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Modeling hydrological variability of fresh water resources in the Rio Cobre watershed, Jamaica

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A B S T R A C T

Freshwater resources and healthy coast lines are the basis of ecotourism in the Caribbean islands. The vulnerability of these islands to natural and human-induced disasters and their inability to cope with the problem necessitate the understanding of the hydrological processes and responses of the watersheds to various stressors. The main objective of this study is to characterize, model and analyze the temporal variability of hydrological processes in the Rio Cobre watershed, Jamaica using the Soil and Water Assessment Tool (SWAT). Determination of the temporal hydrological water balance and the spatial distribution of hydrological processes in the Rio Cobre watershed are discussed. The ability of a watershed model to accurately predict the hydrological processes is evaluated through parameter sensitivity analysis, model calibration and validation. Sequential Uncertainty Fitting (SUFI-2) calibration and uncertainty analysis methods were used for the set-up of the SWAT model. The model evaluation statistics for streamflow prediction show that there is a good agreement between the measured and simulated flows that was verified by the coefficient of determination (R^2) and Nash Sutcliffe efficiency greater than 0.5. Past studies suggested that the prediction efficiency of the calibrated model can be judged as satisfactory if R^2 and NSE values are >0.5. Model simulation results are subject to uncertainties due to input data, model structure and errors in parameter estimates. The choice of the retention parameter estimation method, routing method, evapotranspiration estimation methods might significantly affect the prediction of surface runoff and then the water balance. The hydrological water balance analysis indicated that above 52% of the annual precipitation is lost by evapotranspiration in the basin. Surface runoff contributes more than 12%, whereas the ground water contributes more than 42% to the total water yield. The calibrated model can be used for further analysis of the effect of climate and land use change as well as other different management scenarios on streamflow and other hydrological components. The model output can be used as a tool to develop appropriate adaption strategy to the effect of land use and climate changes.

1. Introduction

Freshwater availability is a major requirement for food security, public health, ecosystem protection and human wellbeing. Nowadays, freshwater resources' availability to meet all the consumptive and non-consumptive needs is a global challenge facing many communities. There are a number of major environmental threats to the Jamaican watersheds which include water contamination and pollution mainly, due to soil erosion, agrochemical runoff, sedimentation and unsustainable use of land and water resources. This challenge is further complicated at a time when demands for freshwater are increasing owing to population increase and the need for more food production in the face of uncertainty of the rainfall emanating from a changing climate.

The Caribbean islands encompass over 1.9 million km^2 ranging from small, low islands to large, mountainous terrains with large variations in rainfall pattern, landform, climate, and land use. The population in the coastal zone of Caribbean nations (~100 million) is projected to be doubled by the next 30 years at the current growth rate, placing them among the most vulnerable regions in the world. This population pressure, along with climate and upstream land use changes, will greatly intensify the stress on their fresh water and coastal resources. According

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to the Intergovernmental Panel on Climate Change (IPCC) prediction, there will be a reduction in precipitation over the region by as much as 20% during the next 50–100 years. Their tourism based economy and the increased urban development along the most sensitive coastal areas have already endangered the myriad of interlinked open marine and coastal ecosystems. The Caribbean islands are also highly vulnerable to climate change induced disasters such as hurricanes and flooding. Global warming will further compound the growing hazard and vulnerability of the Caribbean islands.

Freshwater resources and healthy coastal lines are the basis of economy for tourist attractions in the Caribbean islands. The vulnerability of these islands to natural and human-induced disasters and their inability to cope with the problem necessitate the understanding of the hydrological processes and responses of the watersheds to various stressors. Moreover, assessments of the spatial and temporal distribution of the different components of freshwater availability are essential for informed decision-making in water resources planning and management. In the Rio Cobre watershed, Jamaica, the water resources are highly stressed with the demand being 94% of the exploitable yield (WRDMP, 2005). Climate change is likely to tip the slight surplus into a deficit over the coming years/decades. Besides quantity issues, the quality of the water resources is under intense pressure.

In the Caribbean region in general and in Jamaica in particular, there is a limitation of long-term hydrometeorological data, which contributes for limited studies. In this study, the freshwater components blue water flow (water yield plus deep aquifer recharge), green water flow (actual evapotranspiration), and green water storage (soil water) were estimated using limited input data at a sub-basin level in the Rio Cobre watershed, Jamaica.

There are many hydrological models developed to quantify the water resources and sediment yield at the watershed level. Some of the available watershed models include CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), EPIC — Erosion Productivity Impact Calculator (Williams, 1995), AGNPS (Agricultural None Point Source model) (Young, 1989), SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) and HSPF (Hydrologic Simulation Program — FORTRAN) (Bicknell et al., 2001). Among the foregoing models, physically based semi-distributed models such as SWAT are well established models for analyzing the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds. A comprehensive review of SWAT model applications is given by Gassman et al. (2007).

