improvements to SRES by catalyzing the process that produced the Representative Concentration Pathways (RCPs). The RCPs are the latest iteration of the scenario process and are used in the next IPCC report - Assessment Report Five (AR5) in preference to SRES (Wayne, 2013)

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3.5.1. RCP (Representative Concentration Pathways)

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) is owing for publication in 2013-14. Its findings will be based on a new set of scenarios that replace the Special Report on Emissions Scenarios (SRES) standards working in two previous reports. The new IPCC scenarios are called Representative Concentration Pathways (RCPs). There are four pathways: RCP8.5 (high rate), RCP6, RCP4.5 (moderate rate) and RCP2.6 (low rate) - the last is also referred to as RCP3-PD. (The numbers refer to forcing for each RCP; PD stands for Peak and Decline) (Wayne, 2013).

RCP2.6 (RCP3PD) assumes that through radical policy intervention, greenhouse gas emissions are reduced almost immediately, leading to a slight reduction on today's levels by 2100. The worst case scenario is RCP8.5 - assumes more or less unabated emissions. The trends of CO_2 emissions the RCP8.5 is representative of the high range of non-climate policy scenarios. The forcing pathway of the RCP4.5 scenario is comparable to a number of climate policy scenarios and several low emissions reference scenarios in the literature, such as the SRES B1 scenario. The RCP2.6 represents the range of lowest scenarios, which requires strict climate policies to limit emissions. The trends in CH4 and N_2O emissions are largely due to differences in the expected climate policy along with differences in model assumptions. Emissions of both CH_4 and N_2O indicate a rapidly increasing trend for the RCP8.5 (no climate policy and high population). For RCP6 and RCP4.5, CH_4 emissions are more-or-less stable throughout the century, while for RCP2.6, emissions are reduced (Wayne, 2013).

4.Hydrological modelling

According to Sharma et al. (2008), a model is a simplified representation of real world system. The best model is the one which give results close to reality with the use of least parameters and model complexity. Models are mainly used for predicting system behavior and understanding various hydrological processes. A model consists of various parameters that define the characteristics of the model. A runoff model can be defined as a set of equations that helps in the estimation of runoff as a function of various parameters used for describing watershed characteristics. The two important inputs required for all models are rainfall data and drainage area. Along with these, water shed characteristics like soil properties, vegetation cover, watershed topography, soil moisture content, characteristics of ground water aquifer are also considered. Hydrological models are now a day considered as an important and necessary tool for water and environment resource management.

4.1.Soil and Water Assessment Tools (SWAT)

The Soil and Water Assessment Tool (SWAT) was developed at United States Department of Agricultural Research Service in a modeling experience that span roughly 30 years (Arnold et al., 1998). It is a semi-empirical and semi-physical model; it is a basin scale, continuous time, conceptual and long term simulation model that operates on daily and hourly time step. The model can predict the impact of land use change on hydrological regimes in watersheds with varying topography, climate and soils, land use and management over long periods and serves primarily as a strategic planning tool (Olivera et al., 2006). The model development was an outgrowth of SWRRB (Simulators for water resources in rural basin) model with coupling with

United State Agricultural Development research services ARS (Agricultural Research service) (Arnold and Williams, 1987).

There are two-level scales of subdivisions: (1) a sub division based on the drainage area of the tributaries, and (2) based on the threshold level of land use and land cover. Soil and slope assigned by the user on each sub-watershed is further divided into a number of Hydrologic Response Units (HRUs) (Wu and Xu, 2009). The model uses continuous daily time steps and focuses on land and water interaction in predicting runoff simulation over for long time span. The SWAT model was built with an attempt to simulate the stream flow processes and the effects of land management on water quality and quantity. The model uses readily available inputs as it is coupled with an GIS environment. This enables the users to study long-term impacts of land cover and climate, land management and nutrient supply on the water resource potential.

The major components simulated by SWAT are hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch *et al*., 2011). Evapotranspiration, surface runoff, infiltration, percolation, shallow aquifer and deep aquifer flow, and channel routing are simulated by the hydrologic components of the SWAT model (Arnold and Allan, 1996). The hydrological component divides the simulation into four processes: surface flow, subsurface flow, and interflow, shallow aquifer and deep aquifer, and open channels. Total stream flow is determined by summing the surface flow into lateral flow and base flow which are returned to the stream from the shallow aquifer. The deep recharge to the aquifer is considered as a loss from the hydrologic components.

The model simulates a basin by dividing it into sub watersheds that account for differences in soils and land use. The sub-basins are further divided into hydrologic response units (HRUs); and these HRUs are the product of overlaying of slope, soils and land use. SWAT was evaluated by performing calibration and uncertainty analysis using SWAT-CUP (Neitsch et al., 2011).

4.1.1. SWAT-CUP

SWAT-CUP (SWAT Calibration and Uncertainty Procedures) is designed to integrate various calibration and uncertainty analysis programs for SWAT using different interface. Currently, this program can run SUFI2 (Abbaspour *et al*., 2007), GLUE (Beven and Binley, 1992), and ParaSol (van Griensven and Meixner, 2006), PSO, and MCMC procedures. Currently the program links with Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol) (Abbaspour, 2011). Sequential Uncertainty Fitting (SUFI2) and Markov chain Monte Carlo (MCMC) procedures. For most studies, various SWAT parameters related to discharge and sediment were estimated using the SUFI2 and ParaSol optimization technique. These optimization techniques use the range of the parameters as constraints and 7 of the model evaluation coefficients as Objective Functions (OF) during calibration. They are 1) A multiplicative form of the square error (mult); 2) A summation form of the square error (sum); 3) Coefficient of determination (r2); 4) Nash-Sutcliffe (1970) coefficient (NS); 5) Chi-squared χ2 (Chi2); 6) Coefficient of determination R2 which is multiplied by the coefficient of the regression line (br2); and 7) sum of square of residual (SSQR). In SUFI2 all of the OF are exist, there is also a possibility to improve the model evaluation coefficients by using different OF, but in ParaSol there is only one objective function that is SSQR (Abbaspour et al., 2007).

5. Conclusion and recommendation

Rainfall-runoff models are the standard tools used for investigating hydrological processes. SWAT is semi-empirical and semi-physical model; it is a basin scale, continuous time, conceptual and long term simulation model that operates on daily and hourly time step.The model can predict the impact of land use change on hydrological regimes in watersheds with varying topography, climate and soils, land use and management over long periods and serves primarily as a strategic planning tool. A proper knowledge of subsurface flow pathways and hydraulic characteristics is necessary otherwise it will create adverse effect on model calibration. Various researches are still going on to make better predictions and to face major challenges.

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