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FINAL REPORT

Hydrologic Modeling

Integrated Management of the Yallahs River and Hope River Watersheds

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1. Introduction

Land use influences the hydrologic regime and the water quality of streams draining watersheds. Watersheds provide substantial hydrologic services to society including clean water for drinking, domestic use, irrigation, hydropower production, and ecological clean habitat for fish. The Yallahs River and Hope River Watershed Management Units (WMUs) are adjoining hydrologic basins on Southern slopes of the Blue and John Crow Mountain ranges and east of the capital city of Kingston (population 667,000). Together, these WMUs extend for 44,486 ha and supply 37% of Kingston's water. The Yallahs River also recharges the aquifers and provides irrigation water for farmers in the rural Yallahs Valley. This water is vital for the livelihoods of the farmers because the competitiveness of agriculture in the Yallahs watershed is affected by water supply which is mainly rain-fed and limited. The area contains 7% of the island's farmland and has more poor households (29%) than the national average (19%). The mountains provide water for domestic, agricultural and industrial uses to 40% of Jamaica's population. Rainfall ranges from over 7000 mm per annum on the northern slopes, to less than 1200 mm on the lower southern slopes.

Degradation and un-sustainable use of these watersheds will affect and substantially reduce the services provided to these communities which may cause increase in vulnerability, water treatment cost, water shortages and potentially poverty. The Department of Forestry estimates that flood-prone areas make up 8% of the area of the WMUs; 49% is prone to landslides while 65% of the two WMUs are subjects to soil erosion due to the steep slopes and poor land use and agricultural practices (at 163 tons/ha/year in the Hope watershed). Approximately 10% of the forest in the Blue and John Crow Mountains National Park is located on the upper slopes of these two watersheds.

Improving the watershed landscape and health will enhance hydrologic stability and water quality in the Yallahs and Hope Rivers Watersheds. Restoring perennial vegetative cover, reforestation, and enhancing best management practices in these watersheds can potentially improve hydrologic stability and enhance water quality by reducing annual peak flows, sustaining low flows, and reducing sediment loading in streams.

In this study, we simulated the impacts of land use land cover changes on the hydrologic regime and water quality (sediment) in the Yallahs and Hope Rivers Watersheds. Riverside's task in this multi-disciplinary project was to estimate and map hydrological and bio-physical production functions (water and sediment production) throughout the watersheds focusing on project sites selected by the project team. Our main objectives were to estimate the possible impacts of proposed land use changes on the quality and quantity of water availability for downstream users. Also, we investigated how these impacts will be mitigated with the actions that would be implemented with the current integrated watershed management project. Finally, we are presenting and supporting the elements of a monitoring plan to assess the hydrological impacts of this project.

2. Methodology

2.1. Model Characteristics

The model selection process is dependent on several problem-specific factors addressed by the study. Among the significant factors are the type of hydrological processes to which the model will be applied, the scale of the area where the model is applied and the data availability for the model. There is a family of hydrologic simulation models, which can be used in simulating land use changes at the watershed scale. The chosen model also needs to simulate hydrological processes including climate-plant-soil processes in a holistic continuous approach (i.e., not event specific) with a small computational time step to meet the objectives of this project.

In this study, we looked at the available models that can help address the project's goals. We focused on models that are available in the public domain, have available technical support, are popular and user-friendly, do not require extensive datasets as inputs and are scenario-based. The Soil Water Assessment Tool (SWAT) model was selected for the purpose of developing a hydrologic model for the Yallahs and Hope Rivers Watersheds, assessing the current hydrologic conditions and simulating the changes in water quantity and sediments associated with land-use changes.

SWAT is a continuous hydrologic model built to quantify the impacts of land management practices in large, un-gaged agricultural watersheds allowing the user to predict the effect of alternative land management decisions on water, sediment, nutrients, and pesticide yields with reasonable accuracy. It is a semi-distributed model that operates on a daily time step. It is user-friendly with a Graphic User Interface and it is based on ArcGIS, which eases the pre-processing of data inputs, model development, and post-processing of model results.

The SWAT model has a built-in database of parameter values for different land use land cover types. However, this database was developed based on climatic and soil conditions in the Southern United States. The user must modify and adjust these parameters, through calibration, to meet the conditions of the study area.

The SWAT model has been successfully used worldwide to investigate the impacts of land use change and best management practices on water quantity, sediment and water quality in watersheds of different sizes in various eco-regions. Recently, SWAT has also been used to investigate the impacts of climate change on hydrologic regime components including instantaneous peaks, seasonal runoff, low flows and other characteristics.

