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Assessing climate change impacts on the Rio Cobre basin, Jamaica

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Abstract Anthropogenic activities may be causing an increase in the atmospheric concentrations of carbon dioxide and other "greenhouse gases" resulting in a shift of the atmosphere's radiative balance. Consequently, global and regional temperatures, rainfall patterns and other climatic variables may be altered. The timing and magnitude of runoff, soil moisture storage, lake and river depths and water quality may also be affected. These possible changes could have serious implications for future global and regional water resources and their management. The availability and management of water in tropical areas are paramount concerns. With growing populations, mostly agrarian economies and mass migration from rural areas to urban centres, the demand for adequate and safe supplies of water has never been greater, especially in the over-populated capitals of these tropical countries. A persistent problem in water resources management for tropical areas is the lack of reliable information on the quality, quantity, and spatial and seasonal distribution of available water. Expected climate change may exacerbate the complexity of this problem. To this end, climate change scenarios from the General Circulation Model (GCM) of the Goddard Institute for Space Studies (GISS) were used in conjunction with the Sacramento Watershed Model to assess possible climate change impacts on a major watershed in Jamaica. Preliminary studies show that the watershed is expected to become severely stressed. Adequate adaptation and mitigation strategies should, therefore, be considered.

Evaluaciòn de los posibles impactos del cambio climático sobre la cuenca Rio Cobre, Jamaica

Resumen Las actividades antropogénicas pueden estar provocando un incremento de las concentraciones atmosféricas de dióxido de carbono y otros "gases de invernadero" que resultan en un cambio del balance de radiación de la atmósfera. En consecuencia, las temperaturas globales y regionales, los patrones de precipitación y otras variables climáticas pueden verse alteradas. El tiempo y la magnitud de la escorrentía, de almacenaje de humedad en el suelo, la profundidad de lagos y ríos y la calidad del agua también pueden verse afectados. Estos posibles cambios podrían tener graves implicancias para los futuros recursos hídricos globales y regionales y su gestión. La disponibilidad y el gerenciamiento del agua en las zonas tropicales son preocupaciones de consideración. Con poblaciones crecientes, economías principalmente agrarias y migración masiva desde las zonas rurales a los centros urbanos, nunca ha sido tan grande la demanda de un suministro de agua suficiente y segura, especialmente en las sobrepobladas capitales de estos países. Un problema persistente de la gestión de los recursos hídricos en las zonas tropicales es la falta de información confiable sobre la calidad, cantidad y distribución espacial y estacional del agua disponible. El cambio climático que se espera puede exacerbar la complejidad del problema. A tales fines, se utilizaron los escenarios de cambio climático del Modelo General de Circulación (GCM) del Instituto Goddard de Estudios Espaciales (GISS), en conjunción con el Modelo de Cuenca de Sacramento, para evaluar los posibles impactos del cambio climático sobre una cuenca mayor de Jamaica. Los estudios preliminares muestran que se espera que la cuenca sufra una tensión importante. Por ello se debe considerar la adopción de estrategias adecuadas de adaptación y mitigación.

INTRODUCTION

A greenhouse is a glass building used to provide heat for growing plants especially in the cold winter months. The glass of the greenhouse permits sunlight to enter the building, but prohibits heat from escaping, thus warming the greenhouse. In a simplified but similar manner, the Earth's atmosphere behaves like the glass of a greenhouse. It allows the sun's short-wave radiation to pass through with relatively no obstruction, but some of its constituent trace gases—greenhouse gases—trap the long-wave, infrared, terrestrial radiation emitted by the Earth and re-emits it back toward the surface. This leads to a warming of both the lower atmosphere and the Earth's surface.

Before the middle of the next century, the mean temperature for the Caribbean region is expected to increase within the range of 1.0–3.0°C. The regional rainfall pattern is expected to be spatially varied, but no major shifts are anticipated. However, with warmer ocean temperatures comes the concern of increased frequency and intensity of hurricane activity. Sea levels are also expected to rise by about 30 cm according to Granger (1991). This would result in the inundation of the islands' coastlines and the intrusion of salt water into coastal aquifers. This paper presents a methodology and the results of an assessment of possible climate change impacts on the Rio Cobre basin of Jamaica (Fig. 1).

