# Application of the Soil and Water Assessment Tool (SWAT Model) on a small tropical island (Great River Watershed, Jamaica) as a tool in Integrated Watershed and Coastal Zone Management

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Received 17-X-2013 Corrected 07-II-2014 Accepted 24-III-2014

**Abstract:** The Great River Watershed, located in north-west Jamaica, is critical for development, particularly for housing, tourism, agriculture, and mining. It is a source of sediment and nutrient loading to the coastal environment including the Montego Bay Marine Park. We produced a modeling framework using the Soil and Water Assessment Tool (SWAT) and GIS. The calculated model performance statistics for high flow discharge yielded a Nash-Sutcliffe Efficiency (NSE) value of 0.68 and a $R^2$ value of 0.70 suggesting good measured and simulated (calibrated) discharge correlation. Calibration and validation results for streamflow were similar to the observed streamflows. For the dry season the simulated urban landuse scenario predicted an increase in surface runoff in excess of 150%. During the wet season it is predicted to range from 98 to 234% presenting a significant risk of flooding, erosion and other environmental issues. The model should be used for the remaining 25 watersheds in Jamaica and elsewhere in the Caribbean. The models suggests that projected landuse changes will have serious impacts on available water (streamflow), stream health, potable water treatment, flooding and sensitive coastal ecosystems. Rev. Biol. Trop. 62 (Suppl. 3): 293-305. Epub 2014 September 01.

**Key words:** Soil and Water Assessment Tool, Integrated Coastal Zone and Watershed Management, GIS.

Increasing population along with increasing pressure on land for food, expansion, and the need for infrastructure facilities have given rising alarm to conflicting demands on finite land and water resources (Biswas, Sudhakar & Desai, 2002). Additionally, anthropogenic land use changes tend to result in various geomorphic and hydrologic changes. These include changes in the spatial and temporal aspects of flood peaks, and in the extent and type of soil erosion (Magilligan & Stamp, 1997).

To adequately handle the stresses to our natural resources from climate change (e.g., flooding) and 'burgeoning populations' innovative methods have been conceptualized over the years. As it relates to challenges at the watershed scale, various management policies have been formulated under several titles; the most common being integrated watershed management, integrated environmental management, integrated water management, adaptive management and integrated coastal zone management (Margerum, 1999; Hooper, 2003; Ferreyra & Beard, 2007).

The primary focal point of watersheds is the river systems. Rivers provide the hydrologic link and as such represent the key management unit within a watershed, particularly in tropical island states and other equatorial regions. Rivers provide the link between upland regions and coastal zones and the regions surrounding them. By receiving water inputs from the land through infiltration and groundwater inputs, they convey the excesses from precipitation to areas such as seas, oceans, and lakes. Therefore, the importance of a river's ecological health is of paramount importance as it reflects the status of the land surrounding it and indicates the potential impact of practices within the watershed (particularly upper watershed management areas) (Hooper, 2003; Jakeman & Letcher, 2003; Ferreyra & Beard, 2007).

In an effort to achieve environmental sustainability, an integrated watershed and coastal zone management (IWCZM) approach must be incorporated, particularly as it relates to coastal zones irrespective of their definition by geographic or political boundaries. It is critical that an ecosystem-based approach to management is taken that will ensure a holistic management that integrates the impacts within the watershed and the resultant effect cumulatively on our coastal zones (Nobre et al., 2010).

According to the Coral Reef Alliance, coral reefs are among the world's most productive ecosystems (Goreau & Hayes, 2008). They are a major natural resource providing coastal protection, fisheries, and tourism income. The survival of coral reefs is largely dependent on a set of environmental parameters including low nutrient and sediment levels. Therefore, the management of watersheds plays a vital role in their survival because they are easily altered through land use changes (e.g., agriculture, degree of deforestation, and the extent of coastal development) that affect the quantity and quality of water flowing through a watershed and into the coastal zone. Effective management of watersheds, in conjunction with the coastal zone, can therefore improve the protection of the health of our coral reefs, wetlands, and the people that rely on them (OECD, 1993; NRCA, 2001; OECS, 2002).

The location of the island, its geography and geology make Jamaica susceptible to several natural hazards such as earthquakes, landslides, hurricanes, floods and droughts. The country has also acknowledged the increasing importance of climate change due to the high vulnerability attributed to the high concentration of development and infrastructure within the coastal zone. Coupled with this, human induced pressures on ecosystem goods and services are significant and highlighted within the major national development plan, Vision 2030 (PIOJ, 2009).