SWAT uses either the SCS curve number (CN) or Green-Ampt method to determine runoff. The Green-Ampt method requires sub-daily (Hourly) precipitation data input. With the CN method, runoff is calculated as a function of hydrologic soil group, cover type, land treatment, hydrologic condition, and antecedent runoff condition (Rawls et al. 1993). Also, the SCS CN method can be applied in watersheds of various ranges of slope, land use types, rainfall and soil. As for sediment modeling, SWAT uses the USLE equation that is widely used to estimate erosion and sediment yields in a wide variety of watersheds worldwide. The model applies these equations on homogenous land segments called Hydrologic Response Units (HRU). The HRU is a homogenous land segment that has similar land use land cover, slope class and soil type. The model applies the selected governing equations (CN and Green-Ampt) for different hydrologic processes on these HRUs; the HRUs hydrological outputs are then summed to the sub-basin level. The user defines sub-basins either manually by selecting sub-basin outlets or automatically by identifying a drainage area threshold. In this exercise, we selected 50 ha as sub-basin drainage area allowing SWAT to delineate sub-basins automatically. It is important to mention that one sub-basin can contain many different HRUs and one HRU can be in different sub-basins.

In this study, we used SWAT with the CN method. Limited precipitation data were the reason for the selection of this approach to calculate the direct runoff. The SCS curve number method is a simple, widely used, and efficient method for determining the approximate amount of runoff from a rainfall event within any particular HRU. This method requires rainfall depth and curve number (CN). The CN is a runoff parameter based on the HRU's hydrologic soil group, land use, management practice, and hydrologic condition. The SCS-CN method is defined as follow:

$$S_x = \frac{25400}{CN_x} - 254$$

$$\begin{cases} Q_{sx} = 0 & \text{if } P_s \le 0.2S_x \\ Q_{sx} = \dfrac{(P_s - 0.2S_x)^2}{P_s + 0.8S_x} & \text{if } P_s > 0.2S_x \end{cases}$$

where CN_x is the Curve Number value for the HRUx; S_x is the potential maximum retention after runoff begins; and Q_x is the direct runoff or quick-flow that is potentially generated by the rainfall P_s at x.

For sediment modeling, SWAT uses a Modified Universal Soil Loss Equation (USLE) (Wischmeier, Smith 1978). The USLE predicts erosion based on the energetic ability of rainfall to move soil and cause erosion, the erodibility of a given soil type, HRU slope, erosion protection provided by the presence of vegetation, and management practices (Roose 1996). The Modified forms of the USLE are used, at a minimum, to provide the relative potential of a HRU for sheet wash erosion (Reid, Dunne 1996). The USLE is defined as follows;

$$USLE_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x$$

R_x is the rainfall erosivity, which represents the ability of rainfall to move and erode soil and is a function of average regional rainfall intensity and duration. K_x is the soil erodibility, which represents the soil's susceptibility to erosion and is a function of soil texture and characteristics. LS_x is a slope-length index which characterizes the potential energy associated with the uninterrupted slope leading up to HRU x. Breaks in slope length are based on Renard (1997) and the algorithm for LS_x from Stone and Hilborn (2000). C_x is a dimensionless ground cover variable that varies from 1 on bare soil to 0.001 for forest. Finally, P_x is a management factor that accounts for specific erosion control practices such as contour tilling or mounding, or contour ridging. P_x varies from 1 on bare soil with no erosion control to about 0.1 with tiered ridging on a gentle slope (Roose 1996).

2.2. Study Area

Hydrologic modeling was one task of the comprehensive project investigating practices for integrated management in the Yallahs River and Hope River Watersheds. This modeling exercise took place in the larger watersheds of the Yallahs and Hope rivers. These watersheds are adjoining hydrologic basins on the Southern slopes of the Blue and John Crow Mountain ranges and east of the capital city of Kingston (population 667,000). Together, these WMUs extend for 44,486 ha and supply 37% of Kingston's water.

Table 1 summarizes the land use land cover distribution in both major basins in the current conditions (scenario provided as current). The spatial resolution is very coarse and the classification is considered coarse for the limited number of land use land cover types. In the Hope basin, urban land use occupies about half of the watershed, open dry forest occupies about 14%, and the rest is forest cover. As for the Yallahs basin, it is clear that the majority of the area is forest cover.

Table 1: Land use land cover percents in the study area for the current scenario

Basin	LULC	Description	% Area
Hope	BBFD	Bamboo and Fields	0.7
	DBFD	Secondary Forest and Fields	10.9
	DSBL	Primary Forest or Secondary Forest	11.6
	FDDB	Fields and Secondary Forest	8.4
	FIDS	Fields: Herbaceous crops, fallow, cultivated vegetables	7.8
	RNGB	Open dry forest - Tall (Woodland/Savanna)	13.4
	UIDU	Bare Rock	0.2
	URHD	Buildings and other infrastructures	47.4
	WATR	Water Body	0.2
	WETN	Herbaceous Wetland	0.0
Yallahs	BBFD	Bamboo and Fields	0.0
	DBFD	Secondary Forest and Fields	12.6
	DSBL	Primary Forest or Secondary Forest	31.8
	FDDB	Fields and Secondary Forest	7.5
	FIDS	Fields: Herbaceous crops, fallow, cultivated vegetables	42.3
	RNGB	Open dry forest – Tall (Woodland/Savanna)	2.4
	UIDU	Bare Rock	0.0
	URHD	Buildings and other infrastructures	3.3
	WATR	Water Body	0.0
	WETN	Herbaceous Wetland	0.6

In **Figure 1** we show the spatial distribution of these (LULC) types within both basins. It is clear that the Western part of the Hope basin is Urban LULC classification.