BACKGROUND

There is a dearth of research on the possible impacts of global climate change on the Caribbean region. Gable (1987) and Granger (1991) have done initial studies. Far more of this type of research is necessary, especially for assessments of possible climate change impacts on regional water resources. Before any such assessments can be made, plausible scenarios of the future climate must first be obtained. The state-of-the-art method of obtaining these climate change scenarios is by using General Circulation Models (GCMs). GCMs are highly complex, time-dependent, three-dimensional computer models which simulate the many interrelated physical and dynamic processes that are a part of the Earth's intricate climate system. They are based upon the known laws of physics, and they represent the interactions which exist between the atmosphere, the oceans and the land. GCMs provide numerical solutions for the prognostic simultaneous equations for conservation of mass, momentum and energy and the equation of state on a grid. They provide the most

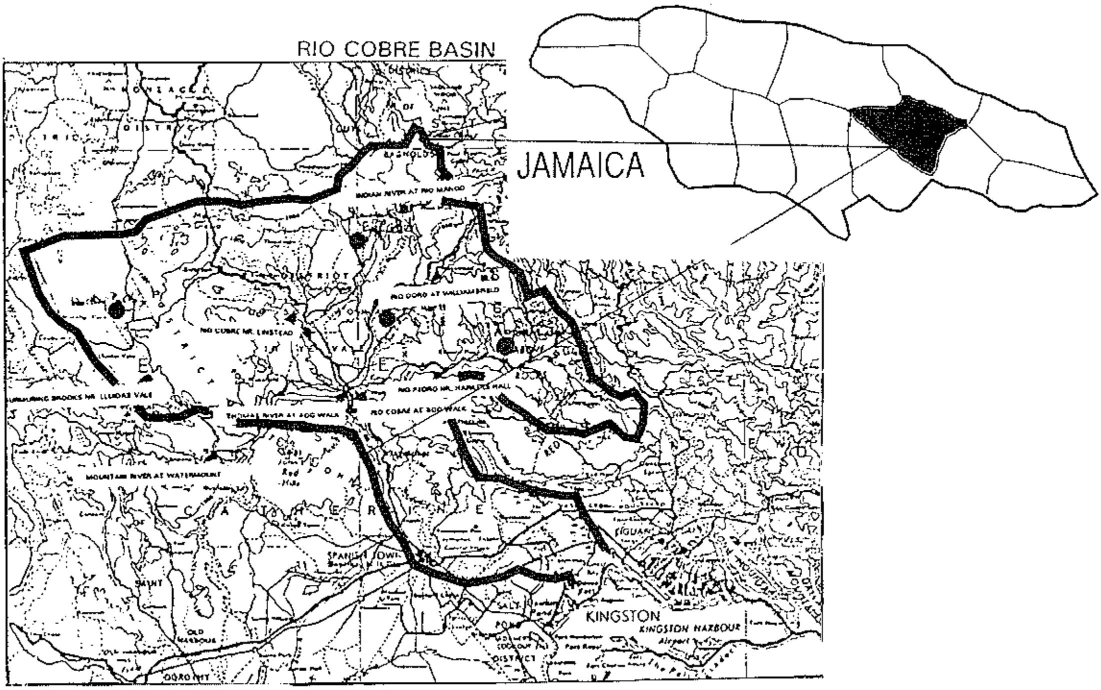

Fig. 1 Map of Jamaica and location of the Rio Cobre basin.

scientifically consistent information on the response of the atmosphere to increasing concentrations of greenhouse gases, and they provide researchers with the capability of studying both past and possible future climates under a variety of conditions.

The use of GCM outputs alone to assess climate change impacts on a regional scale does not produce acceptable results. However, GCMs are always being upgraded, although it will take years before these limitations are significantly improved. Until then, and even then, one accepted way to study climate change impacts on regional hydrology is and will be to link GCMs to regional hydrologic models (see Gleick, 1989). To determine the effects that possible climate change may have on regional water resources, if only for a first estimate, researchers first obtain a variety of climate change scenarios so as to include a range of plausible changes in the major climatic variables of temperature, precipitation and evapotranspiration. More than one GCM should be used to provide the climate change scenarios. The authors used only the GISS GCM in this study because of the unavailability of evapotranspiration data from the other GCMs which were slated for use (GFDL—Geophysical Fluid Dynamics Laboratory, UKMO—United Kingdom Meteorological Office and CCCM—Canadian Climate Centre Model). Uncertainties also arose concerning the distribution of land in the gridbox that has Jamaica within these other GCMs. Unlike the GISS GCM gridboxes, that are divided into land and ocean fractions, these others seem to have Jamaica as an all ocean gridbox. This would seriously affect the evapotranspiration, among other things, that these models calculate for the island. The authors, however, intend to extend this research via the use of additional GCMs, for conclusions drawn from only one GCM may be biased.

