Topic: Integrated Water Resources and Coastal Areas Management

An investigation into the feasibility of using SWAT at the sub-basin level for simulating hydrologic conditions in Jamaica

Johanna Richards[1], Chandra A. Madramootoo[2]

[1,2] Department of Bioresource Engineering, McGill University, 21,111 Lakeshore Road, St. Anne de Bellevue, QC, H9X 3V9

ABSTRACT

The Soil and Water Assessment Tool (SWAT) was used in order to simulate the hydrologic characteristics of the Rio-Nuevo sub-basin, located in the parish of St. Mary. Historical climatic data (precipitation and temperature) was obtained for the watershed, while streamflow data was obtained for the Rio Nuevo, which drains the watershed. The model was calibrated over the period 2002-2004, and validated from the period 2005-2007. Nash-Sutcliffe Efficiency (NSE) coefficients of performance of 0.8 and 0.5 were obtained for calibration and validation respectively for streamflow. It has been determined that SWAT can effectively be used to simulate surface water hydrology in this region. This paper outlines the development of SWAT for the Rio Nuevo watershed, and describes the potential for use in agricultural water scarcity management.

Keywords: Hydrology, Streamflow, Basin-scale Modelling, SWAT, Distributed Modelling, Calibration, Validation, Irrigation Planning

1.0 Introduction

Jamaica's water resources are under increasing risk of degradation and depletion, especially in light of increasing population growth and urbanization (Ricketts, 2005). As a result, the use of hydrologic models in the island is an increasingly important tool for use in agricultural water planning, as distributed parameter models such as SWAT are key to basin-level assessment of water resources availability (Jayakrishnan et al., 2005). A pro-active approach to agricultural water scarcity management needs to take place through planning. The understanding of which cropping methods can be used in order to save water etc., can lead to decreased demands on water, thus lessening the stress on water resources during water scarce conditions.

SWAT is a continuous, long-term, physically based, semi-distributed hydrologic model, developed by the U.S. Department of Agriculture (Neitsch et al., 2005; Zhang et al., 2008). It is an effective planning tool, in that it can be used in order to gain an improved understanding of the water balance, while at the same time determining water savings from different management scenarios (Immerzeel et al., 2008; Santhi et al., 2005). It was specifically with this issue in mind that the SWAT model was built for the Rio Nuevo watershed, which is the location of the Caribbean Water Initiative (CARIWIN) Jamaican pilot site.

SWAT is a conceptual model that works on daily time steps (Arnold and Fohrer, 2005). SWAT can simulate surface and sub-surface flow, soil erosion, nutrient data analysis and sediment deposition, and has been applied worldwide for hydrologic and water quality simulation (Zhang et al., 2008). SWAT has also been applied extensively over a wide range of spatial scales. Gollamudi (2007) applied SWAT to two fields in Southern Quebec, while Zhang et al., (2007), applied SWAT to the 5239 km^2 watershed in China for the simulation of daily and monthly stream flows.

SWAT was initially developed to predict the impact of land management practices on water, agricultural chemical yields and sediment in large, complex watersheds (Neitsch et al., 2005). It consequently requires a large amount of specific information such as land use, weather, soil types etc. This input data is then used to directly model physical processes such as sediment movement and nutrient cycling (Neitsch et al., 2005). SWAT has been integrated with the Geographical Information Systems (GIS) (ArcSWAT 2005), simplifying the process of integrating spatial and temporal datasets into the model. In addition to this, multiple simulations can be carried out using SWAT due to its high computational efficiency (Arnold and Fohrer, 2005). This is particularly useful in light of the fact that the Rio Nuevo basin consists of a mosaic of agricultural plots, natural woodland, and urban settlements. For this reason, SWAT was particularly desirable as it allows for the easy input of spatially variable landuse and soil data.

There are several hydrologic models which could also have been potentially used in this study, such as ANSWERS-2000 (Bouraoui and Dillaha, 2000) or AGNPS (Young and Onstad, 1990). However, SWAT is a model available to the public domain, and one which has successfully been used extensively in many countries worldwide, including developing countries (Zhang et al., 2008). Due to limited resources, it is important that any model used in Jamaica be as robust as possible, while at the same time cost effective. A few of the many advantages of SWAT are that it is computationally efficient, uses readily available inputs, and enables users to study long term impacts (Neitsch et al., 2005). In addition, SWAT can be used in the future for modelling water quality and sediment characteristics, as well as streamflow.

SWAT is described as a semi-distributed model as Hydrologic Response Units (HRUs) are used for the organization of simulations and outputs (Salerno and Tartari, 2009). These HRUs represent areas of homogeneous management, land use, and soil type characteristics. Run-off is calculated for each HRU, and then combined at the sub-basin level. This run-off is then routed in order to account for total run-off (Salerno and Tartari, 2009). Three methods of calculating evapotranspiration have been incorporated into SWAT: (i) the Penman-Monteith method (Allen, 1986; Allen et al., 1989; Monteith, 1965), (ii) the Preistley-Taylor method (Preistley and Taylor, 1972) and (iii) the Hargreaves Method (Hargreaves and Samani, 1985). The relevance of each method to the model depends not only on the types of inputs available, but also on the climatic conditions of the geographic area in question.