The current study examines the applicability of the Soil, Water and Assessment Tool (SWAT) on a tropical island watershed to evaluate the ability of the model to predict stream flow, and impacts of landuse changes on stream flow to allow for better understanding of how these tools can aid in water resources management. The following objectives were established:

- Calibration and validation of the hydrologic component of SWAT model in the Great River Watershed;
- Investigation of fluctuations in annual and seasonal stream flows and other hydrological parameters due to three projected landuse scenarios.

The Great River Watershed is located in the northwestern section of the island of Jamaica and is one of 26 watersheds in the island. The Great River is approximately 74km (46mi) long with an area of 327.27km$^2$ and has five major tributaries: Brown's River, Sevens River, Quashies River, Lambs River and Roaring River (Hayman, 2001; ARD, 2003). The Great River Watershed (GRW), similar to most watersheds in Jamaica, is considered to be in a state of environmental and economic decline. Agriculture, the major economic activity, faces many challenges, and as returns on investment decline, management is reduced. With reduced management comes less attention to natural resource conservation. Although there are numerous small communities scattered throughout the watershed, a large number of squatter-type settlements exist. These settlements generally lack adequate facilities for solid waste and sewage disposal (NRCA, 1997; Hayman, 2001; STATIN, 2001).

Regular monitoring of water quality within the watershed is not routinely carried out and as such monitoring data are inconsistent (Hayman, 2001; Greenaway, 2004). The water quality throughout the watershed is generally good with the exception of fecal coliform contamination triggered by human and animal fecal waste. The most recent assessment conducted from April 2002 to July 2003 by the University of the West Indies (Greenaway, 2004) suggested a river system in good health with relatively low nutrient (primarily nitrogen and phosphorous) and high dissolved oxygen levels. During the wet season when flow is fairly high nitrate levels were often detectable. Although soil erosion potential is moderate to high in the upper watershed, fairly low suspended sediment loads were observed outside adverse weather patterns such as tropical storms and hurricanes with significant precipitation. Flood plumes into the coastal zone were only observed during these episodes. No pesticide contamination was detected in the water samples taken during that period (Greenaway, 2004).

There are relatively few peer-reviewed, published SWAT model applications in tropical regions (Gassman, Reyes, Green & Arnold, 2007; Oestreicher, 2008). This is primarily due to the diversity of soils, species and climate of these regions in comparison to those of temperate zones. The model is very flexible and can be applied to a wide range of different environmental conditions (Arnold & Fohrer, 2005). The SWAT model, a freeware, was developed by the USDA-Agricultural Research Service to assist with assessment of watersheds ranging in sizes from small (a few hundred square kilometers) to large watersheds (several thousand square kilometers) (Neitsch, Arnold, Kiniry, Williams & King, 2002). One advantage of SWAT is the integration of the basin-scale model with GIS providing much improved modelling linkages within a management basin (Srinivasan & Arnold, 1994). SWAT has several components including: hydrology features, landuse, soil and slope attributes, and an improved weather generator, among other factors. The model is complete with documentation for equations and algorithms, a user manual describing model inputs and outputs, and an ArcGIS interface manual (Arnold & Fohrer, 2005; Neitsch, 2005; Santhi, Srinivasan, Arnold & Williams, 2006; Setegn, Srinivasan & Dargahi, 2008). This study focuses on the climate, land management and hydrology components.

Although the model has significant advantages, it is important to recognize that limitations exist. SWAT unfortunately is lacking in relation to the spatial representation of the hydrological response units within sub-basins (Gassman et al., 2007). The impacts on the predictions of evapotranspiration, percolation and soil water content are significantly affected despite the increase in spatial heterogeneity experiences with using large sized sub-basins. Generally, it is found that surface runoff is not significantly impacted by having larger and less sub-basins (Tripathi, Raghuwanshi & Roa, 2006). Additionally, SWAT incorrectly models infiltration into aquifers in hard rock areas by assuming unlimited capacity for water infiltration (Garg, Karlberg, Barron, Wani & Rockstrom, 2012, Batchelor, 2013). Despite these limitations, SWAT has been applied in tropical regions as support system for environmental management decision and policy making (Oestreicher, 2008). Oestreicher in his study identified several studies where the application of the SWAT model was met with acceptable performance. These included the modelling of the effects of hypothetical land-use change scenarios (primarily deforestation and reforestation of croplands) on flow, sediment, and nutrient yields in Honduras, Costa Rica, Brazil, Kenya, and China.