After the possible climate change scenarios are obtained from the GCMs, regional hydrologic, basin specific models can then be used to simulate the hydrology of the basin being studied by using the hydrological variables from the climate change scenarios to drive these models.

METHODOLOGY

The GISS GCM gridbox that contains Jamaica is mostly occupied by the ocean. The island occupies a very small portion of the gridbox. Therefore, the averaged climatic variables that the GCM produces are apt for the larger gridbox and far less apt for the small landmass of Jamaica that lies within the gridbox. Therefore, any study of climate change for the island based on the scenarios produced by the GCM must first be scaled down from the gridbox average to the island average and then further down to the watershed average. This is a major unresolved problem in the study of possible climate change impacts, via GCM scenarios, on small regional watersheds. There is no consensus within the community as to how this scaling problem should be solved. An alternative approach is to nest a higher resolution model within the GCM gridbox, but this approach also has flaws because of the inadequate modelling of the boundaries between the two models. The authors have therefore used a very simplistic, zeroth-order, first estimate approach to this problem. Since there must be some relationship between the gridbox averaged climate variables and the island averaged variables, a correction factor was used to scale the GCM climate variables down to the island averaged climate variables. Real world, gridboxed, observed data from the Legates global data set were used to develop the correction factor. The idea then is to make the relationship that exists between the Legates gridbox data and the island averaged data the same as the relationship that exists between the GCM gridbox data and the island averaged data (see Table 1). The percentage change between the corrected GCM gridbox data and the island averaged data is then used to scale the basin data. This is not the only way to get around this problem, and it may not be the best way, but it is far better than not to do any correction at all. The relationship may not hold for future climate, but it at least holds true now, and this is a straight, simple method of obtaining a zeroth order estimate. This method also captures the natural monthly climate variability as seen in Table 1.

SACRAMENTO WATERSHED MODEL

The Sacramento watershed model (Burnash *et al.*, 1973) simulates the hydrologic processes of a river basin, accounting for the movement of water from when it initially enters the basin as precipitation until it leaves as runoff or evapotranspiration. It is a deterministic or conceptual hydrological water balance model that expresses hydrological processes as mathematical equations and then solves them analytically. This model is generally accepted to be one of the most tested and reliable watershed models. The model was constructed to adhere to Barnes' theory on recession analyses, Darcy's law of flow through porous media and the work of Hanks & Klute on moisture phases of water and their vertical movement. This model

Table 1 Linking mean Jamaican rainfall (mm day^{-1}) to GISS (4 × 5) GCM via a Legates correction.

Month	Legates	Jamaica	Correction factor	GISS (1 × CO_2)	Corrected GISS (1 × CO_2)	GISS (2 × CO_2)	Corrected GISS (2 × CO_2)
January	1.3	3.5	2.7	1.6	4.3	1.6	4.3
February	1.1	3.1	2.8	1.8	5.0	1.5	4.2
March	1.2	3.1	2.6	1.9	4.9	1.4	3.6
April	2.2	4.6	2.1	2.4	5.0	1.8	3.9
May	4.9	7.5	1.5	4.1	6.2	3.4	5.1
June	5.4	6.1	1.1	4.2	4.6	3.7	4.1
July	3.8	4.3	1.1	4.4	4.8	3.1	3.4
August	4.1	5.8	1.4	3.4	4.8	2.6	3.6
September	5.1	6.8	1.3	3.5	4.6	2.3	3.0
October	5.7	8.7	1.5	5.3	8.0	4.9	7.4
November	2.7	6.2	2.3	5.2	12.0	5.7	13.1
December	1.5	4.8	3.2	2.3	7.4	2.4	7.7

