CHAPTER 2.6

HYDROLOGIC MODELING FOR WATER RESOURCE ASSESSMENT IN A DEVELOPING COUNTRY: THE RWANDA CASE STUDY

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Abstract

Accurate water resources assessment using hydrologic models can be a challenge anywhere, but particularly for developing countries with limited financial and technical resources. Developing countries could most benefit from the water resource planning capabilities that hydrologic models can provide, but these countries are least likely to have the data needed to run these models. Model-based hydrologic assessments are a necessity in developing countries due to limited national and international funding for water improvement projects. WaSSI (Water Supply Stress Index) is a relatively simple hydrologic model requiring a limited number of data inputs. Despite the simplicity, WaSSI predictions of streamflow at the watershed scale have been shown to correlate well with measured data at the monthly and annual time step. Therefore, WaSSI is a good candidate for use in hydrologic modeling in developing countries. As a case study, this paper presents an example of hydrologic model development, testing, validation, and projection using WaSSI for the developing country of Rwanda. Rwanda has a mixed landcover with approximately 20% of the nation covered in forest that range from dense mountain forests, to lower elevation open forests types. Leaf Area Index (LAI) is a primary driver of evapotranspiration (ET) within WaSSI. Therefore, as forest LAI increases with density, predicted ET increases and streamflow decreases. We found

that the data for validation of model streamflow from long term monitoring stations was limited due to measurement error. However, the WaSSI model showed promise when modeled streamflows were compared to the limited measured data using globally available model input parameters. Although we suggest that global model input data is sufficient for long-term water resource planning, we strongly encourage the development of increased hydrologic monitoring capacities in developing countries as part of international water conservation and development efforts.

Modélisation Hydrologique pour l'Evaluation de la Ressource en Eau dans un Pays en Voie de Développement : le Cas d'Etude du Rwanda

Résumé

L'évaluation précise des ressources en eau au moyen de modèles hydrologiques peut constituer un enjeu partout, mais tout particulièrement pour les pays en voie de développement aux ressources financières et techniques limitées. Les pays en voie de développement pourraient beaucoup bénéficier des capacités de planification de la ressource en eau qu'offrent les modèles hydrologiques, mais ces pays sont les moins susceptibles de disposer des données nécessaires pour faire fonctionner ces modèles. Les évaluations hydrologiques basées sur la modélisation sont une nécessité dans les pays en voie de développement du fait du caractère limité des financements nationaux et internationaux pour les projets concernant la ressource en eau. WaSSI (Indice de Stress pour l'Alimentation en Eau) est un modèle hydrologique relativement simple qui requiert une quantité limitée de données d'entrée. En dépit de cette simplicité, il a été montré que les prédictions du débit des cours d'eau établies avec WaSSI à l'échelle du bassin versant sont bien corrélées avec les données mesurées aux pas de temps mensuel et annuel. De ce fait, WaSSI est un bon candidat pour une utilisation en modélisation hydrologique dans les pays en voie de développement. En termes de cas d'étude, cet article présente un exemple de construction d'un modèle hydrologique, de test, validation et simulation prospective au moyen de WaSSI pour le Rouanda. Le Rouanda présente une occupation des sols mixte avec environ 20% du pays couvert de forêts, depuis la forêt dense de montagne jusqu'à des forêts ouvertes de plus basse altitude. Dans WaSSI, l'indice foliaire (LAI) constitue le principal facteur de l'évapotranspiration (ET). Ainsi, lorsque le LAI de la forêt augmente avec sa densité, l'ET simulée augmente et le débit des cours d'eau décroît. Nous montrons que les données disponibles pour la validation des simulations du débit des cours d'eau, issues des stations de suivi à long terme, sont limitées du fait des erreurs de mesure. Cependant, le modèle WaSSI tient ses promesses lorsque les débits modélisés sont comparés au nombre limité de données mesurées, en utilisant des paramètres d'entrée du modèle disponibles globalement. Bien que nous suggérions que des données d'entrée globales pour le modèle sont suffisantes pour la planification à long terme des ressources en eau, nous encourageons vivement le développement de capacités de suivi hydrologique dans les pays en voie de développement.

1. Introduction

Water is critical to the security and well-being of any country regardless of the country's wealth (Falkenmark, 2001). An abundance of other natural resources such as fertile soil, wood, or fisheries are of little use if people have limited access to potable water. Therefore, accurate assessments of water demand and supply are of great importance for national economic and social development and stability. However, access to the tools and data needed to conduct such water resource assessments are often limiting, especially in developing countries with limited capacity of science and technology, and funding.

Forests, grasslands, and other natural areas are increasingly being valued for their ability to stabilize river flows and climate, provide sources of bioenergy, and as buffers to the harmful impacts of climate change on society through their ecosystem services. However, these ecosystem functions are threatened by global change. For example, in the United States widespread hydrologic manipulation and consumptive of stream water use practices have altered river flows (Vörösmarty et al. 2004), threaten the sustainability of the water resource (Alcamo et al., 2003), and degraded ecosystem function (Carlisle et al., 2010). Future changes in climate will place additional pressure on freshwater supplies (Bates et al., 2008). The effect of these stressors will be highly variable over both time and space, making it difficult to assess effects on water availability into the future even with the relative abundance of financial resources of which developed countries have ready access. Developing countries face similar water stress issues as developed countries but with limited resources to address these challenges.