Of the two main classes of hydrological models identified in the literature: lumped and distributed models; the former is considered generally not spatially explicit largely representing a collection of changes in watershed land-use while the latter is more spatially explicit and highlight aspects such as surface runoff control factors. Despite the greater data requirement of the latter model, which includes SWAT, there is increased and improved forecasting ability of hydrological processes (Ward & Robinson, 2000; Evelyn, 2009). Several watershed modelling software have been developed and are universally accepted such as the Better Assessment Science Integrated Point and Nonpoint Sources (BASINS), Modelo

Hidrodinâmico (MOHID), SWAT, Water Quality Analysis Simulation Program (WASP), and Watershed Modelling Systems (WMS) among others (Erturk et al., 2006). Despite the vast wealth of models, the diversity and cost-effective approach, as well as the significantly large and growing model extensions has increased SWAT's application worldwide in developed and developing countries in a wide range of watershed sizes and conditions. In many cases these applications are requirements of government agencies evaluating the impacts of different scenarios such as climate and land-use change (Wang & Yin, 1997; Gassman et al., 2007; Zhang, Srinivasan & Hao, 2007; Graiprab, Pongput, Tangtham & Gassman, 2010).

## MATERIALS AND METHODS

In order to setup SWAT various inputs are required. These include: the Digital Elevation Model (DEM), soil data, landuse data, stream network layers, weather data (rainfall and temperature) and stream discharge data. A 56m DEM, supplied by Mona GeoInformatics Institute (UWI-Mona, Jamaica), was used to determine the slope and flow direction, which was used to determine sub-basin outlets and areas contributing discharge to the outlets. Spatial datasets and input files were organised according to guidelines by Neitsch et al. (2002). Land-use/Land-cover data were supplied by the Forestry Department of Jamaica. Weather data (daily rainfall and daily temperature) were supplied by the Meteorological Service of Jamaica for the period 1998-2006. Of the eight available stations only four stations had complete data to undertake this study greater than 5 years between the period 1960 and 2010. The decision criteria required using the longest complete dataset exceeding 5 years for as many stations as possible. Minor pre-processing of data was done to format the data according to SWAT's input style. Stream network and soil data were supplied by the Water Resources Authority of Jamaica (WRA). Additional data layers were supplied by the Natural Environment and Planning Agency (NEPA). All digital datasets were projected to the Lambert Conformal Conic Projection, and the projected coordinate system used was the JAD 2001 Jamaica Grid.

The SWAT 2005 model was used through the ArcSWAT interface embedded in the ArcGIS software. This allows one to employ all available tools of ArcGIS in handling spatial datasets. SWAT allows for the discretisation of a watershed by dividing it into multiple sub-watersheds, which can then be further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics (Neitsch, 2005). ArcGIS was used to calculate: basic hydrologic information for the model (i.e., surface slope, water flow paths), the position and size of the HRUs, and the necessary files to be used by SWAT (Winchell, Srinivasan, di Luzio & Arnold, 2007; 2009). The model, through the two phases (land and stream routing), simulates the routines for evapotranspiration, surface runoff, infiltration, percolation, return flow, groundwater flow, channel transmission losses, channel routing, and plant water use processes among others (Arnold, Srinivasan, Muttiah & Allen, 1999).

The modeling process generated 30 HRUs that represent the entire GRW. Calibration of the model was performed by comparing the simulated discharge with the monitoring (measured) discharge data in situ. The measured data were divided into two time periods covering the period 1998 to 2006 and represented complete data for the longest time period with the most meteorological stations in the watershed. The period 1998 to 2002 was selected for calibration and the period 2002 to 2006 for validation.

Calibration of the discharge was achieved by adjusting the input parameters. The top ten parameters were selected based on ranking achieved from the sensitivity analysis conducted. Adjusting the selected parameters allowed for a better match of measured and simulated discharges. The most sensitive parameters were used to calibrate the model for the GRW. The first year data (1998) was used as start-up/

warm-up in the calibration process and was therefore not included in the final model simulations. No formal optimisation procedure during calibration exists and therefore subjective decisions were generally made in calibrating the model (Santhi et al., 2006). Modifications of values were made by replacement, by addition of an absolute change or by a multiplication of a relative change. A parameter is never allowed to go beyond the model embedded predefined parameter range. Sensitivity tests and preliminary model run were carried out in order to identify the most sensitive model parameters. To avoid over parameterization, only the most sensitive parameters (top 10 ranked) were adjusted in model calibration.