The main objectives of this study were to (i) apply the SWAT model to the Rio Nuevo sub-basin, (ii) calibrate and validate the model to streamflow, using 6 years of measured data, and lastly (iii) assess the feasibility of the model for further use as a tool in agricultural water scarcity planning in Jamaica, while providing recommendations as to how this planning can be done.

2.0 Materials and methods

2.1 Site description

The Rio Nuevo sub-basin is a 110 km^2 sub-basin, located in the Blue Mountain North watershed, which ranges from the Blue Mountains to the northern shore of the island. Figure 1 shows the watershed location. The Rio Nuevo flows northward towards the coast, and originates in the Blue Mountains, a mountainous ridge that runs throughout the island.

The Rio Nuevo watershed is located in the parish of St. Mary, which is in the north-eastern section of the island. St. Mary's largest industry is agriculture, with crops such as bananas, citrus, coconuts, coffee and sugar cane being produced (St. Mary Parish Library, n.d.). St. Mary was formerly a leading contributor to the Jamaican economy through agricultural production. However, it has suffered significant economic decline over the past two decades. This is mainly due to the collapse of the coconut and sugar industries, which were the main agricultural mainstays of the parish (St. Mary Partnership, 2006). Despite the decline which has occurred in the agricultural sector in St. Mary, agriculture and agro-processing are still thought to be the main factors in St. Mary's journey to economic recovery (St. Mary Partnership, 2006). Consequently, diversity in agricultural production, both on a small and a large scale, is being heavily encouraged by the St. Mary Parish Council.

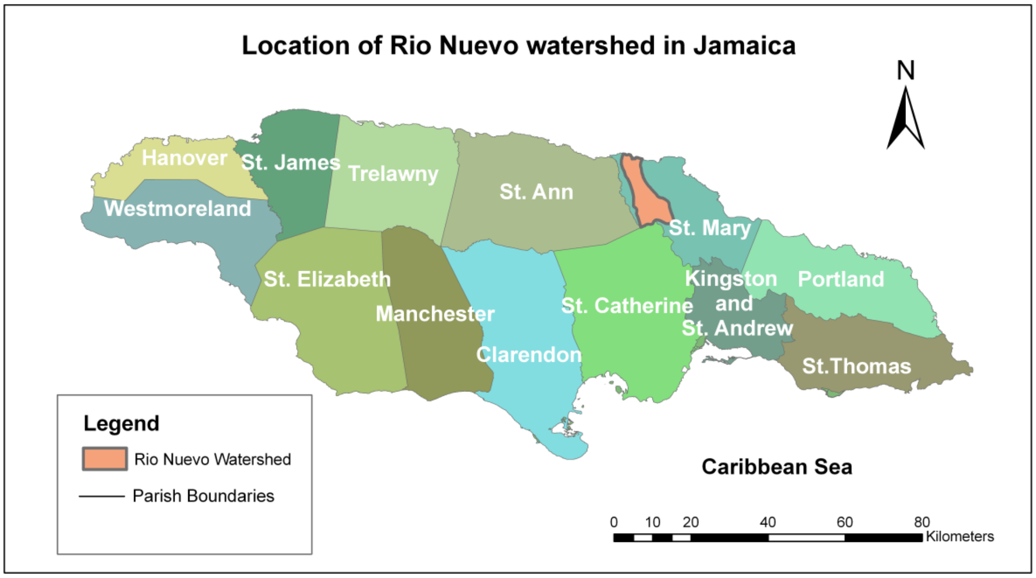

Figure 1: Location of Rio Nuevo watershed

The watershed is rural, with agriculture and woodland occupying most of the basin. Crops grown in this area include bananas, plantains, papayas, scotch bonnet peppers, red peppers, cabbages, tomatoes and bok chow (Edwards, 2009 , *personal communication*). Land use throughout the watershed consists mostly of agricultural lands, as well as forested or woodland areas. The land use distribution is described in Table 1. Small farmers dominate the agrarian landscape in Jamaica, and are defined as those with farms of size 2 ha or less (FAO, 2003). There is therefore a mosaic of woodland and small farms throughout the watershed. A description of the landuses, as how they were defined in SWAT, is shown in Table 2. These descriptions were obtained from Evelyn (2007), and were developed by the Jamaica Department of Forestry. Lastly, the area is dominated by soils high in clay content, the distributions of which are shown in Table 3. The hydrologic soil groups shown in the tables represent the infiltration capacity and drainage characteristics of the soils, with group A having the highest infiltration and drainage capacities, and group D having the lowest.