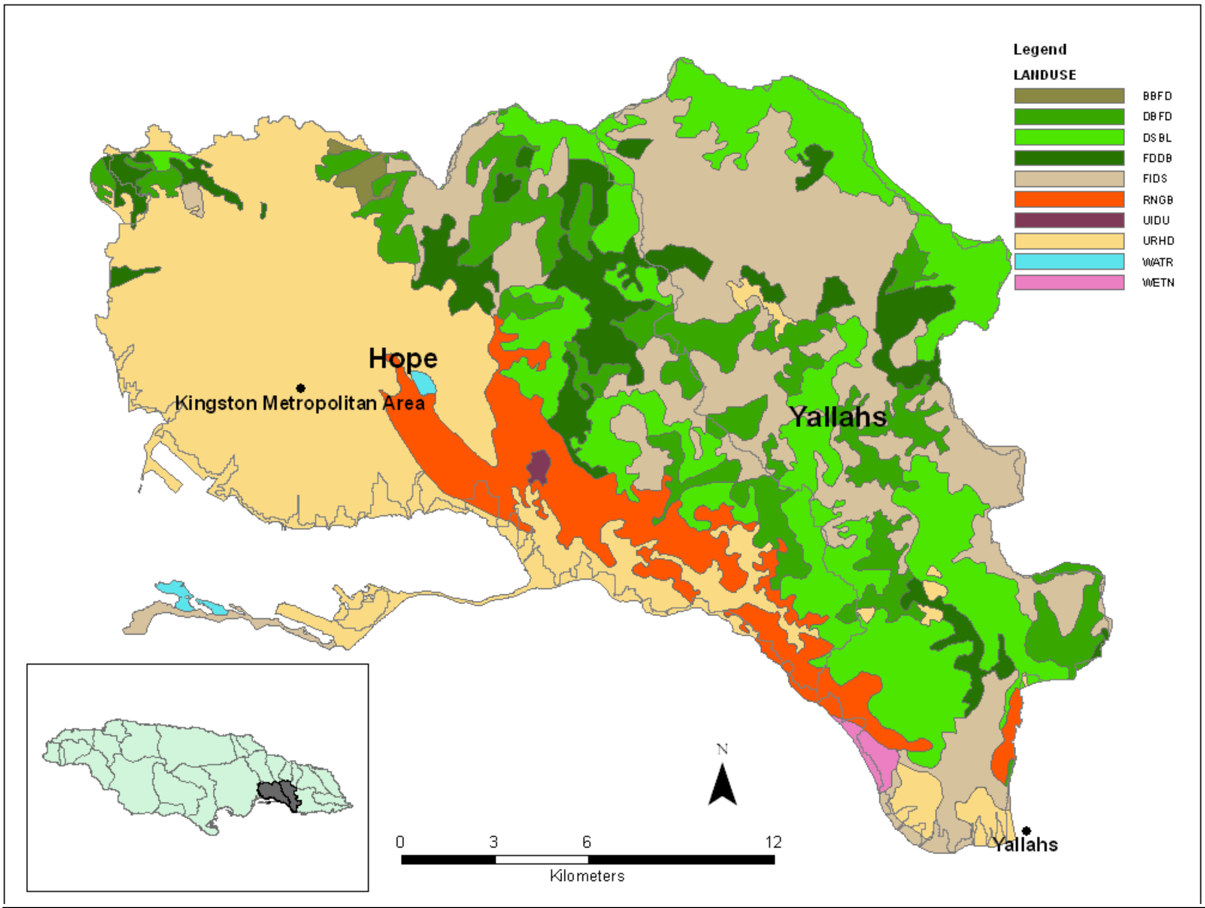

Figure 1: Map of land use land cover within the study area

2.3. Model Input requirements

SWAT requires physical, climatic and hydrologic data. **Table 2** presents the data requirements and data availability for these two watersheds. Most data were provided by Aedan Earle, data consultant.

SWAT requires observed daily time series of precipitation, air temperature, solar radiation, wind and other variables at specific weather stations within or surrounding the watershed of interest. Otherwise, it requires stochastic parameters of these weather stations which are used by the model in its weather generator to simulate daily time series for the simulation period.