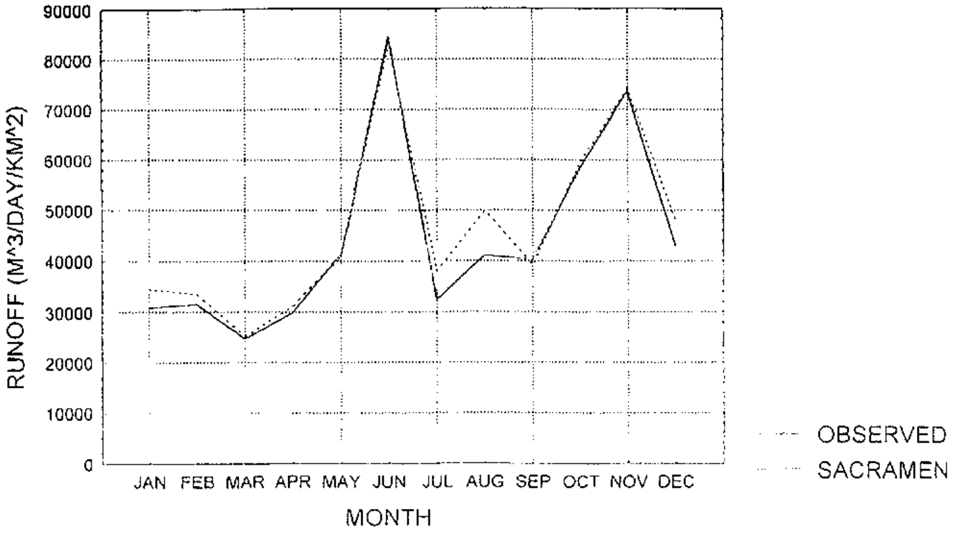

Fig. 2 Eight years (1980–1987) calibration of the Sacramento watershed model for the Rio Cobre basin.

was used to simulate runoff under climate change conditions for the 202 square mile watershed area of the Rio Cobre. Before it was used for climate change assessment for the basin, it was first calibrated and verified. Eleven years (1980–1990) of observed rainfall and runoff data from the Rio Cobre basin were used in this calibration/verification process. Eight years (1980–1987) were used for calibration (see Fig. 2), and the remaining three years were used for verification (see Figs 3(a), 3(b) and 3(c)). This was the only complete data set available for the basin. In the verification Figs 3(a)–3(c), the runoff error is the simulated Sacramento model runoff minus the observed runoff. If the model were perfect, the runoff error would be zero, and all the points would lie on the 45° line. A positive runoff error means that the model over predicts runoff, and the points would lie above the 45° line. A