Table 1: Watershed distribution of land uses in SWAT

Landuse	% Watershed Cover
Disturbed Broadleaf	39.19
Fields and Disturbed Broadleaf	33.53
Fields	17.2
Disturbed Broadleaf and Fields	6.74
Bamboo and Disturbed Broadleaf	1.28
Bamboo and Fields	1.01
Plantation (Redefined as agricultural row crops)	0.69
Built up	0.36

Table 2: Reclassification of land uses in SWAT (adapted from Evelyn, 2007)

Original Landuse	Definition of land use	SWAT definition
Disturbed Broadleaf	Disturbed broadleaf forest with broadleaf trees at least 5 m tall and species indicators of disturbance such as Cecropia peltata (trumpet tree)	DSBL
Built-up	Urban areas, including low to high density	Residential-Medium/low density (URML)
Fields	Herbaceous crops, fallow cultivated grass/ legumes	FIDS
Bamboo and broadleaf	> 50% bamboo, > 25% disturbed broadleaf forest	BBDB
Bamboo and fields	>50% bamboo, >25% fields	BBFD
Disturbed Broadleaf and fields	> 50% disturbed broadleaf forest, >25 % fields	DBFD
Plantation	Tree crops, shrub crops like sugar cane, bananas, citrus and coconuts	Cabbages (CABG) Tomatoes (TOMA) Hot peppers (HTPR) Bananas (BANA)
Fields and disturbed broadleaf	>50 % fields; >25% disturbed forest	FDDB

Table 3: Soil type distribution for Rio Nuevo watershed

Soil	% Watershed Area	% Clay	% Silt	% Sand	Hydrologic Group
Killancholly	33.89	60	20	20	B
Carron	22.67	48	34	18	B
Donnington	15.67	29	45	26	A
Bonnygate	12.48	55	29	16	A
Union	9.73	53	38	9	C
Waitabit	3.59	58	17	25	B
Belfield	1.18	22.5	52.7	24.8	C
St. Ann	0.5	45	54	1	A
Bundo	0.28	60	20	20	B

Elevation in the watershed ranges from 3 m above sea level near the coast to 591 m above sea level in the Blue Mountain range (Figure 2). Approximately 85% of the watershed consists of aquiclude rock material, thus resulting in low potential for interaction between surface, or soil water and groundwater throughout the majority of the watershed. The remaining 15% is limestone (karstic) aquifer. A hydrostratigraphic map is shown in Figure 3.

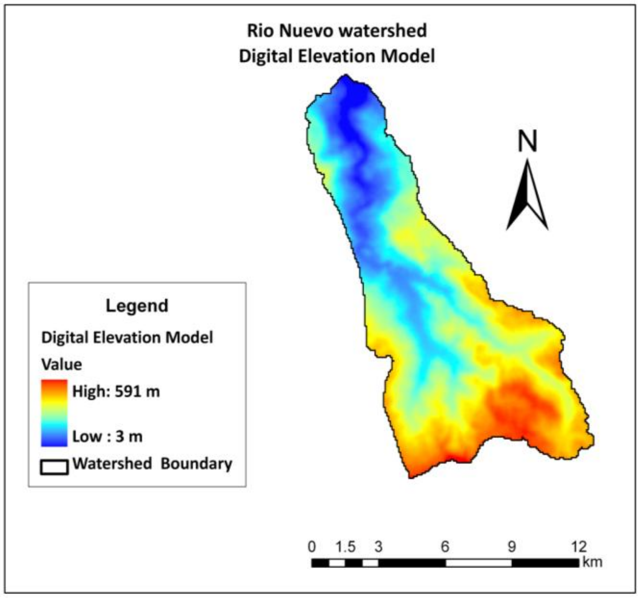

Figure 2: Digital Elevation Model (DEM) of Rio Nuevo watershed

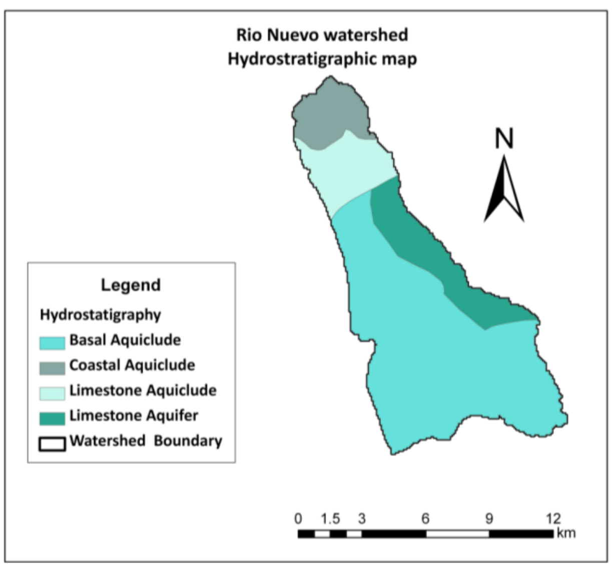

Figure 3: Hydrostratigraphic map of Rio Nuevo watershed

2.2 Model Inputs

SWAT requires land use data, soil type data, a digital elevation model (DEM), and optionally, stream network data (Neitsch et al., 2005). Each of these was used as input into the model, and Table 4 shows the source of each digital data set. All digital datasets had a Lambert Conformal Conic Projection, and used a JAD 2001 Jamaica Grid projected coordinate system. SWAT requires daily precipitation data, as well as daily maximum and minimum temperature data (Neitsch et al., 2005). In addition, long term (at least 20 years) climatic data is needed in order for SWAT to simulate rainfall events.