Table 2: Data inputs requirements and availability

SWAT Input Data	Type	Gage	Period	Missing	Source/Comments
Digital Elevation Model	grid				Aedan
Land Cover Grid	grid				Aedan
Land Cover Parameters					Richards, J. F. (2010). *Drought assessment tools for agricultural water management in Jamaica*. Unpublished master's thesis, McGill University, Quebec, Canada
Soil Grid	grid				
Soil Type Parameters					Richards, J. F. (2010). *Drought assessment tools for agricultural water management in Jamaica*. Unpublished master's thesis, McGill University, Quebec, Canada
DEM Mask	shapefile				Created using a buffer around the given watershed boundaries
Streams & Gullies-Drains	shapefile				Used to burn in flow lines in flat areas
Precipitation Data	timeseries	Cavaliers FP	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Constant Spring FP	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Dallas	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Half Way Tree	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Hope FP	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Irish Town	1992 - 2010		Meteorological Service, Jamaica

Table 2: Data inputs requirements and availability

SWAT Input Data	Type	Gage	Period	Missing	Source/Comments
	timeseries	Jacks Hill (Ivor)	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Mona Reservoir	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Newcastle	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Norbrook Park	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Palisadoes	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Waterloo Rd	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Norris	1992 - 2010		Meteorological Service, Jamaica
	timeseries	Ramble	1992 - 2010		Meteorological Service, Jamaica
Temperature Data	timeseries	Manley	1993 - 2008		
Solar Radiation Data	timeseries	Manley	1992 - 2010	Aug - Sep 1993; all of 1995; Jan 2010	

The model also requires the location of these weather stations. The map in **Figure 2** below shows the spatial location of the weather stations considered for this modeling project. The Hope River watershed has a good network of precipitation stations with complete records. Unlike the Hope, the Yallahs watershed has only two precipitation stations within the watershed.

In addition to data input requirements, streamflow data and gauging locations are needed for model calibration and verification (See **Figure 2**).