Model based, hydrologic assessments are useful for the development of water policy to assess general conditions, patterns and trends in natural resource supply and demand, and to develop strategies for reducing the risk of shortage, or to exploit opportunities using limited available funding. Hydrologic models are often an important part of water resource assessment in forecasting long-term changes in water supply (both surface, and groundwater), demand by urban centers, for agricultural production, water navigation, or hydro-electric power generation.

Ideally, ample data would be available for hydrologic modeling and assessment, but this is seldom the case even in developed countries. Hydrologic assessments require extensive data collection to adequately represent large spatial areas. A commitment to long-term (e.g., 10 years or more) data collection is required to establish trends in hydrologic supply and demand. In addition to committing to data collection, the methods used to collect the data should be held constant across locations and time.

Limited funding to allocate toward monitoring, a lack of trained personnel, inconsistent or non-existent power supplies, and a lack of access via road systems are all problematic factors that prevent the collection of data needed for hydrologic model assessment in developing countries. Therefore, global datasets are often used as a primary information source by many developing countries. Global datasets have both advantages and disadvantages. The datasets are generally universal in extent (i.e., a single complied database may exist for the entire globe), and as the product of an international effort (e.g., International Panel of Climate Change, UNESCO), the data would have been carefully error checked, and developed in a standardized format. However, global datasets have the disadvantage of frequently being developed at a coarse temporal and/or spatial resolution. The coarse nature of the data can limit the precision at which assessments can be conducted.

In this study, we used a relatively simple hydrologic model called WaSSI (Water Supply Stress Index) (Sun et al., 2011; Caldwell et al., 2012) to examine current and alternative future hydrologic condition scenarios for the east African country of Rwanda. Rwanda was chosen because it contains very diverse ecological conditions (including forests (20%), agriculture (70%)) in a relatively small geographic area (26,000 km^2). Climate change is projected to significantly impact this Rwanda in the coming decades, and as a developing country, it has limited resources with which to rapidly address the effects of climate change. The focus of the paper is not so much on the hydrologic model algorithms and structure, but rather to provide an example of how developing countries with limited fiscal resources and databases can access, apply and validate predictions of a hydrologic model for use in assessing future water resource needs. A strategic assessment of Rwanda's water resources will provide the country with more time to adapt and prepare for potentially negative impacts of climate change.

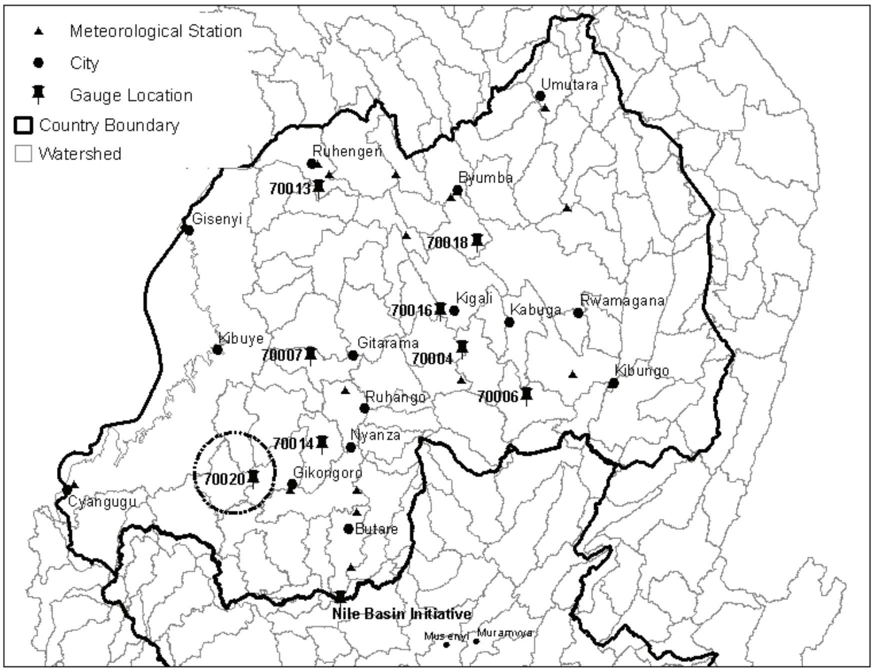

Figure 2.6-1 - Location map of stream gauge and meteorological stations. Site 70020 is circled in the map.

2. Methods

2.1. Study Area

The study area is the country of Rwanda, but the project encompassed the entire countries of Rwanda and Burundi, along with portions of Tanzania, Uganda, and the Democratic Republic of the Congo. Rwanda is relatively small in area so multiple countries were needed to fully evaluate hydrologic flow patterns within Rwanda. The mountainous terrain of western Rwanda becomes more rolling toward the countries eastern border. Annual precipitation patterns follow elevation with the highest rates occurring in the western (i.e. > 1600 mm^{-1} yr^{-1}) and least in the eastern parts (i.e. < 800 mm^{-1} yr^{-1}) of Rwanda (United Nations, 2010).