Table 4: Data inputs into SWAT

Data Type	Source
Digital Elevation Model (DEM)	Digital contours provided by the Jamaica Water Resources Authority (250 ft /76.2 m resolution)
2001 Land Use	Forestry Department, Jamaica
Soils data	Rural Physical Planning Unit- Ministry of Agriculture
Stream network	Jamaica Water Resources Authority

There were two rain gauges within the immediate area (but not within the bounds) of the watershed from which historical daily rainfall data ranging from a period of 2002 – 2007 was used. These rain gauges are operated by the Meteorological Service of Jamaica. In addition, there was one stream gauge on the Rio Nuevo, the location of which is also shown in Figure 4. Daily streamflow data was obtained from the Water Resources Authority for this stream for the period 2002 to 2007. Figure 4 also shows the stream network which was used within the model. Lastly, both minimum and maximum daily temperatures were obtained for the Norman Sangster International Airport, as well as the Michael Manley International airport, provided courtesy of the Meteorological Service of Jamaica.

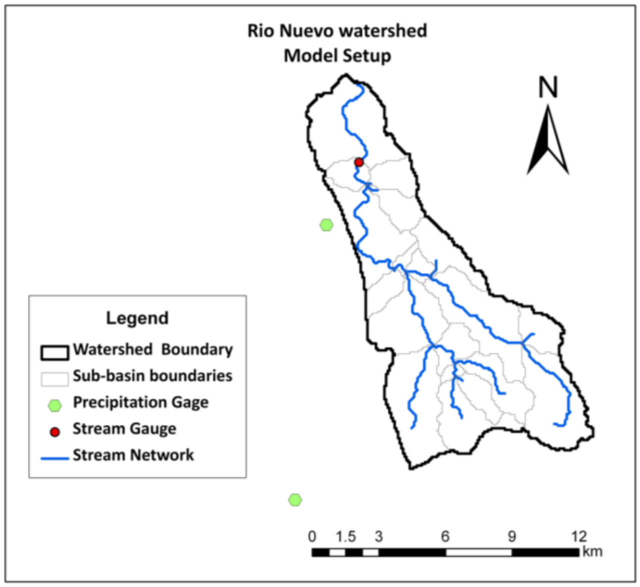

Figure 4: Location of monitoring points and precipitation gauge

The landuses did not exist previously in the SWAT database, and so new landuse classes were created into the SWAT database, using all available information for each landuse. There were, however, several parameters which were not available by measurement for the landuses. Hence, these parameters were obtained from other similar landuses previously defined in SWAT.

The "Fields" and "Built-up" land uses were the only ones that were re-classified using pre-existing SWAT land uses. The Fields land use was redefined as Agricultural Row Crops (AGRR) in SWAT. However, this landuse was split into 4 sub-landuses: hot peppers, bananas, cabbages and tomatoes. These crops were chosen as they are grown throughout the entire region. The SWAT design team was most kind in providing the parameters for the hot peppers and bananas. The "Built-up" land use was reclassified as the pre-existing SWAT land use termed Residential medium/ low density (URML). This pre-existing land use was chosen as the watershed is rural, and any industrial area would be minimal. An HRU threshold of 20% was chosen for land use. This was done in recognition of the spatial variability of the land use.

Despite the fact that there are 15 soils in the watershed, only 9 were represented in the model. This is due to the fact that sufficient information was not available for all the soils. A description of the data available for each of the soils is provided in Section C.1. This data was provided by the Rural Physical Planning Unit of the Ministry of Agriculture. In addition, a threshold of 15% of each hydraulic retention unit (HRU) was set for the model for soil types, meaning that once a soil type did not represent at least 15% of the sub-basin, then it was not represented in the model. This was done in order to capture the spatial variability of soil types throughout the watershed.

Before the SWAT model can be run, the methods which the model would use to determine evapotranspiration, precipitation events, run-off, and stream routing needed to be determined and defined in SWAT. The Preistley- Taylor method was used in order to determine evapotranspiration, while precipitation was simulated as a skewed normal distribution. The Soil Conservation Service (SCS) Curve Number method was used in order to determine run-off, while the Muskingum method was used for stream routing. These methods were chosen iteratively through the calibration process, in other words, the best results were found when these methods were used.

Weather generator data

In order for SWAT to simulate relative humidity and wind speed, detailed statistical information on each of these parameters was required by the model. This information, along with other statistical information relating to precipitation and temperature, was compiled in an input table termed the Weather Generator Input table. However, in order for relative humidity and wind information to be compiled, monthly average wind speeds, average daily solar radiation in the month, and average dew point temperature in the month, were required (Neitsch et al., 2004). Ideally this data would be available over a minimum period of 20 years. Unfortunately, this data could not be obtained by the researchers over any significant period of time for any area of Jamaica. Therefore, data for the Florida Keys was used instead, as this was the closest location for which weather generator statistical data was available in the SWAT database. The climatic data parameters will not be published in this document due to the large amount of information; however, they are readily available in the SWAT database.