Land use scenarios used in this study were designed to offer management planning for the protection of the watershed by assessing the potential impact of land use changes on hydrological parameters such as surface runoff, stream flows, and potential evapotranspiration. Land use scenarios were designed around real macro development possibilities within the watershed. Three scenarios were designed as follows: (1) an increase in agriculture to meet the projected demand of an increasing population and also to support the tourism industry with locally grown produce, (2) an increased conservation strategy by increasing the forest cover, and (3) increased urbanization of the watershed in line with long-term development plans to increase residential, tourism and commercial activities with new and improved road network. Though hypothetical each scenario mapped defines a potential maximum change in landuse that is realistic in nature. These three major landuse scenarios were designed by making changes to the SWAT reclassified landuse/land-cover map.

## RESULTS

**Watershed modelling & streamflow**: The measured and simulated monthly discharges (Fig. 1) showed that the SWAT model mirrored

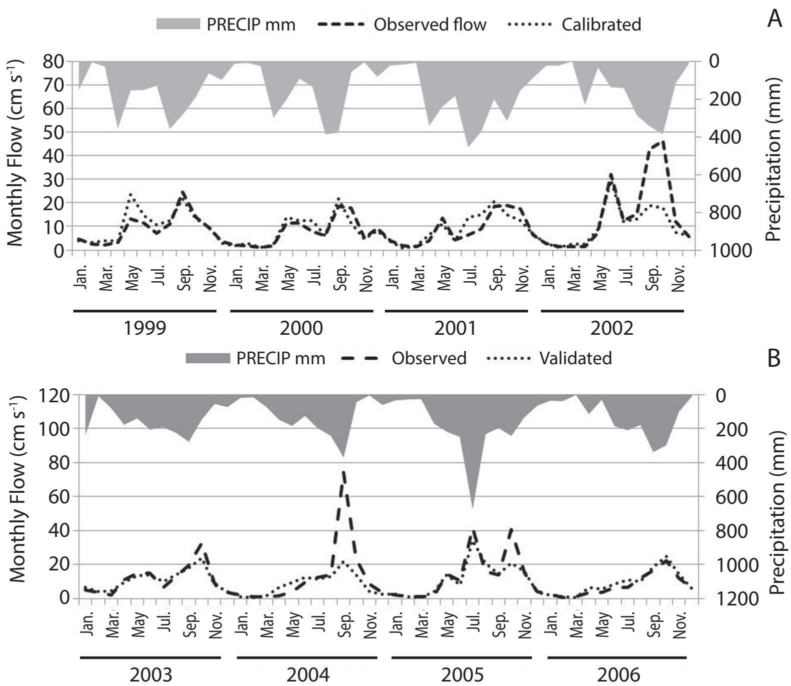


**Fig. 1.** Performance of Model under Calibration (A) and Validation (B) modes with influence from monthly rainfall data.

the measured monthly flow very closely. The mean calibrated measured monthly flow volume was 10.18cm $s^{-1}$ (std. dev.= 9.94) slightly lower than the mean simulated monthly flow volume of 10.25cm $s^{-1}$ (std. dev.= 7.06). The model was run during the validation period on the basis of the parameters from the calibration process only. The mean validation measured monthly flow volume was 11.50cm $s^{-1}$ (std. dev.= 13.32), slightly higher than the mean simulated monthly flow volume of 10.66cm $s^{-1}$ (std. dev.= 7.72).

The calculated model performance statistics for discharge yielded a Nash-Sutcliffe Efficiency (NSE) value of 0.68 and a $R^2$ value of 0.70 suggesting a fairly good correlation between measured and simulated (calibrated) discharge. The validation period similarly demonstrated good model performance. The NSE value of 0.61 and $R^2$ value of 0.67 also suggests a fairly good correlation.

**Landuse scenarios modelling – Impact on stream flow:** The land-use change scenarios performed reasonably well in comparison to the simulated baseline when calculated for mean monthly stream flow (Fig. 2). Simulated mean annual stream flow was less than measured stream flow using the validated period with a range of 10.67cm $s^{-1}$ (agriculture) to 10.86cm $s^{-1}$ (urban). These changes represented a 5.5% (urban) to 7.17% (agriculture) reduction in annual mean stream flow when compared with the baseline measured flow at the single discharge gauge station located approximately 3km from the river sea interface. The simulated land-use changes suggest no noticeable impact on mean stream flow with no more than a 3% increase for the dry season (December to April) and a 2% increase for the wet season shown for the urban scenario when compared with the simulated baseline.