Likewise, dense, mountainous mixed forests supported by high rates of annual precipitation dominate western Rwanda while agricultural and grazing land can be supported in the lower rain fall areas in the central and eastern region (Figure 2.6-1). Between the east and west, crop and grazing lands are the predominant vegetation cover classes, and forests occupy approximately 20% of the land area (UN, 2010), Figure 2.6-1).

2.2. Model Overview

We selected the Water Stress Supply Index (WaSSI) hydrologic model for use in the Rwanda case study to develop a hydrologically based landscape scale assessment for a developing country. The WaSSI model was developed by the USDA Forest Service for assessing impacts of land management and climate change on water availability and ecosystem productivity at the continental scale (Sun et al., 2011; Caldwell et al., 2012). WaSSI was originally developed for southern US forests (McNulty et al., 2007; Cohen et al., 2007; Sun et al., 2008a, 2008b). The premise of WaSSI is that leaf area, latitude, air temperature and precipitation are the primary drivers of plant water use (Sun et al., 2008). If these and a few other variables (e.g., soil water holding capacity) are known, then ecosystem water use can be predicted for any ecosystem type (e.g., forest, grassland, agricultural crops (Sun et al., 2008)). WaSSI uses leaf area and vegetation type to determine rates of evapotranspiration (ET). As leaf area increases, so does vegetative water use, and stream flow decreases. Given that different vegetation types have different water use efficiencies (WUE), the same leaf area across different vegetation can also alter plant water use and therefore stream flow. Climate, land use change, and human population predictions are integrated into WaSSI (when available) to examine multiple stresses on water stress. Some of the data needed to predict water demand (e.g., residential, commercial, agricultural water use) are not available for most developing countries, including Rwanda. Therefore, this water resource assessment can only address the issue of water supply. The focus of this paper is not on model development; rather we focus on the broader development of water resource assessment in developing countries. As such, the details on the WaSSI model are not included here. For a full description of WaSSI see Sun et al. (2011) and Caldwell et al. (2012).

2.3. Need for Model Evaluation

Data collection and monitoring are costly, especially in developing countries with limited financial resources. However, model evaluation is critical if major management decisions are going to be made based on resource assessment studies, and the models input that goes into those studies. A poorly tested model can lead to erroneous decisions, and the significant potential for loss of economic gain, or even the loss of human life in a developing country through poor resource use planning. Therefore, both data for model assessment, and statistical tools for evaluation of model performance are needed. The coefficient of determination (i.e., R^2), generated with linear regressions is commonly used to assess how well a model simulates the variability of measured values.

2.4. Monitoring Data

Stream flow gauge stations are a potentially excellent source of model validation data. Gauges are generally located at the base of various size watersheds. The stations measure water flow at an incremental time period over many years or even decades. Some stations in developed countries may have gauges that have continuously measured stream flow from every few minutes for many decades. For example, the Coweeta Hydrologic Laboratory in western North Carolina, USA has several gauged watersheds that have been in continuous operation since 1935. This long period of record allows for very accurate assessment of climate change impacts on stream flow, and serves as a valuable source of data for model validation.

Unfortunately, such high quality records are very rare (even in developed countries). The amount of high quality, long term data for Rwanda was extremely limited. After an extensive search, nine stations were identified and compared to the estimated outputs from WaSSI. These nine stations drained catchment areas of various sizes and were located throughout Rwanda. Of those nine stations, this paper will focus on Station 70020 (Figure 2.6-2). Although the data for gauge Station 70020 was not very complete, it was among the most complete and error checked dataset available. Station 70020 had three complete years of measured data. A year was considered complete if there was data for every month in the year. Complete measured years (i.e., 1988, 1996, and 1997) and other partially complete measured years were compared to the WaSSI predicted monthly and annual stream flow and runoff predictions. Therefore, broad generalities regarding the WaSSI models predictive performance must be made with caution due to the limited spatial and temporal extent of the validation data. However, the data was sufficient to provide an example of the complete assessment process.