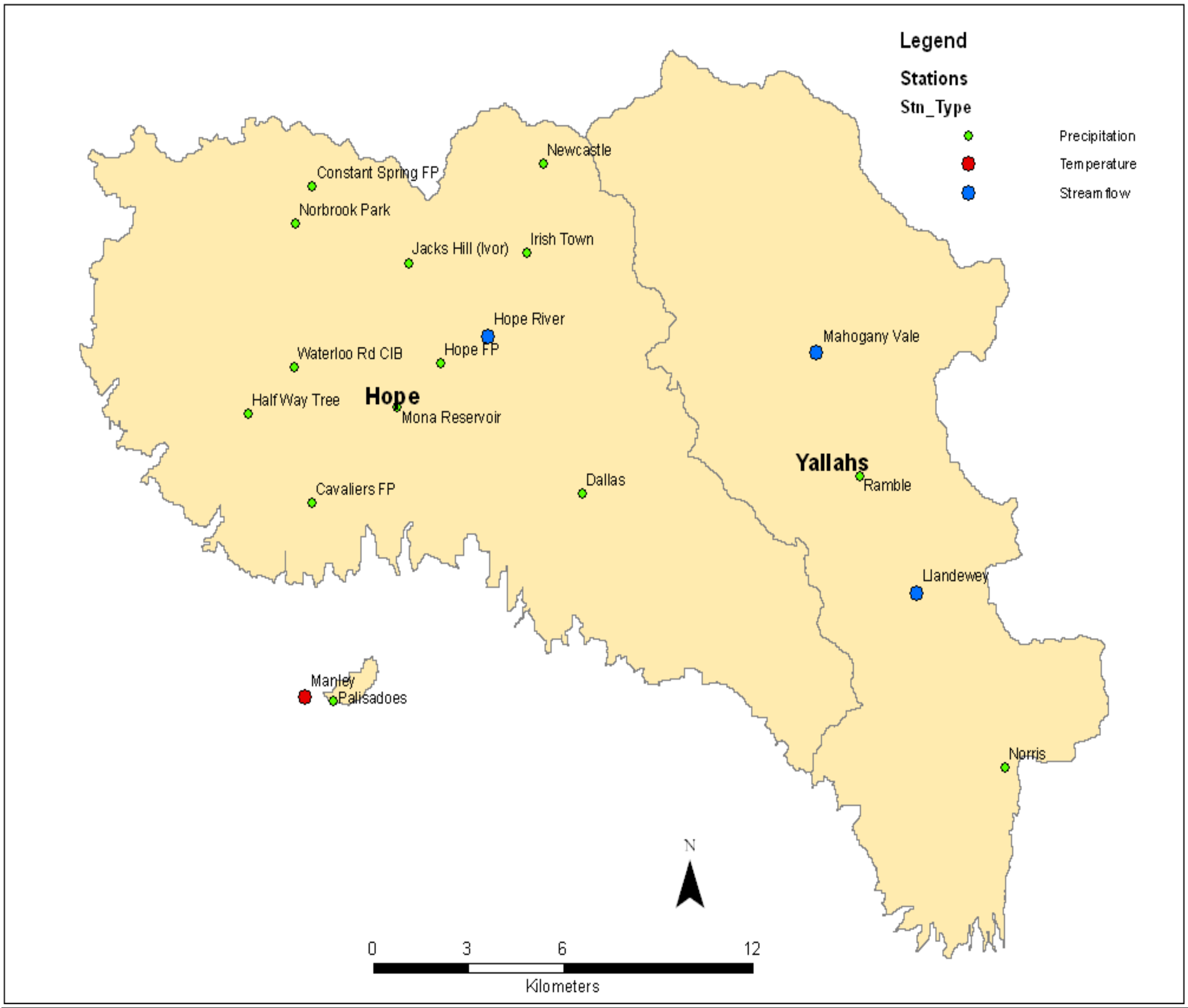

Figure 2: Location of weather and gauging stations

We plotted the precipitation data per each sub-basin (See **Figure 3**) using Thiessen Polygon method. The map shown in **Figure 3**, illustrates the gradient in the precipitation and the heterogeneity in the rainfall distribution within the two watersheds. Because of the temporal and spatial distribution of rainfall, we recommend additional Quality Control and Quality Assurance methods to improve the quality of these data in future work.

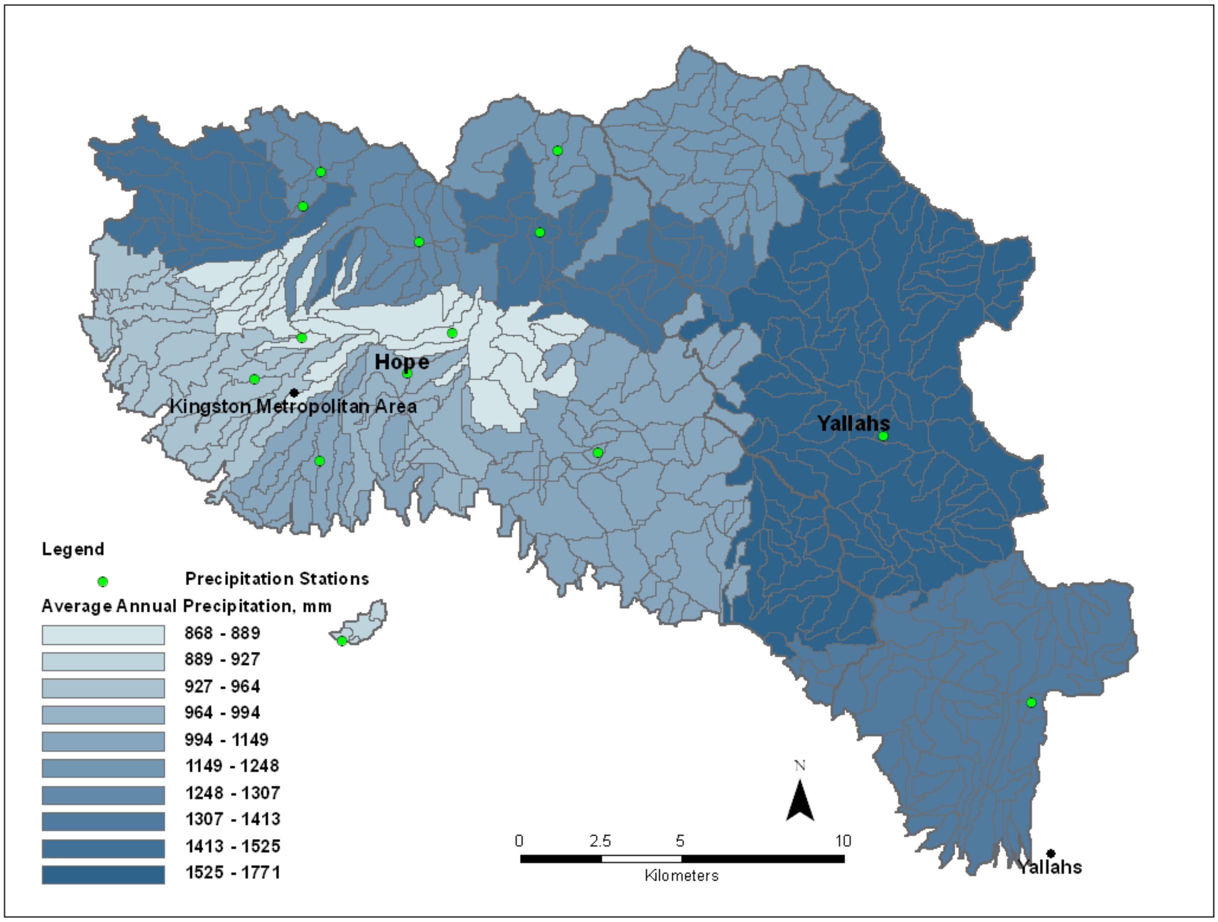

Figure 3: Average Annual Precipitation per sub-basin

2.4. Segmentation and sub-basin delineation

In many hydrological modeling projects, the watershed must undergo a process called segmentation. The purpose of this exercise is to divide the watershed into land segments that are assumed to have relatively homogenous hydrologic and water quality behavior. These segments will have similar model inputs and parameter values representing watershed functions. In SWAT modeling, we call these homogenous segments, Hydrologic Response Units (HRU).