2.3 Simulation

The simulation process was divided into three main steps: setting up and running of the model, calibration, and validation. Simulation was performed over the years of 2002 to 2007. Calibration was performed using streamflow data from 2002 to 2004, while validation was carried out using streamflow data from 2005 to 2007. Once all the inputs were properly defined and integrated into GIS, the model was then run using the default SWAT parameters for the model. In order to test the validity of the model, a water balance was performed in order to ensure that the outputs that the model was giving were reasonable. The water balance was performed according to the following relationship:

$$\Delta SW = PCP - ET - PERC - LATQ - SURQ \qquad (1)$$

Where:
ΔSW is the change in soil water (mm),
PCP is precipitation (mm)
ET is evapotranspiration (mm),
PERC is deep water percolation,
LATQ is the lateral shallow sub-surface flow to the reach
SURQ is the surface runoff

After the model was run, a sensitivity analysis was conducted. The One at a Time (OAT) Sensitivity Analysis was conducted through a Sensitivity Analysis tool in SWAT. This analysis was performed in order to assess the quantitative effects of SWAT input parameters on the output. These parameters were related to different aspects of the water balance, including movement of soil water to shallow aquifers, base flow to streams, lateral movement of soil water to streams, evapotranspiration, and stream routing. A 0.05 parameter change for the OAT was set in SWAT, with the 10 intervals within the latin hypercube. All errors which were identified in the input data were rectified and resolved during the simulation process.

Calibration and Validation

In order to maximize the accuracy of the model, the results were then calibrated. In this process, the most sensitive model parameters determined from the OAT sensitivity analysis were identified. The parameters were changed with the assistance of the Manual Calibration tool in SWAT. The model parameters were changed in pre-determined intervals, and the magnitude of these intervals was relative to the magnitude of the parameters. Similarly to the sensitivity analysis, each parameter was adjusted one at a time. After each parameter was adjusted, the model was re-run, and the model performance quantitatively determined by the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measure data (RSR), as developed by Moriasi et al., (2007). The NSE provides a quantitative indication of how well the plot of simulated data versus observed values fit a 1:1 line (Moriasi et al., 2007). The PBIAS is a measurement of the tendency of a simulated value to be smaller or larger than its observed counterpart. Lastly, the RSR gives an indication of residual variation, and incorporates the benefits of error index statistics (Moriasi et al., 2007).

Stream flow was used in order to compare the simulated to the observed results. It should be noted that the calibration was performed on a monthly basis. Any month for which 3 or more days of observed data was missing was not included in the model evaluation. This was done as missing data most likely represented high stream flows due to storm conditions. The omission of these stream flows from the determination of the monthly values would have significant effects on the monthly values, thereby throwing off the reliability of the observed data. Calibration was performed using stream flow data from 2002 to 2004. The months that were omitted from the calibration process due to missing data are January and September 2002, December 2003, January 2004, April to July and September to October 2004.

The validation process was performed using simulated and observed stream flow from 2005 to 2007. After the model was calibrated, the accuracy of the model was determined during the validation process. For this process, the monthly simulation stream flow results for 2005 to 2007 were compared to the observed monthly stream flow results for the same period. All the afore-mentioned model evaluation parameters were also used in the validation process. Performance ratings (unsatisfactory, good, excellent) for each of these statistics are available in Moriasi et al., (2007). These guidelines were used for both the calibration and validation process in order to assess the effectiveness of both processes.

3.0 Results

3.1 Calibration

The calibrated parameters, along with their descriptions (obtained from Neitsch et al., (2004)) are shown in Table 5 below. The calibrated and uncalibrated values are shown in Table 6.

Table 5: Calibrated parameters

Parameter	Units	Description
Threshold water depth in shallow aquifer for return flow (GWQMN)	mm	Groundwater flow to the reach is allowed only if the depth of water in the aquifer is equal to or greater than GWQMN
Soil Evaporation Compensation Factor (ESCO)	-	This coefficient defines the depth of soil from which water can be taken from the soil in order to meet evaporative demand.
Groundwater delay (GW_DELAY)	days	The time lag between when water exits the soil profile and enters the shallow aquifer
Deep aquifer percolation fraction (RCHDP)	-	The fraction of percolation from the root zone which recharges the deep aquifer
Baseflow recession constant (ALPHA_BF)	days	An index that represents the response of groundwater to changes in recharge
Groundwater ‘revap’ coefficient (GW_REVAP)	-	This coefficient defines the restrictions relating to the movement of water from the shallow aquifer to the root zone
Threshold water depth in shallow aquifer for deep percolation to occur (REVAPMN)	mm	A threshold depth, under which movement of water from the shallow aquifer to the unsaturated zone is not allowed

Table 6 shows the calibrated parameters, including the original (uncalibrated) parameter values, as well as the calibrated parameter values.

Table 6: Calibrated and uncalibrated values for calibration parameters

Parameter	Range	Unit	Un-calibrated	Calibrated
GWQMN	0-5000	mm	0	1
ESCO	0-1	-	0.95	0.99
GW_DELAY	0-500	days	31	35
RCHDP	0-1	-	0.05	0.15
ALPHA_BF	0-1	days	0.048	0.9
GW_REVAP	0.02-0.2	-	0.02	0.12
REVAPMN	0-500	mm	1	2

5.3.2 Surface flows

The model output was obtained for the same location along the stream reach as the actual stream gauge. The observed and simulated stream flows were then compared on a monthly basis for both the calibration and validation time periods. During the calibration period, SWAT under-estimated the two large events that occurred in October 2003 and March 2004. During the validation period, SWAT over-estimated some of the run-off events that occurred in January and July 2005, as well as November 2007. Figures 5 and 6 show the calibrated and validated streamflow hydrographs, showing observed and simulated flows.