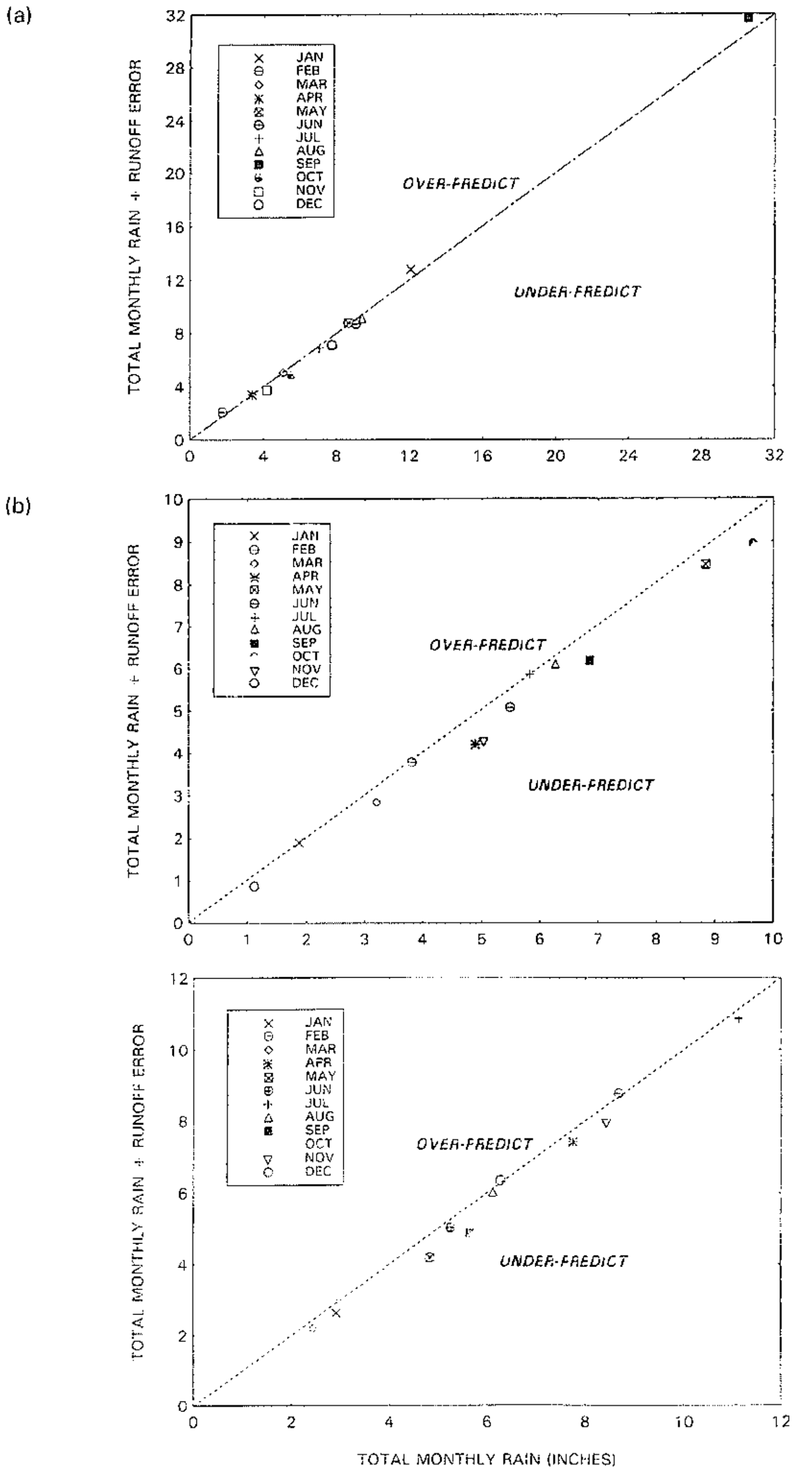

Fig. 3 Rainfall–runoff verification for the Rio Cobre: (a) 1988; (b) 1989; and (c) 1990.

negative runoff error means that the model under predicts runoff, and the points would lie below the 45° line. The Figures also indicate the distribution of runoff error in relation to the total rain.

RESULTS AND DISCUSSION

After verifying that the Sacramento model does well in simulating the observed rainfall–runoff process within the basin, the climate change scenarios for rainfall and evapotranspiration were used as inputs to the model to simulate the possible future runoff for the basin. These results are shown in Fig. 4(a). The Figure shows that, with the exceptions of January and December, the future mean monthly runoff may be less than the current mean monthly runoff, and the months of September and October may experience the most severe reductions in runoff. Figure 4(b) indicates that with the exceptions of November, December and January, mean monthly rainfall will be reduced. The most severe reductions may occur in the months of July, August and September. So, in general, the Rio Cobre basin may become more severely stressed during the months June–October when both rainfall and runoff may be at their lowest. Figure 4(c) shows that for all months evapotranspiration may be reduced. This can be attributed to less water being available for evapotranspiration.

The Kolmogorov-Smirnov statistical test for the normality of probability distributions was implemented at the 0.05 significance level to aid in the determining of return periods for the extreme cases of annual minimum and annual maximum rainfall and runoff. The results are tabulated in Table 2. All the GISS scenarios in the tables are for a 2 × CO_2 climate. Table 2 indicates that with the exception of minimum runoff, the extremes of the basin's rainfall and runoff may become more extreme for all the return periods considered.

Table 2 Return periods for rainfall (mm) of the annual minimum series.

	Return period 10 (years)	20 (years)	50 (years)	100 (years)
	Return periods for rainfall (mm) of the annual minimum series			
Rio Cobre	129	154	187	211
GISS	104	123	146	165
	Return periods for rainfall (mm) of the annual maximum series			
Rio Cobre	676	796	947	1062
GISS	575	667	783	872
	Return periods for runoff values (m^3 day^{-1} km^{-2}) of the annual minimum series			
Rio Cobre	21 114	22 666	24 627	26 125
GISS	37 979	41 721	46 447	50 058
	Return periods for runoff values (m^3 day^{-1} km^{-2}) of the annual maximum series			
Rio Cobre	288 582	354 717	438 257	502 072
GISS	265 515	310 968	368 383	412 242