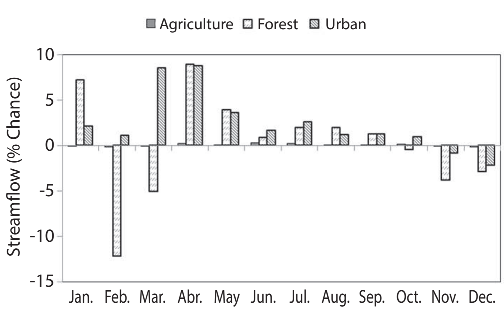


**Fig. 2.** Variability in mean simulated monthly stream flow as a percentage of baseline.

Although changes in simulated stream flow are fairly small in real values, the percent change in stream flow during the dry season for the forest and urban land-use scenarios are more exaggerated, ranging from an increase of 5% to 9% primarily during the dry season. Interestingly, the forest land-use scenario reflected similar fluctuations in reduction in stream flow during the same period particularly in the months of February and March while the agriculture scenario showed little or no change from the baseline throughout both dry and wet seasons.

**Land-use scenarios modelling – Impact in stream nutrients**: Simulated agriculture and urban land-use changes produced consistent increases in organic nutrients for most months with the greatest increase (106%) being predicted under simulated urban land use changes in March. The greatest increase in organic nitrogen for the agriculture land-use change was observed for the dry season month of January (~56%) when stream flow is lower and outside the main growing season of April-May. Increases exceeded 12% for all months in the year. Increases of 20-40% were also observed for wet season months of May to September when average monthly stream flow increases (Fig. 3).

Simulated agriculture and urban land-use changes produced consistent increases in organic phosphorous for each month with urban land use changes in March having the highest % change. Increases of 28-48% were also observed for wet season months of May to November for organic phosphorous within the stream (Fig. 4). Similar to organic nitrogen, phosphate contributions to stream flow were greatest during low-flow period.

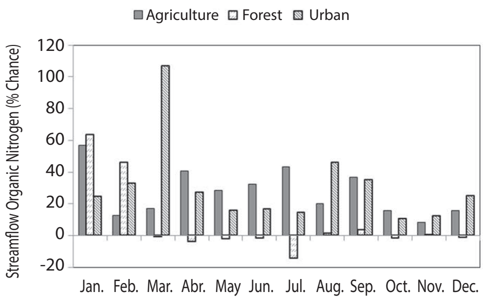


**Fig. 3.** Variability in mean simulated monthly organic nitrogen as a percentage of baseline.

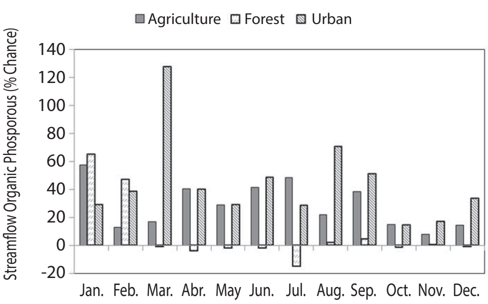


**Fig. 4.** Variability in mean simulated monthly organic phosphates as a percentage of baseline.

**Land-use scenarios modelling – Impact on surface runoff to streams:** Increase in surface runoff were generally observed for all three land-use changes, however forest land-use change recorded marginal decreases in some dry season months. While agriculture land-use scenario projected small increases in surface runoff contribution to stream flow ranging from 3.13% to 12.70%, forest land use change contributions ranged from -5.1% to 52%. The urban land-use scenario unlike the others projected greater monthly increases in surface runoff contributions. During the dry season the increase in surface runoff was in excess of 150% for the urban scenario. During the wet season the increase in surface runoff had a range of 98% to 234% (Fig. 5).

## DISCUSSION

Despite the slight over-estimation at some peaks, the SWAT watershed model was able to adequately match the measured flow. Peak flows tend to be over-predicted for calibrated discharge; this difference may be attributed to rapid discharge during and following periods of storm events. Validation of the model is important in instilling confidence in the suitability and applicability of the model. The storm events may not be well captured due to the location from which rainfall station data used in the simulations was acquired. It is possible that the under-estimation is in part due to the model's assumption of uniform soil texture and land use in the watershed that is not a real world scenario. The under-prediction observed in this study has been reported in other studies for rainy periods (Tripathi, Panda & Raghuwanshi, 2003; Gassman et al., 2007). However, the statistical evaluations for both calibration and validation can be considered