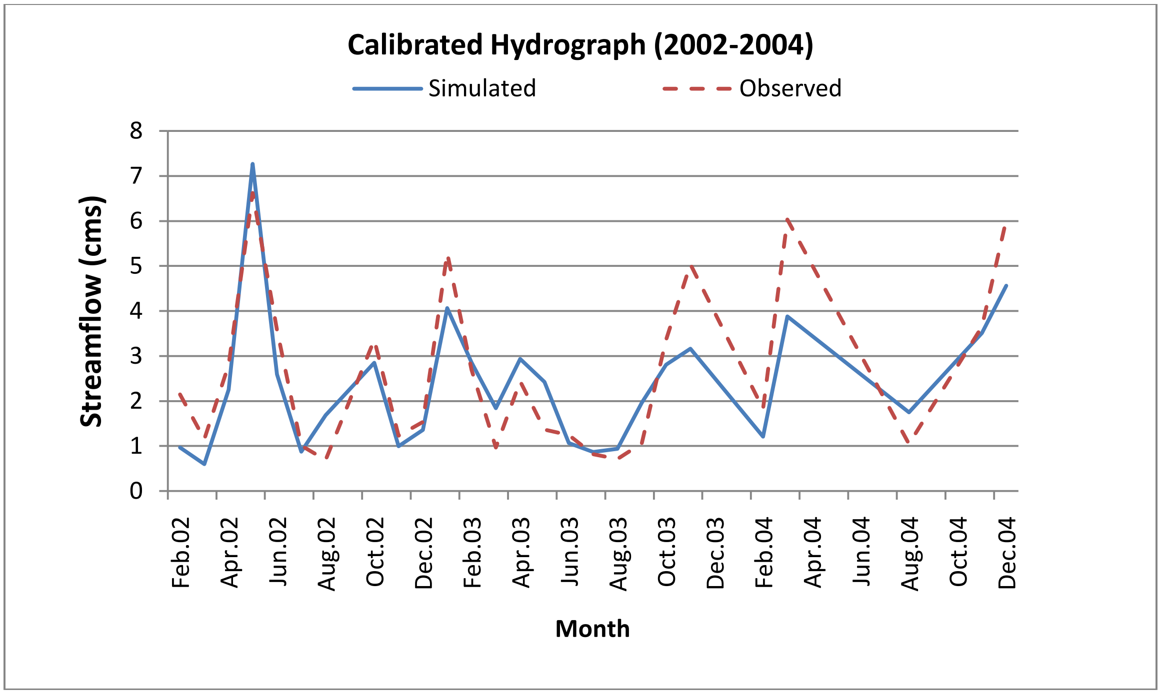

Figure 5: Calibrated hydrograph for Rio Nuevo

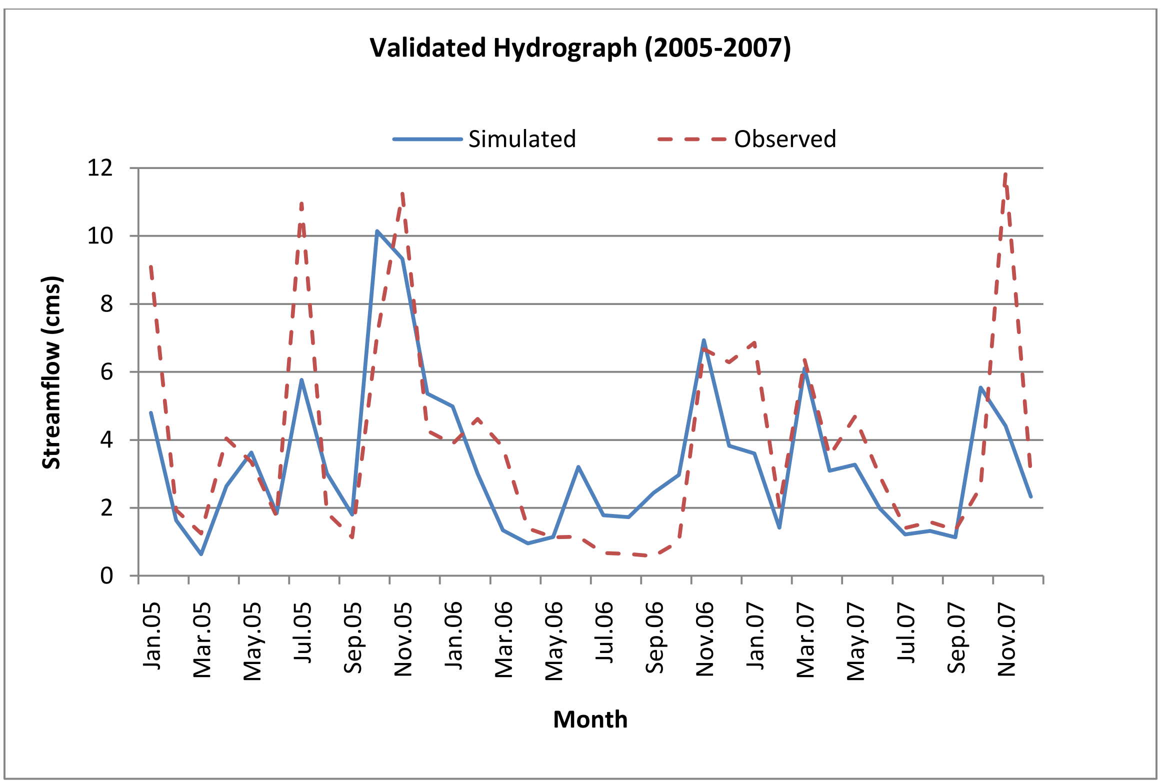

Figure 6: Validated hydrograph for Rio Nuevo

5.3.4 Model Evaluation

The calibration and validation performance ratings are shown in Table 7 below. The NSE value is right on the verge of being satisfactory, while the RSR is slightly in the unsatisfactory range. However, the validation performance is generally expected to be less than the calibration performance (Moriasi et al., 2007). The validated parameters will therefore be treated as satisfactory for the purposes of this research. The range and ideal values of each of the performance indicators were obtained from Moriasi et al., (2007).

Table 7: Calibration and validation model performance ratings

Performance Indicator	Calibrated	Performance Rating	Validated	Performance Rating	Range	Ideal
NSE	0.758	Very Good	0.504	Satisfactory		1
PBIAS	9.496	Very Good	12.767	Good		0
RSR	0.492	Very Good	0.704	Satisfactory	0 to a large positive number	0

5.4 Discussion

Overall, the model performed satisfactorily, achieving an NSE of 0.76 for calibration, and 0.50 for validation. This is in keeping with results from other studies, which have reported successful applications of SWAT in other developing countries. It was applied in Ethiopia by Mekonnen et al. (2009), resulting in R^2 coefficients of 0.88 and 0.83 for calibration and validation respectively for streamflow. SWAT was also successfully applied in Tunisia, with NSE coefficients of 0.73 and 0.43 for calibration and validation respectively for streamflow (Ouessar et al., 2009).

The fact that the rain gauges used in the model were not actually in the watershed would have negatively impacted the results. In addition, land uses would have changed over time, and unfortunately, the most recent landuse data which was available for this research was from 2001. In addition, weather data from Florida was used in order for SWAT to simulate relative humidity and wind conditions. There are orographic effects which would affect the relative humidity and wind conditions within the Rio Nuevo watershed. However, the Florida Keys are relatively flat, resulting in different characteristics for these climatic conditions. Overall, the inherent error that exists in the input data would have resulted in a compounded error throughout the modelling process.

An attempt was of course made to improve these results through the calibration process. There are no actual measurements relating to groundwater flow within the watershed, and so all the calibration results are based simply on which values provide the optimal model response. The question therefore arises as to whether or not these calibrated values are representative of what actually happens within the watershed. Unfortunately, due to a lack of published data on groundwater flow, not only within the larger Blue Mountain North watershed, but within the island, the assumption must be made that the calibrated values are indeed within reasonable ranges for Jamaican sub-surface systems.