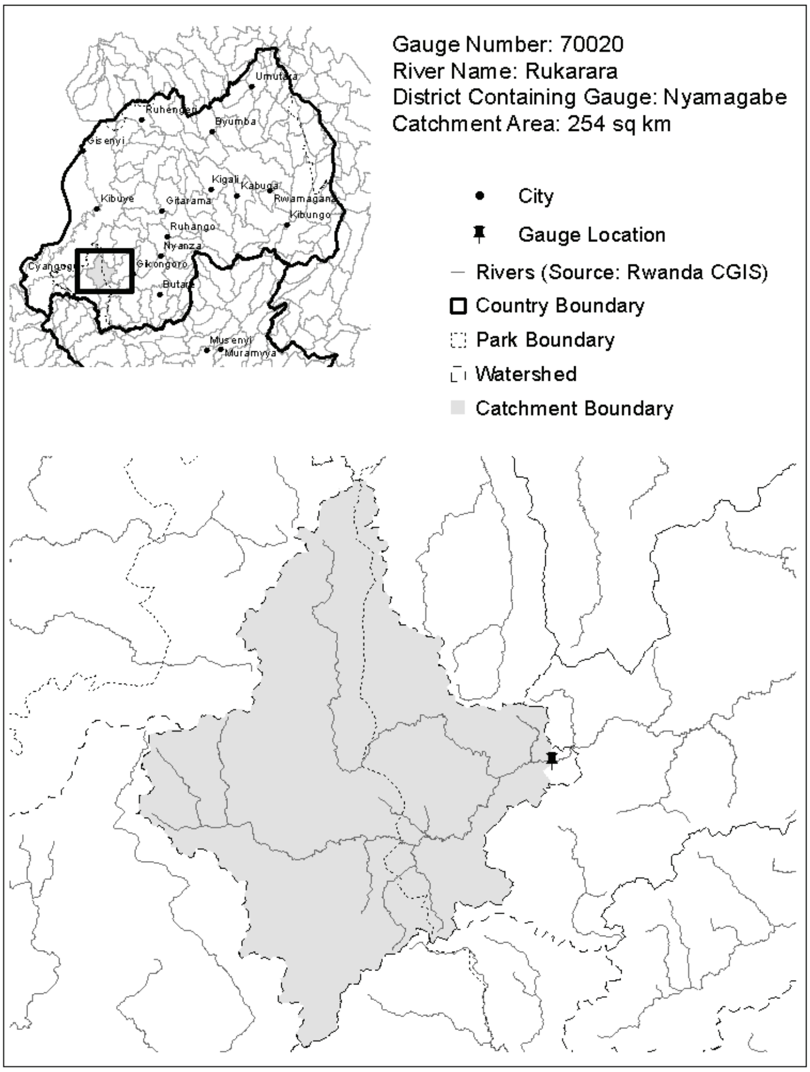

Figure 2.6-2 - Gauge Station70020 on the Rukarara River.

The station drains a catchment area of 254 km^2 and is located on the Rukarara River. The area where we validated the model predictions was predominately covered in forest (i.e., crop 1%, deciduous forest 37%, mixed deciduous and coniferous 42%, grassland 17% and shrubland 1%). Historic climate data were derived from gridded 0.5^o x 0.5^o monthly climate data developed by the University of East Anglia Climatic Research Unit (Table 2.6-1). The watershed monitored by Gauge Station 70020 had annual mean precipitation of 1,522 mm per year, and a mean annual air temperature was 19°C corresponding to the time of stream record (Figure 2.6-3).

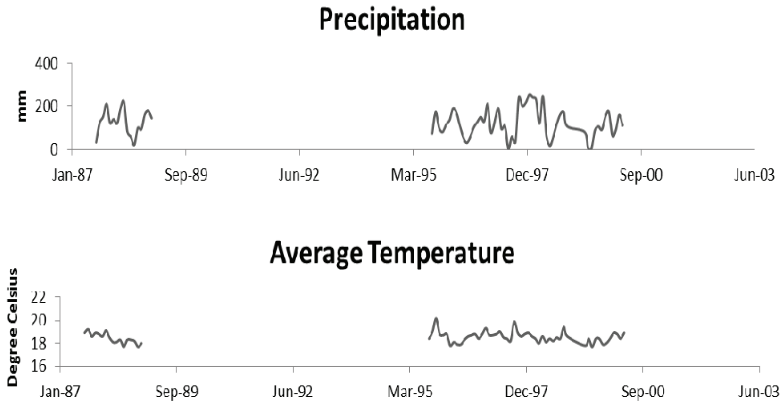

Figure 2.6-3 - Time series of precipitation and average temperature for the watershed monitored by Gauge Station 70020.

Twenty-four percent of the daily measurements for station 70020 were instantaneous measurements taken once a day and seventy-five percent was taken three times a day. By comparison, streamflows at the Coweeta hydrologic laboratory are recorded every five minutes. The instantaneous nature of the stream flow measurements likely introduces some error to the modeled streamflow predictions because the model is predicting mean flows for each month.

2.5. Hydrologic Projection

Hydrologic model projections for use in water resource assessments should only be conducted after the accuracy of a model has been determined. There are additional costs associated with model projections including data acquisition, quality control and data quality assurance measures (i.e., built-in system checks to minimize the potential for collecting, assessing or using inaccurate data), the potential need for modifying the data format to fit the model being used, and the evaluation of model outputs before this information is useful for water resource assessment. The need for this evaluation step is critical, and should not be skipped before using model projections for assessments. Some aspects of data collection such as data quality assurance measures go beyond the short-term objectives of this paper, but should be considered for long-term model prediction accuracy. However, other data checks (e.g., comparing data from alternative sources that are more than two standard deviations beyond the mean value) were conducted for this exercise, and the data was found to be suitable for model validation.