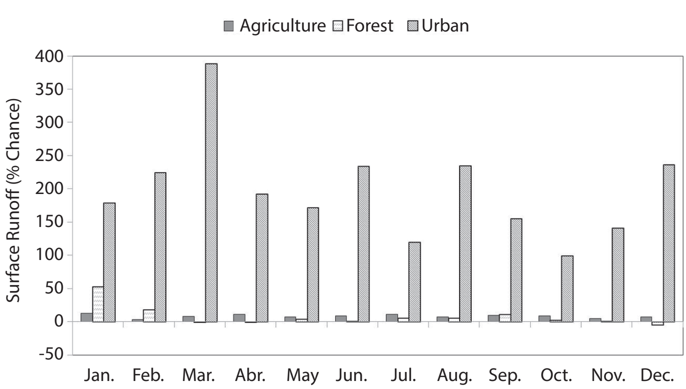


**Fig. 5.** Variability in mean simulated monthly surface runoff as a percentage of baseline.

to be satisfactory based on the criteria outlined by Moriasi et al. (2007). Therefore, based on the statistics returned, the SWAT model can be considered an effective tool in simulating the hydrology of tropical island watershed such as the Great River Watershed in Jamaica, although the simulated results, though realistic, can only be considered as experimental and ongoing and not conclusive or final.

Stream flow is projected to be impacted most with an increased urban landscape. An increase in the forest and agricultural land-use change does not suggest any real measureable increases in stream flow. Simulated agriculture land-use change has less of an impact and may be attributed to the regions within the watershed where substantive simulated changes were made. The lower-reach had little or no change in agriculture land-use, significant changes were made to the mid- and upper-reach, particularly the upper reach in the southern portion of the watershed. The southern section of the watershed has numerous ridges and potentially impacts on the distribution of rainfall to a greater extent than is experienced in the mid- to lower-reach. An increase in forest cover may have a more pronounced effect on stream flow in the dry season when evapotranspiration is expected to be highest. The modeled urban scenario revealed the very real possibility of surface runoff increasing to levels that may become disastrous. The drive to increase the agricultural component of the watershed may be setback due to a reduction in available water and soil moisture content, an increase in surface runoff, and a reduction in forest cover that provides the microclimate needed. The potential impacts to life and property are very significant.

Little or no data were available for hydrological parameters throughout most of the watershed. Where available the data were often incomplete due to faulty or non-functional equipment. No adequate historical land-use maps for the watershed were available to observe change in land-use over a prolonged period of time to compare with the macro changes in the hypothetical scenarios. A better spatial coverage of functioning rain gauges would afford a much better modelling effort to accurately gauge the impact of rainfall on land-use and its subsequent impact on stream flow. The results obtained from the model can be used exclusively or as an input of river flow and loads to the other models such as the MOHID estuarine models. As such, the model can be utilized to focus on possible interactions between coastal and riverine ecosystems and the social environment through incorporating three key activities: the nutrient loads generated from land based activities transported by surface waters and groundwater, use of coastal fauna associated with income generating activities such as fishing and dredging, and site specific key features arrived at in consultation with stakeholders and resource managers.

Nutrient contamination is a very important aspect of water quality monitoring in rivers and coastal environments globally. In Jamaica, the impact of nutrient contamination has been evident in some rivers and along the coast particularly in areas with coral reefs (Hayman, 2001; Greenaway, 2004; Espeut, 2012). This is evidenced by instances of fish kills, coral reef damage, and eutrophication. Levels of nutrients within stream flow suggest potential nutrient contamination with simulated land-use change scenarios, and are corroborated by existing data from the National Water Commission for the GRW during the period 2006-2010 showing elevated levels of nitrates and phosphates at the point of extraction, as well as water quality data within the river at various sections (Hayman, 2001; Greenaway, 2004). The dataset indicates several instances of coliform tests exceeding the standard of 300MPN/100ml as well as the domestic limit of 0MPN/100ml for potable water. Recorded spikes of 221 and 19.4mg $PO_4$ $L^{-1}$ were recorded in June 2008 and October 2009 as well as nitrates routinely at or near the upper limit standard of 7.5mg $PO_4$ $L^{-1}$. Land-use change influences suggest local water balance and quality will be significantly impacted as suggested in the literature (Heathwaite & Johnes, 1996; Fohrer, Möller & Steiner, 2002; Heuvelmans et al., 2005; Abbaspour et al., 2007). This is easily proved when the sources of organic nitrogen within the watershed such as sewage from pit latrines, agriculture, urban, and rural developments are taken into consideration. Greenaway (2004) found occasionally elevated levels near the mouth of the river; however, concentrations were frequently elevated at some mid to upper reach stations. These locations are typical of small farm holdings with cattle. This corresponds well with findings in the 2001 Ridge to Reef report (Hayman, 2001). There are no centralized sewerage systems within the watershed, and an increase in residential homes is expected to impact on this and other water quality parameters.