For the purpose of this modeling effort, we focused on the impacts of LULC on the hydrologic regime and sediment yield in the watersheds. Therefore, we segmented the area based on the LULC type and the area of the sub-basin. Our objective was to have a well "discretized" finer spatial resolution model so we can target specific areas for change. The initial segmentation was discussed with the Team; Hector, agroforestry consultant, and Maurice, socio-economist, approved that segmentation. The following map (See **Figure 4**) shows the sub-basins resulting from this segmentation-delineation process.

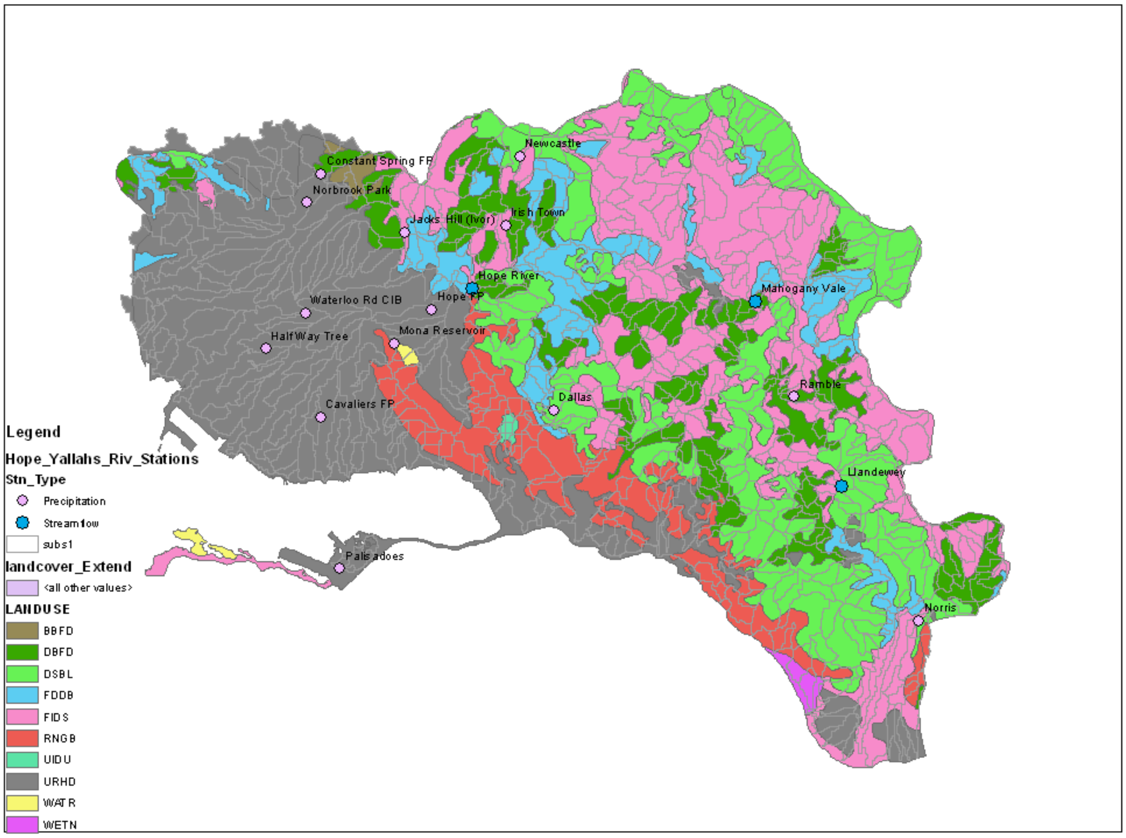

Figure 4: Sub-basins delineation

We kept the same HRU segmentation and sub-basin delineation for all future scenarios in order to maintain the spatial factor and spatial distribution. We performed the analysis on the same sub-basins for all future scenarios to detect the impacts of LULC on the hydrologic regime and sediment yield in the project sites. The results and impacts were analyzed at the sub-basin level where LULC changes occurred.

2.5. Model Outputs

For the purpose of this modeling study, we focused on the outputs that will be used in our hydrological analysis and those of other consultants to highlight the impacts of land use changes on the socio-economic aspects in the Yallahs and Hope river watersheds. We set up the SWAT model in these two watersheds to generate daily time series of water quantity and sediment yield in the 426 sub-basins earlier delineated.

For each sub-basin, for the length of the simulation period, there are three daily time series: water yield (mm), baseflow (mm), and sediment yield (tons). We processed these time series to generate monthly and yearly time series, and monthly and annual averages for these sub-basins.

Using these time series, we calculated:

- The water yield as the total water depth that is produced by each sub-basin. It is the total water volume per area that reaches the outlet of the sub-basin. It includes the surface, subsurface, and groundwater discharge.
- The Baseflow as the portion of streamflow that comes from the sum of deep subsurface, delayed shallow subsurface flow, and groundwater discharge.
- The sediment yield as the sediment produced by each sub-basin. It is the sum of sediment that reaches the outlet of the sub-basin.