To assess the potential impact of climate change on stream flows, downscaled future climate data from the 4th Assessment of Intergovernmental Panel on Climate Change (IPCC) was used as input into the WaSSI model. Specifically, the UKMO-HadCM3 model with the A2 emissions scenario were used. The A2 emissions scenario represents a future with high population growth, regional economic development, and slow fragmented technology change. This emissions scenario predicts the highest amount of global surface warming by the end of the 21st century (IPCC, 2007) and is the model that is currently tracking atmospheric CO_2 emission rates. However, the objective of the paper is meant to be more illustrative than predictive. In that regard, any of the scenarios would have been acceptable.

The data we used was provided by the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project (CMIP) phase 3 climate projections. This dataset had several advantages including being quality controlled, and in a good format for use in the WaSSI model. The data was available at a 0.5^o x 0.5^o monthly spatial resolution from 1950 - 2099. The WaSSI model was run for a baseline time period (1981-2000) and a future time period (2041-2060) using the UKMO-HadCM3 temperature and precipitation as input for both periods. Additional model parameters (e.g., leaf area index, soil water holding capacity) were all derived from global datasets (Table 2.6-1).

Dataset	Source	Time Period	Native Resolution
Digital Elevation Model	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) GDEM2	Published 2011	30m x 30m
Future Climate Precipitation and Temperature	Global climate model output, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007), were obtained from www.engr.scu.edu/~emaurer/global_data/. These data were downscaled as described by Maurer et al. (2009) using the bias-correction/spatial downscaling method (Wood et al., 2004) to a 0.5 degree grid, based on the 1950-1999 gridded observations of Adam and Lettenmaier (2003).	1950-2099	0.5° x 0.5°
GIS Administrative Boundaries ,Cities, and Streams; Rwanda	Personal communication with Elias Nyandwi; The Center for GIS in the National University of Rwanda	Static	
GIS Administrative Boundary and Cities, Burundi	FAO Africover Project; http://www.fao.org/geonetwork/srv/en/main.home#boundaries	Published 2002	1:100,000
Historic Climate Precipitation	University of East Anglia Climatic Research Unit (CRU) Monthly Time Series Data, Version 3.10.01; http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276	1960-2009	0.5° x 0.5°
Historic Climate Temperature	University of East Anglia Climatic Research Unit (CRU) Monthly Time Series Data, Version 3.10; http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276	1960-2009	0.5° x 0.5°
Landcover	European Space Agency (ESA) Globecover 2009 (Global Land Cover Map) ; http://due.esrin.esa.int/globcover/	2009	300m x 300m

Leaf Area Index	Zhao et al.,2005; Numerical Terradynamic Simulation Group (NTSG) at the University of Montana Missoula; Moderate Resolution Imaging Spectroradiometer (MODIS) Imagery, MOD15(FPAR/LAI)	2000-2006	1km x 1km
Observed Streamflow (Model Validation)	MINITERE/SHER, 2005. Assitance Technique a la Preparation du Project de Gestion Nationale des Ressources en Eau. . Revue des données des Stations limnimétriques. Kigali, Rwanda	Various years between 1971-2000	
Observed Streamflow (Model Validation)	Personal communication with Antoine Niragire; Nile Basin Initiative Decision Support System Unit	1971-1990	
Soils (World)	Harmonized World Soils Database Version 1.2	Published 2012	1km x 1km

Table 2.6-1 - Database used in applying and assessing the WaSSI model in east-central Africa.

3. Results and Discussion

Using the national scale climate data, WaSSI predicted run-off across Rwanda. For example, WaSSI estimated that between 1981 and 2002, the Nyungwe National Park region in southwestern Rwanda (Figure 2.6-2) has the potential to convert 36% (~ 500 mm) of the precipitation in the area into runoff, while the Kigali region of Rwanda has the potential to convert 32% (~353 mm) of precipitation into runoff. Estimates of rainfall to run-off conversion could be very useful for predicting water resource availability. However, this type of information is only useful if WaSSI predictions accurately represent measured validation data.

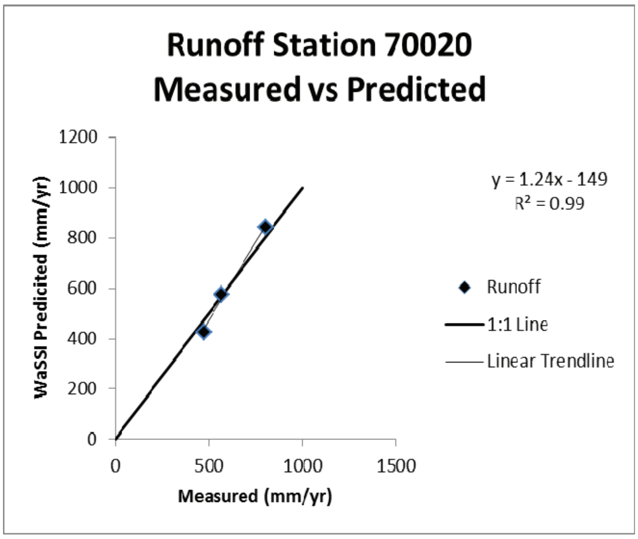

Figure 2.6-4 - Scatter plot of annual measured versus predicted runoff for gauge Station 70020. Between 1981 and 2000.