Phosphorus is generally present in stream flow as dissolved or particulate matter, and is a vital plant nutrient and possibly the most limiting nutrient to plant growth in fresh water. It is rarely found in significant concentrations in surface waters. As such, its presence in fresh water systems may lead to extreme algal growth, hence eutrophication (Hayman, 2001; Fohrer et al., 2002; Greenaway, 2004; Qi et al., 2009). Sources of phosphorous are similar to those identified above for nitrogen. In urban and rural settings, the use of detergents is a major source. Within the GRW, washing of clothes and personal effects such as cars is a common occurrence as well as bathing in rivers and streams. The increase in organic nitrogen projected is understandable particularly in the agriculture scenario due to the possibility of increased use of fertilizers. In regards to organic phosphorous, an increase in urban component will likely yield an increase in use of soaps and detergents and other commercial products that would increase the phosphorous component particularly in runoff.

Many bodies of freshwater are currently experiencing influxes of phosphorus and nitrogen from outside sources. The increasing concentration of available phosphorus allows plants to assimilate more nitrogen before the phosphorus is depleted. Thus, if sufficient phosphorus is available, elevated concentrations of nitrates will likely lead to algal blooms (Dunne & Leopold, 1978; Easton et al., 2008; Harden, Foster, Morris, Chartrand & Henry, 2009). Algal blooms observed throughout the watershed were more noticeable in the dry season. However, in most instances, these blooms were related to areas prone to low or no flow where stagnant standing bodies of water occur until a rain event that disperses the generated plant material. Interestingly, Hayman (2001) and Greenaway (2004) have both recommended a systematic monitoring of nutrient levels throughout the watershed, particularly the central sections that are utilized for citrus orchards and coffee farms as well as an agricultural research station.

Predictably, surface runoff is projected to increase greatly once the land cover is dominated by hard surface which is a characteristic of urbanization or where forested land cover has reduced allowing for greater sheet flow where agriculture is not dominated by tree crops. This is well represented using the simulated urban land-use scenario wherein surface runoff increases nearly three-fold the baseline to a high of mean annual of 19.88 mm of water. Although an increase is projected for simulated increase in forest cover, the change is marginal in real terms. Simulating varied land-use changes on a greater spatial scale may result in even greater surface runoff for urban land-use changes.

The reduced surface runoff potential for agriculture and forest scenarios may translate to reduced flooding incidences but may have impact on water availability, quality (increased concentrations) and sustenance of critical habitats. An increase of the projected magnitudes for the urban scenario will no doubt increase water availability but depending on how that increase is delivered spatially, it could be a significant environmental and socio-economic impact risk. Such increases bring with it the potential for flooding and transference of pollutants to sensitive areas and ecosystems such as flood plains and coral reefs.

The significant increase in surface water observed for the urban scenario may have huge impacts on stream health that will negatively impact on the treatment services of potable water. This is required bearing in mind the expected increase in population, and also the projected increase in tourism related services such as hotels and eco-adventure tours. Improved watershed management is recognized as a critical area of need in Jamaica. These improvements are geared towards providing reliable and adequate supplies of clean water for agriculture, industry, tourism, urban and rural populations, as well as for ecosystem sustainability. This is well documented in a review of the watershed (Hayman, 2001; ARD, 2003).

Future watershed hydrologic changes due to land conversion are expected to be site-specific, and climate variability is an important factor controlling basin hydrologic processes (Qi et al., 2009). Agricultural activities on steep slopes have long been recognized as the single most important cause of the degradation of watersheds in Jamaica (NRCA, 1999; Hayman, 2001).

The increase run-off in urban areas (particularly residential) and maintenance and potential increase in agriculture within the GRW has and will impact significantly on the dynamics of suspended sediments and nutrient contribution to stream flow. The GRW is dependent on the episodic and seasonal flows to maintain watershed health. Suspended sediment transport is greatest during these events. The temporal pattern of these events (short duration and heavy flow) aids greatly in the removal of material reducing the likely entrainment of material along the stream flow.

Based on these dynamics it is possible that there is an efficient system of material transport and limited impact from channel sedimentation and de-nitrification processes (Brodie & Mitchell, 2005). However, with an increase in nutrients particularly from any increases in agriculture and urban landscape coupled with potential reduction in rainfall, it is likely that without proper management this natural resource could be negatively impacted for future use.