Through calibration, the value for the baseflow recession constant (ALPHA_BF) was increased. This increase in ALPHA_BF signified an increased sensitivity of groundwater flow to changes in groundwater recharge. There was a significant increase in this parameter from 0.048 to 0.9. This is especially significant as the range of ALPHA_BF is from 0 to 1, with 1 expressing the highest groundwater flow response. Likewise, the Soil Evaporation Compensation Factor (ESCO) was increased, resulting in an increased depth from which water could be taken in order to meet evapotranspiration demand. The groundwater "revap" coefficient (GW_REVAP) was also significantly increased from 0.02 to 0.12, which allows for easier movement of water from the shallow aquifer to the root zone. The increases in ALPHA_BF, ESCO and GW_REVAP all imply that throughout the watershed, surface and groundwater interactions are actually quite important. This is despite the limited surface and groundwater interactions that can take place throughout the watershed due to the aquicludal hydrostratigraphy.

GW_DELAY (the time lag between when water exits the soil profile and enters the shallow aquifer) was also increased from 31 days to 35 days. Any attempts to lower this value during the calibration process resulted in worse model performance. Considering the fact that the majority of the watershed is indeed aquiclude, the increase in delay time is indeed justified. There was a minimal increase (from 0 to 1 mm) in the GWQMN, which is the threshold depth in the shallow aquifer required for groundwater flow to the reach. Likewise, there was minimal change (1 to 2 mm) in REVAPMN, which is the threshold depth in the shallow aquifer for deep percolation to occur. Both of these values imply that flow occurs very easily between the groundwater systems and surface water systems.

It is important to note that neither the curve numbers, nor the available water capacities of the soils were calibrated. These parameters tend to be very important calibration parameters, and many studies involving SWAT have shown that the calibration of these parameters result in improved model performance (Govender and Everson, 2005; Zhang et al., 2008). However, even though the sensitivity analysis showed these parameters as highly sensitive, changes that were made to these parameters showed no improvement in model response. A similar result was seen in the study performed by Mulungu and Munishi (2007). This result is one more indicator pointing to the importance of sub-surface interactions within this watershed.

The results of the calibration process might seem counter-intuitive, considering the fact that the vast majority of the watershed is underlain by either basal, coastal or limestone aquiclude. However, 15 % of the watershed is karstic, and this karsticity adds a level of complexity that is difficult to simulate. The possible effects of karsticity on the entire watershed dynamics are discussed in the following section.