3.1. Measured versus Predicted Runoff Comparison for gauge Station 70020

Without any calibration, annual timestep WaSSI closely predicted measured runoff (Figure 2.6-4, R^2 = 0.99). On average, measured runoff and predicted runoff WaSSI estimated that 39% (~615mm) of precipitation was converted into runoff. Although WaSSI was able to recreate the general pattern and timing of the annual stream flow and runoff, the model was not highly correlated with monthly stream flow and runoff from Gauge Station 70020 (R^2 of measured and predicted (Figure 2.6-6) was 0.47). Annual correlations between measured and predicted run-off are of limited use given that a drought of even a few months could have disastrous consequences on water availability for residential use and crop irrigation, and would not be observed at an annual time-step.

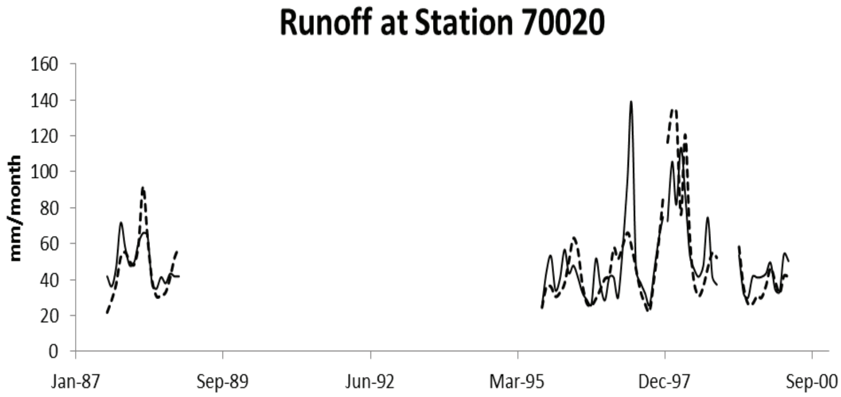

Figure. 2.6-5 - Monthly measured (solid line) versus predicted (dashed line) runoff for Station 70020 between 1981 and 2000).

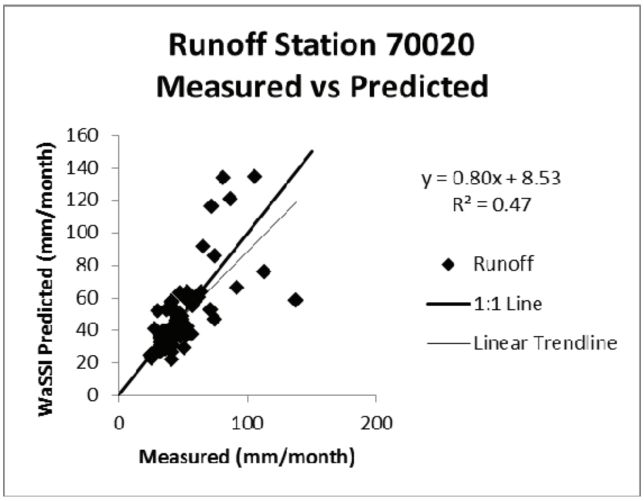

Figure 2.6-6 - Monthly measured versus predicted runoff for Station 70020 between 1981-2000.

WaSSI consistently over predicted flow in the wet season and under predict the dry season for Gauge Station 70020 (Figure 2.6-7). Climate data is at the core of the WaSSI model. The inherit trends of the precipitation data with respect to high rainfall and low rainfall are reflected in the model results. WaSSI models the natural water balance and does not account for any engineering structures on the stream like dams or diversion. However, dams would not have a large impact at a monthly timestep after the basin is full, and much of the water would be pass through if precipitation had no seasonal pattern. Conversely, in areas with distinct wet and dry seasons there could be lags, and that would be a source of error. Additionally, WaSSI routes all water to the outlet of the watershed, so the runoff and flow estimates are at the outlet (that could be wrong when including ground waters). If the WaSSI watershed area is larger than the gauge catchment area (not the case in this study) or if the gauge is located upstream of the outlet of the watershed, then it is possible for WaSSI to overestimate the flows and runoff. For our study the gauge catchment footprint aligned well with the WaSSI watershed footprint.

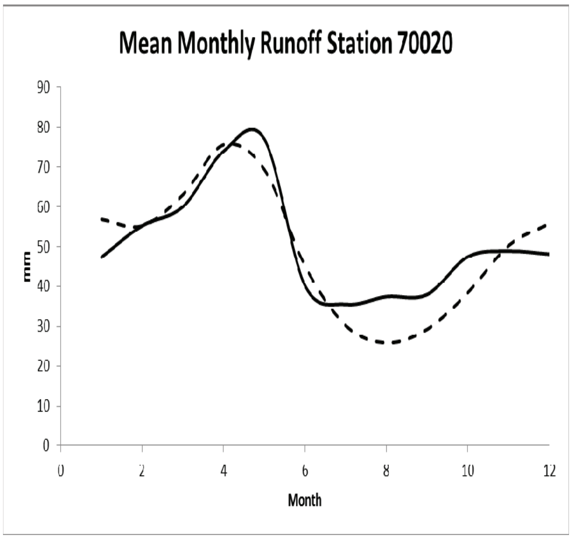

Figure 2.6-7 - Average monthly measured runoff (solid line) versus predicted runoff (dashed line) runoff for Station 70020 from 1981 to 2000.