Using GIS techniques, we plotted the average values of these described variables on the sub-basins map. In the following maps (See **Figure 5**, **Figure 6**, and **Figure 7**), we present the annual average water yield (mm), baseflow (mm), and sediment yield (tons/ha) per sub-basin, respectively. It shows the magnitude and pattern of the water production and sediment yield for every sub-basin in this study area.

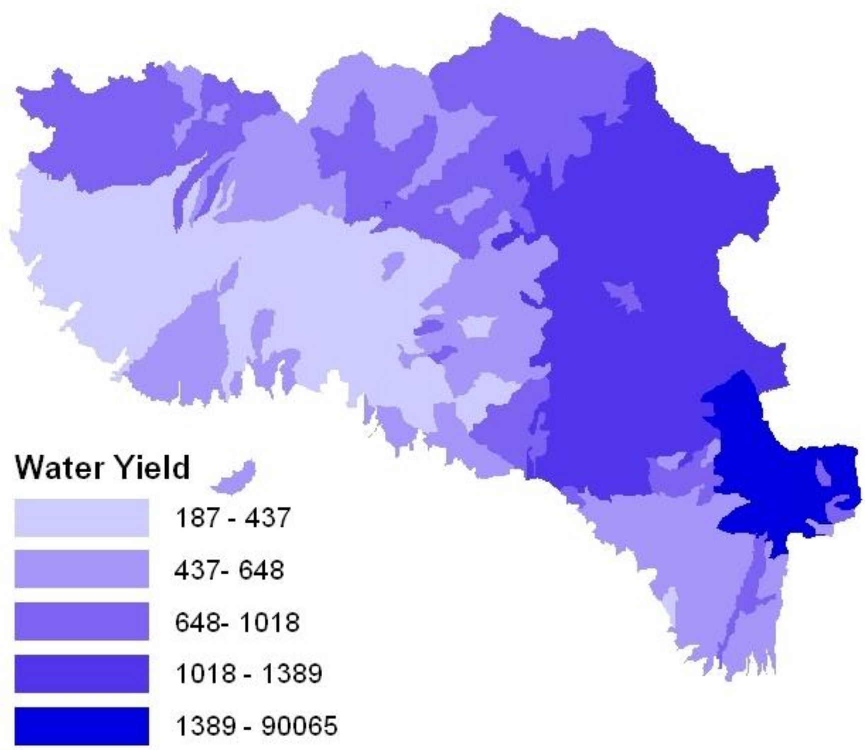

Figure 5: Annual average water yield (mm) per sub-basin

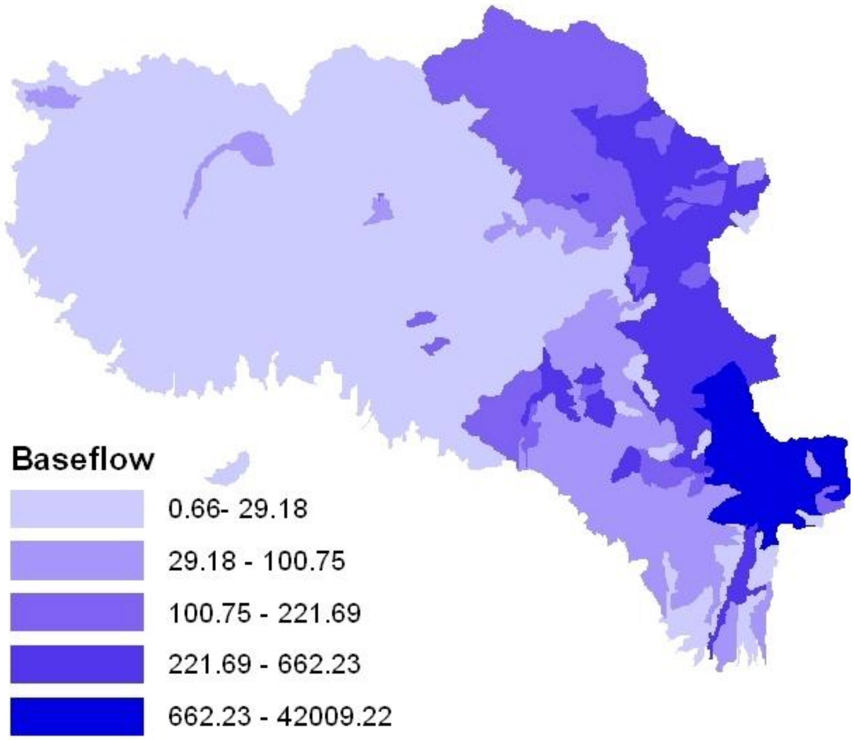

Figure 6: Annual average baseflow (Groundwater) (mm) per sub-basin

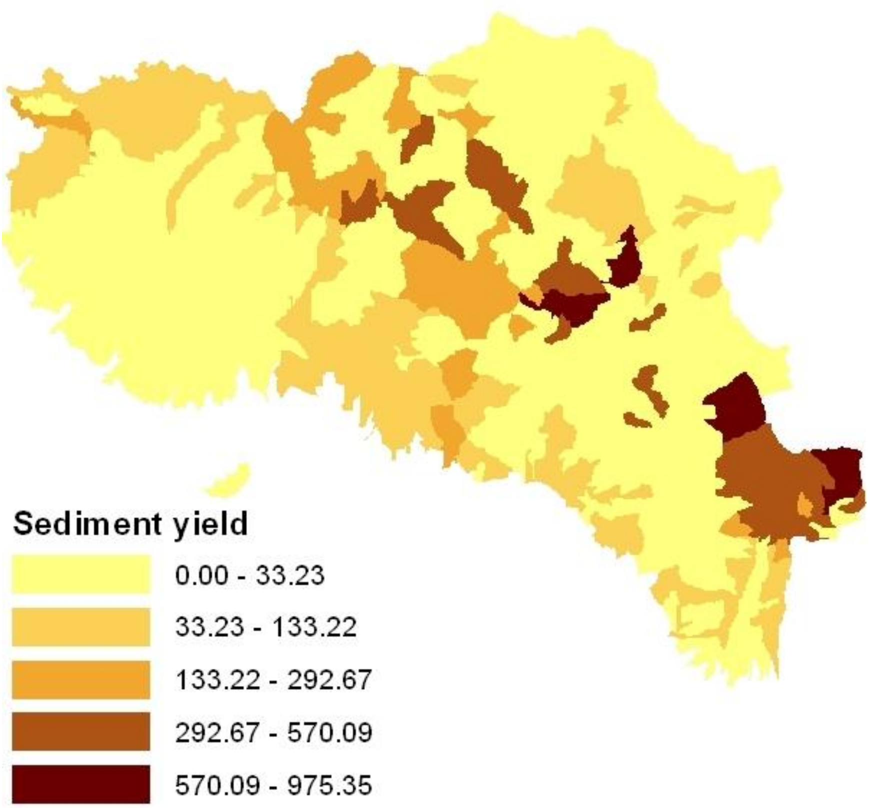

Figure 7: Annual average sediment Yield per sub-basin (tons/ha)

2.6. Calibration

In any hydrological modeling application, model calibration and validation are critical steps for a credible modeling application. Calibration is an iterative comparison of a model simulated time series to observed time series data with different parameter sets. In the SWAT model, there are some parameters that need calibration such as the Curve Number (CN). Other parameters are estimated from topographic, climatic, and/or physical characteristics of the watershed. Validation is a comparison of model results with observed data, using data that are independent of data used in calibration, and without changing model parameters that were determined from the calibration process.

As mentioned above, the SWAT model generates water yield time series for each sub-basin in the watersheds. For the purpose of this model calibration, we focused on the sub-basins that are within the drainage area of the gauging stations located in the Hope River watershed. **Table 3** presents the streamflow gages and the available period of record.