This study focuses on model setup, calibration, evaluation and application of SWAT model for simulation of the hydrology of the Rio Cobre watershed, which flows to the Kingston Bay. The temporal distribution of freshwater availability for the watershed was predicted and partitioned in to the different hydrologic components: blue water flow, green water storage and green water flow.

The ability of a watershed model to accurately predict the hydrological process is evaluated through parameter sensitivity analysis, model calibration and model validation. An important issue to consider in the prediction of hydrology, sediment yield and water quality is uncertainties in the predictions.

According to Yang et al. (2008), the main sources of uncertainties are 1) simplifications in the conceptual model, 2) processes occurring in the watershed but not included in the model, 3) processes that are included in the model, but their occurrences in the watershed are unknown to the modeler or unaccountable, 4) processes that are not known to the modeler and not included in the model, and 5) errors in the input variables such as rainfall and temperature.

The main objective of this study is to adapt a hydrological model and analyze the temporal variability of hydrological processes in the Rio Cobre watershed, Jamaica. The paper mainly discusses (1) the calibration and validation of the SWAT model, (2) identification of the most sensitive flow parameter in the watershed and calibration of the SWAT model, and (3) the annual and seasonal hydrological water balance of the Rio Cobre watershed.

2. Description of Rio Cobre basin and water resources challenges

2.1. Study area

The Rio Cobre River is the main river in Jamaica that flows to the Kingston Bay (Fig. 1). The watershed has an approximate drainage area of 646 km^2 and is located in south central Jamaica. The watershed extends from Lluidas Vale in the west to Guys Hill in the east and ends at the coast where the Rio Cobre discharges into the Hunts Bay (Fig. 1). The Hunts Bay is a shallow brackish water body 6.5 km^2 in size (KHEPIR, 1992) which flows into Kingston Harbour. The watershed is divided into a northern and southern section. The sections are connected via the Bog Walk gorge. The gorge is the result of the river down cutting through the limestone formation over geologic time. The Rio Cobre flow during dry periods is sustained with inflows mainly coming from Moona and the Rio Pedro streams, with a drainage area of approximately 104 km^2.

The highest elevation of the Rio Cobre watershed is found in the northern section at approximately 500 m above mean sea level. Two basic bedrock geological formations that constitute this hilly area are the pre-White Limestone (volcanic/volcaniclastic) and White Limestone Formations. The pre-White Limestone is relatively impermeable and surface water is the primary water type with a dense network of streams. The rivers flow over the low permeable rocks until they get into contact with the White Limestone where the rivers sink or loose significant flow and replenish the karstic limestone aquifers.

The southern section of the watershed, also referred to as the St. Catherine Plains, is mainly characterized by complex sequences of alluvial clay, sand and gravel deposited by the Rio Cobre River over time. The alluvial deposits were laid down in a freshwater environment and are characterized by good quality groundwater in the upper 30 m which functions as an aquifer. The older deposits are of marine origin and are commonly characterized by saline soils and groundwater (KHEPIR, 1992).

2.2. Hydrologic characteristics

The historical streamflow record (1956–2009) for the Rio Cobre as measured at the stations 03CA002 and 03CA004 indicates a mean daily streamflow of 9.8 m^3/s or 864,700 m^3/day with a minimum and a maximum mean daily streamflow of 0.91 m^3/s and 602 m^3/s, respectively. The reliable yield of the Rio Cobre measured as the flow that is equaled or exceeded 90% of the time is 126.4 Mm^3/yr or 4 m^3/s.

The Water Resources Authority operates fourteen gauging stations along the major rivers within the watershed. Fig. 1 shows the location of one of the station used for our modeling in the Rio Cobre watershed. Station 03CA003 'Rio Cobre combined flows' has been used for the calibration of the ArcSWAT model. Historical data from the 03CA004 station was not continuous enough to be used in the model calibration and validation. The daily data series spans from October 20, 1954 to present comprising 20,090 daily readings with 74 readings missing (0.003% of total records).

The presence and type of water resources depend on the geology and hydrostratigraphy. The upper section of the watershed is underlain by a limestone aquifer and the groundwater therein is tapped for the supply of domestic, agricultural and industrial water. The lower section of the watershed is characterized by both the limestone and alluvial aquifers and most of the wells tap either of these units.

2.3. Water resources challenges

The Rio Cobre while flowing through Spanish Town, which is an urban setting, is subject to receiving urban runoff as well as from gullies that convey untreated or partially treated domestic wastewater from poorly functioning sewage treatment facilities. This is of major concern as the river is used for recreational purposes. At the end of the river prior