The highest peak flows not being captured by the measured data were likely another reason why WaSSI is under predicting the runoff in the dry season. The Rwanda Gauge Station 70020 measured data are instantaneous measurements at a very low interval (i.e., two to three times per day). During a rain event, it is possible that the peak flow for the day occurred at a time that was not captured in the daily measurements. In contrast, the United States Geologic Survey (USGS) monitors thousands of streams in real time throughout the US every 15 minutes (Olson and Norris, 2007). Measuring every fifteen minutes ensures recording peak flow resulting from high rainfall, and it also produces a good record of baseline flow. As previously mentioned, stream flow used for research validation are collected at even more frequent intervals (e.g., every five or ten minutes).

WaSSI soil moisture parameter may have underestimated the soil water storage which would also have led to overprediction of flow in the wet season and under prediction the dry season. Soil moisture, infiltration, surface runoff, and baseflow are estimated in WaSSI using algorithms of the Sacramento Soil Moisture Accounting Model (SAC-SMA) (Koren et al., 2003). This algorithm is composed of eleven parameters that divide the soil profile into two layers, a thin upper layer and thicker lower layer. Those parameters simulate the movement and interaction of water between the upper and lower layer to generate surface runoff. If the estimated soil water storage is lower than reality, then WaSSI will produce low evapotranspiration measurements and thus, predict higher runoff compared to measured values.

Leaf area is the most important vegetation determinant of ET (Sun et al., 2010). Unfortunately, leaf area index is variable and can change inter and intra-annually. The vegetation cover satellite imagery that we used in the project represented a single point in time (Table 2.6-1). Many environmental factors could have decreased (e.g., drought or insect herbivory) or increased (e.g., time of year, above average precipitation) LAI during the years that compared WaSSI predictions to monitoring data.

All considered, WaSSI did fairly well at recreating the stream flow and run-off of Station 70020. The R^2 of measured to predicted streamflow or runoff was 0.99, but while the annual pattern was good, there were many sources of error in the monthly prediction (i.e., $R^2 = 0.47$). At this point, researchers in conjunction with land managers and policy makers need to decide if the relationship between measured and predicted streamflow and run-off was sufficiently correlated to warrant the use of the hydrologic model for forecasting. This decision must be considered in the context of only having a single point to represent an entire country, and the reality of knowing that this is the best available data. For the purpose of illustrating a complete case study, we assumed that the analysis indicated that the WaSSI model was sufficiently accurate to proceed with the application of the WaSSI for water resource assessment, and to more specifically test the impact of forest cover on water use and yield at the watershed scale.

3.2. Impacts of Future Climate Change and Forest Cover Change on Stream Flow

The entire study area was predicted to experience an increase in precipitation and temperature from the 1981-2000 period to the 2041-2060 period. The mean annual precipitation averaged across Rwandan region (i.e., includes Rwanda and surrounding area) increased from 1140mm in 1981-2000 to 1182mm (4%) in 2041-2060, and the mean annual temperature averaged across the study area increased from 20°C in 1981-2000 to 22°C (+2°C) in 2041-2060.

The net effect of increased temperature and precipitation resulted in 157 watersheds having decreased stream flow ranging from a 1% to 11% decrease, 39 watersheds having no change. Additionally, 35 watersheds were predicted to have increased runoff ranging from a 1% to 3% increase (Figure 2.6-8). However, the mean annual stream flow averaged across the study area decreased by 2% in 2041-2060.

Other factors such as a loss of forest cover would likely not have a major long-term impact on stream flow for several reasons. Although previous studies have demonstrated that the removal of forest cover can significantly increase stream flow in the short term, these changes only last a few years unless active management is used to maintain a deforested state (Swank and Miner, 1968). Under natural forest loss, over vegetation quickly occupies the vacated space, and leaf area is quickly re-established even though much of the biomass is gone. Forest conversion in the WaSSI model attempts to mimic this process by changing the leaf area index and water use efficiency terms when forest cover is removed. Therefore, even an extreme change (e.g., 50% reduction) in forest cover has a relatively small impact on long-term, predicted water yield because the forest leaf area is being substituted for another form of leaf area (e.g., crop).