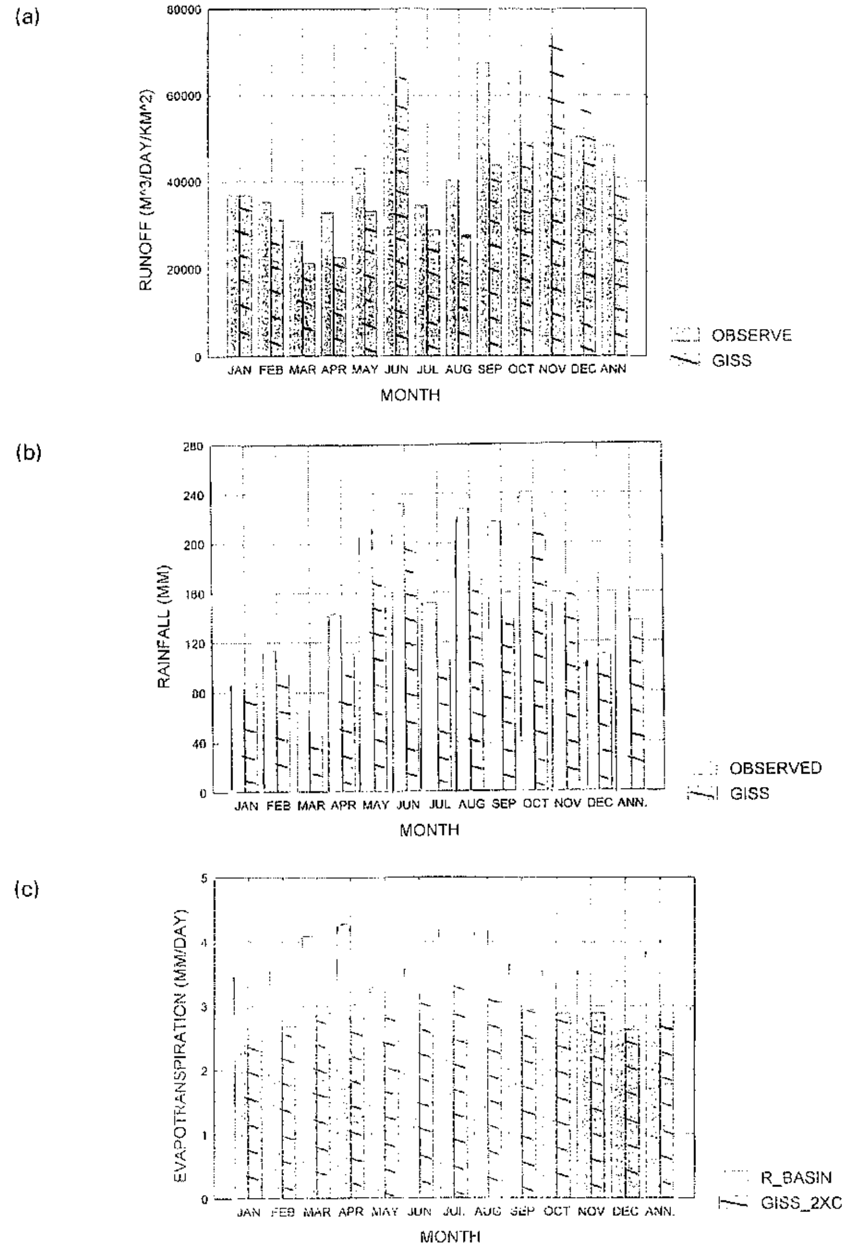

Fig. 4 Projection of (a) runoff, (b) rainfall, and (c) evapotranspiration of the Rio Cobre for a 2 × CO_2 climate scenario.

CONCLUSION/RECOMMENDATIONS

This initial assessment of possible climate change impacts on the Rio Cobre basin indicates that the basin may undergo severe stress as both basin rainfall and runoff decrease. This study, however, is yet preliminary. A more extensive study should be conducted using a much longer historical data set, perhaps even a synthetic one. Similar studies should be done on other catchments in Jamaica and throughout the tropics. More than one GCMs need to be utilized so as to achieve less biased results and a better range of possible climate scenarios. In addition to these recommendations, other relationships should be used to scale GCM gridbox climate variables down to catchment climate variables. Hypothetical scenarios could also be used to develop future climate scenarios. This approach, although less scientific, would eliminate the need for scaling.

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REFERENCES

Burnash, R. J. C., Ferral, R. L. & McGuire, R. A. (1973) A generalized streamflow simulation system conceptual modeling for digital computers. *Report by the Joint Federal-State River Forecasting Center, Sacramento, California.*

Gable, F. (1987) Changing climate and Caribbean coastlines. *Oceanus* **30**(4), 53–56.

Gleick, P. H. (1989) Climate change, hydrology and water resources. *Rev. Geophys.* **27**(3), 329–344.

Granger, O. (1993) Climate change interactions in the Greater Caribbean. *The Environmental Professional* **13**, 43–58.