The integrated watershed and coastal zone management approach must be used to tackle issues such as watershed health, stream water quality, coastal zone and sensitive habitat sustainability in the context of various resource managers. There must be a concerted effort to ensure that these managers are all speaking from the same platform. Presently, resource managers typically utilize software that are restricted to particular agencies with a difficult process of translating to the needs of each other. The application of resources that are freely available, proven in the field in developed and developing countries, and have produced robust results should be made available as part of our planning arsenal to ensure all agencies are able to interact in a cohesive manner. SWAT is one such tool that Jamaica can take advantage of; particular in light of the fact that it is embedded in GIS. GIS is a tool most of our resource managers already make, as it's the national spatial planning platform. Despite the coarse nature of model setup the SWAT model has provided valuable quantitative information on the effectiveness of climate and land-use changes, the need to monitor and make predictions on improving water quality, and highlight the potential costs associated with implementing these improvements.

The performance of the SWAT model using the Nash Sutcliffe Coefficient (E) and the Coefficient of Determination ($R^2$) provided confidence that the model is adequate for use in tropical island watersheds with karts networks. Model predictions are as accurate as the mean of the measured stream flow data with the E values indicating the model is particularly sensitive to low flows but still performs fairly well to peak flows. This research has developed a reasonably calibrated SWAT model for the Great River watershed, given the limited availability of monitoring data and the scope of the study. This tool is available and applicable for use in the remaining 25 watersheds. It has the capability to model water quality, land-use change, climate change and other critical aspects of watershed health at various scales and should therefore be incorporated into Jamaica's national systems as a potential planning tool.

The modelled urban scenario revealed the very real possibility of surface runoff increasing to levels that can be considered catastrophic. The drive to increase the agricultural component of the watershed may be set-back due to a lack of water, a reduction in soil moisture content, an increase in surface runoff and a reduction in forest cover that provides the micro-climate needed. The potential impacts to life and property are very significant and should be further evaluated.

Although this research puts forward impact to watershed based on projected macro changes in land use with projected climate change, it should be highlighted that it is very much theoretical. There is still large uncertainty in predicting future impacts due to climate and land-use changes. The pace at which technology will be developed to arrest the increasing threat of climate change is still unknown. Similarly, the importance of development (economic and social) must be factored and may even be a greater limiting factor. The dynamic shifts in land-use beyond the extent of this study should be investigated to account for the significant climate change projections and their potential impact on land-use changes in watershed.

## ACKNOWLEDGMENTS

The authors would like to thank the Inter-American Institute for Global Change Research (IAI) (Project Number: CRN-II-2061) for the financial support. National Meteorological Service and Water Resources Authority of Jamaica are gratefully acknowledged for providing data.

## RESUMEN

**Aplicación de la herramienta de evaluación de suelo y agua (modelo SWAT) en una isla tropical pequeña (Gran Cuenca del Río, Jamaica) como una herramienta en la gestión integral de cuencas y manejo de la zona costera.** La gran cuenca del Río Grande, ubicada en el noroeste de Jamaica, crítico para el desarrollo, particularmente para vivienda, turismo, agricultura y minería. Es una fuente de sedimentos y nutrientes de recarga para el ambiente costero incluyendo el Parque Marino Bahía Montego. Proponemos un marco integrado de modelado utilizando la herramienta de evaluación de suelo y agua (SWAT) y SIG. Las estadísticas de rendimiento del modelo calculadas para la descarga de alto flujo rindió una eficacia de Nash-Sutcliffe (NSE) de 0.68 y un $R^2$ de 0.70 sugiriendo una buena medición y correlación de descarga simulada (calibrada). Los estados insulares con frecuencia toman decisiones basándose en los impactos de la cuenca. Esto requiere un profundo entendimiento y análisis de factores como los recursos hídricos, uso del suelo/cobertura, sedimentos y nutrientes de recarga entre otros factores a nivel de cuenca. Con financiamiento del Instituto Interamericano para la investigación del Cambio Global (IAI) se examinó la aplicación del modelo de acceso libre en una cuenca jamaiquina. Los resultados de la calibración y validación para caudales fueron similares a los observados en los caudales respectivos, según lo indicado por la eficacia de Nash-Sutcliffe y el coeficiente de determinación. La calibración y validación de los resultados para el caudal son similares a los observados en el caudal. Durante la estación seca el escenario simulado en el uso de suelo urbano predijo un aumento de la escorrentía superficial superior al 150%. Durante la estación lluviosa el aumento de la escorrentía superficial se prevé que alcance desde 98 a 234% lo que representa un riesgo significativo de inundaciones, erosión y otros problemas ambientales. El modelo sugiere que cambios en los usos proyectados de suelo tendrán serios impactos sobre la disponibilidad de agua (caudal), salud de la cuenca, tratamiento de agua potable, inundaciones y ecosistemas costeros sensibles.

**Palabras clave:** Herramienta de Evaluación de Suelo y Agua, zona costera integrada y manejo de cuencas, SIG

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