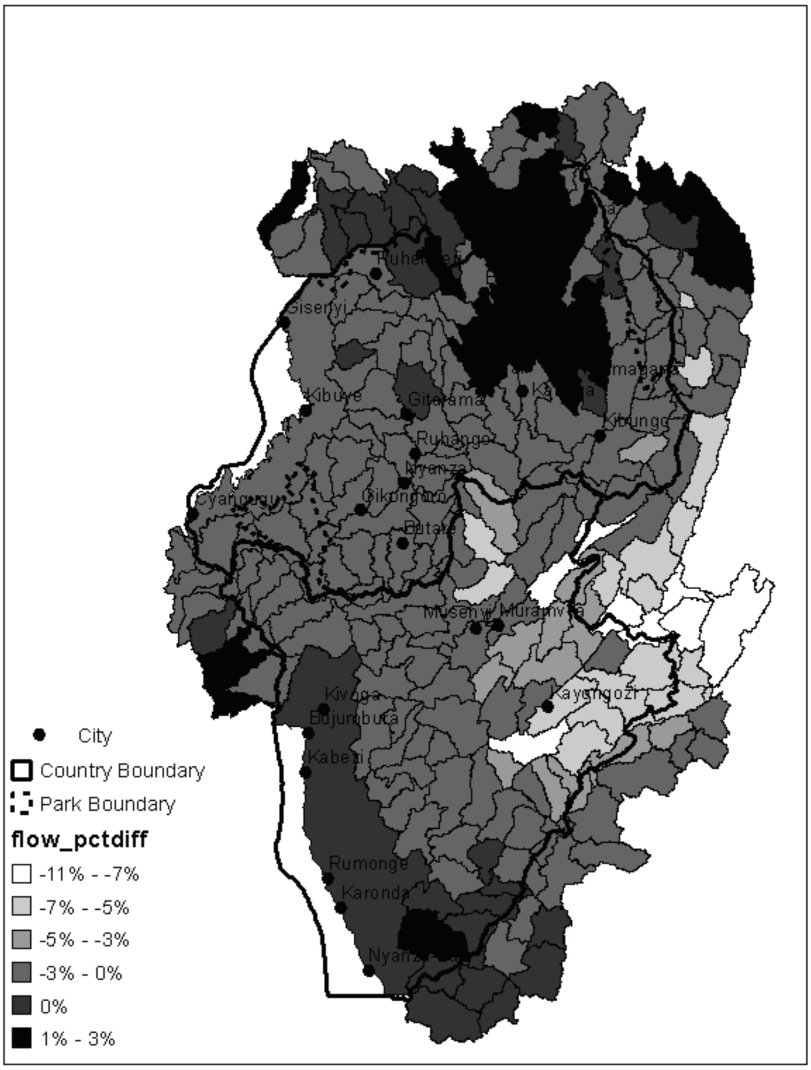

Figure 2.6-8 - Impact of climate change on mean annual water yield by the middle of the 21st century across Rwanda.

These results show the potential value of using a hydrologic model for assessing a complex array of changing environmental conditions on water resource availability. In this case study, both, air temperature and precipitation increased. As air temperature increases, vegetative evapotranspiration increases. However, during the study time period, precipitation also increased so the question was which driver would be the dominant factor in changing stream flow and run-off? The model would suggest that this pattern of change was not universal with increases, decreases and no change all occurring across the country. In a full water resource analysis, a more detailed temporal time step should also be examined. For example, a region may see a 5% reduction in annual precipitation and/or stream flow, but if the majority of that decrease occurs during a rainy season, when water is abundant (or over abundant), the impact on people and ecosystems may be minimal. Conversely, another area may see a 10% increase in precipitation and/or stream flow, but if that increase occurs during the wet season, then the overall impact will be minimal from a water availability standpoint, but could have severe impacts on human welfare (e.g., flooding, landslides, water contamination).

4. Conclusions

We recommend that additional climate and stream monitoring stations are needed to better assess the impact of climate change on water availability across Rwanda. Not only should the number of climate stations and streams being monitored be increased, the frequency of measurement collections should also increase. Developing countries (possibly with the assistance of international aid) should consider investing in automatic stream gauge to take measurements on the order of minutes and not hours. The benefit of an automatic system is the consistency in measuring style, the ability to capture data at regular interval, and therefore capture peak flow during rain events. Even though the recording system is automatic the data retrieval process can be manual by professional or non-professional individuals who can be trained at minimal annual cost. We believe that funding for monitoring and assessment is equally as important as the development of projects and programs designed to relieve current or future water stress. The funding for assessment can substantially improve the likelihood of project success, and the efficiency of project funding allocation.

WaSSI is a useful tool for assessing water resources, and easy to use. It can be used as an educational tool in schools or as a sensitivity tool for land managers or natural resource professionals making decisions. The power of WaSSI is its ability to estimate the impacts of climate change on water resources using on a few readily available model parameters. Our results suggest that climate change impacts on water resources will be minimal, but those impacts do vary spatially and temporally. Validation is important for the use in any model and validation is only possible if field measurements exist. The development of a consistent long-term monitoring network is the key to validation studies, and for historical understanding of the effects of land management activities on natural resources. Access to databases, personal computers and modeling programs is often a challenge in developing countries. Therefore, we have developed a user friendly, web based version of the WaSSI model for Rwanda that is available for use at http://www.wassiweb.sgcp.ncsu.edu/. The program does not need to be downloaded on to a computer, and can be accessed by any public computer that has internet access. We believe that pre-tested/validated hydrologic models with associated historic and projected climate databases can be a significant step forward in helping financially challenged countries to prepare for climate change impacts.

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