4.1 Model performance and karsticity effects

As mentioned in the results, SWAT underestimated some of the peak flow events with the largest under-estimation resulting in a standard error of 35.7 % during the calibration period (2002-2004). During the validation period, SWAT over-estimated some of the peak flow events (2005-2007), with standard errors as high as 62.8 % during these events. In speaking with the Meteorological Service of Jamaica, these storm events were caused by tropical storms, resulting in conditions which would have been difficult for the model to simulate.

However, this model is meant to be used in the context of irrigation management during water scarce conditions. As such, the ability of SWAT to simulate low flows is more relevant to this context than the ability of SWAT to simulate storm flows. During storm conditions, evapotranspiration losses will be replaced by rainfall, and irrigation demand is no longer an issue. However, periods of low flow are a result of low rainfall, and it is during these times that irrigation demand becomes an issue. Unfortunately, SWAT at times had difficulty simulating some low flow conditions, with an over-estimation of a period of low flow occurring in March 2003 during calibration, and an over-estimation of 320% occurring during a very dry period in September 2006. Overall though, the simulation of low flow events was satisfactory (Figure 5 and 6).

It is likely that the geomorphology of the watershed plays a significant role in the inability of the SWAT to capture all of the low-flow events. The karstic portion of the watershed leads to complex interactions between surface and groundwater. The fact that the vast majority of the parameters which were calibrated were in relation to groundwater (baseflow release factors and groundwater delay factors), signifies that the karstic aquifer affects the entire dynamic of the watershed. This highlights the fact that the interaction between surface and groundwater plays an important role in the over-all dynamics of the watershed.

Salerno and Tartari (2009) did some work investigating the use of wavelet analysis (WA) along with SWAT, in simulating streamflow in a karstic watershed. They highlighted the disadvantage that deterministic models such as SWAT face when modelling karstic environments. The use of these kinds of models lead to over or under-estimation of streamflow, due to their inability to accurately compute contributions to streamflow from sub-surface circulation. It is especially difficult to simulate riverflows in karst environments, as the component of flow coming from the karst conduits cannot be directly measured (Salerno and Tartari, 2009). The authors found that the use of wavelet analysis was able to circumscribe the problem. Therefore, the coupling of SWAT with a groundwater assessment tool or model can result in significant reduction of the karstic effects. Therefore, due to the role which this aquifer is likely to have played in these interactions, it is recommended that future studies in Jamaica using SWAT in karstic watersheds use tools such as wavelet analysis to improve results, and circumscribe the karstic effect.

4.2 Use of SWAT in agricultural water scarcity management

The use of a modelling tool such as SWAT can be pivotal in irrigation planning, especially in light of water scarce conditions. SWAT can be used in order to determine water savings from different water management scenarios (Santhi et al., 2005). This is especially important in light of the competing uses for water among different watershed stakeholders. The irrigation planning process requires a basin wide perspective, as water supplies cross both local and parish boundaries. What this research sought to do therefore is to introduce SWAT as a tool for carrying out this type of quantitative analysis on a watershed level in Jamaica.

The aim of this research was not to carry out the actual management scenarios, but to determine if the potential existed for this tool to be used for that purpose. In light of this, no management scenarios were carried out with this model, however, in future research, this model can be used in order to gain an improved understanding of the water balance, as the determination of irrigation amounts for normal precipitation conditions is just one step in the process of managing water resources. The model can be used in order to assess water productivity and crop water use. In addition, it can be used in order to determine which cropping system would result in the most efficient water use, by assessing which cropping system would minimize evapotranspiration losses. This calibrated model can be used for analyzing different management scenarios for better crop management practices and irrigation planning.

A significant problem with the use of hydrological models in Jamaica lies not only in a severe shortage of data (hydrologic, climatic, and agricultural), but also a shortage of human and financial resources. However, models such as SWAT provide such powerful tools, that further investment into the future collection of data, and the future development of human resources, would go a long way in ensuring that Jamaica can adequately plan for the ever-changing climatic conditions.

5.0 Conclusions

A hydrological model was developed for the Rio Nuevo watershed in St. Mary using SWAT. This model was examined for its applicability for use in Jamaican agricultural watersheds. Streamflow was simulated, and the model was calibrated using observed streamflow from 2002 to 2004, and validated using observed streamflow from 2005 to 2007. An NSE correlation coefficient of 0.76 was obtained for calibration, while a coefficient of 0.50 was obtained for validation. Groundwater interactions played a really important part in the hydrologic dynamics of this watershed, despite the fact that the majority of this watershed is underlain by basal aquiclude. As a result, the most critical calibration parameters included GWQMN, RCHDP, ESCO and ALPHA_BF.

SWAT had some difficulties in simulating high-runoff events. Despite this, it has been determined that SWAT is a suitable model for use in simulating streamflow in this watershed, and holds much potential for future agricultural water resources planning, not only in this sub-basin, but also in other watersheds in Jamaica. It is important that pre-emptive action be taken towards water scarcity planning, and SWAT provides a very important tool for achieving this, as it can be used to determine strategies which could be put into place in order to maximize agricultural water savings. The land use and soil parameters that were used for this model are published with this paper, with the intention that they be used as a reference in the development of future hydrologic simulations within the island.

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