Table 3: Gauging stations in the study area

Streamflow Gage	Period	Missing	Source	Drainage Area (ha)	Comments
Hope	1955 – 2010	Jan – Mar 1955	Water Resources Authority	4026	
Llandeway	1971 – 2001	Jan – Apr 1971; Oct 1988 – Jun 1989; Dec 2001	Water Resources Authority	12171	SWAT model run ends in 2008, data not available after 2001
Mahogany Vale	1971 – 1993	Jan – Mar 1971; May 1988 – Dec 1989	Water Resources Authority	5995	SWAT model run begins in 1993, data not available after 1993

We initially considered the Hope and Llandeway stations for calibration (See **Figure 2**). Due to limited budget for this project, we limited our calibration effort on the Hope River Watershed. We used the available climate and streamflow data, and we were able to run the model from 1993 to 2008, but focused our calibration on the period from 1994 to 2000.

We focused our calibration on the following comparisons of simulated and observed values:

(a) Annual and monthly runoff (means or volumes) (m^3) (See **Table 4**)

The Dv shows a value of -33%. This can be explained by the fact that we did not include the intake volumes into consideration. The simulated volumes include the total water volume produced in the watershed. The observed is the water production minus the intake volumes.

Table 4: Annual and Monthly average water yield (10^7 m^3)

	Observed	Simulated	Deviation Error (Dv) (%)
Annual	79.2	106	-33.93
Monthly			
Jan	5.2	4.6	11.6
Feb	3.2	3.1	2.7
Mar	2.8	3.1	-11.0
Apr	2.8	3.9	-40.2
May	4.8	9.4	-94.5
Jun	4.8	6.9	-42.5
Jul	2.6	6.3	-143.4
Aug	5.9	10.5	-76.5
Sep	12.9	15.5	-20.1
Oct	13.3	21.7	-62.9
Nov	12.8	13.9	-8.8
Dec	8.0	7.1	10.7

(b) Monthly Runoff Volumes (Mm^3) (See **Figure 8**)

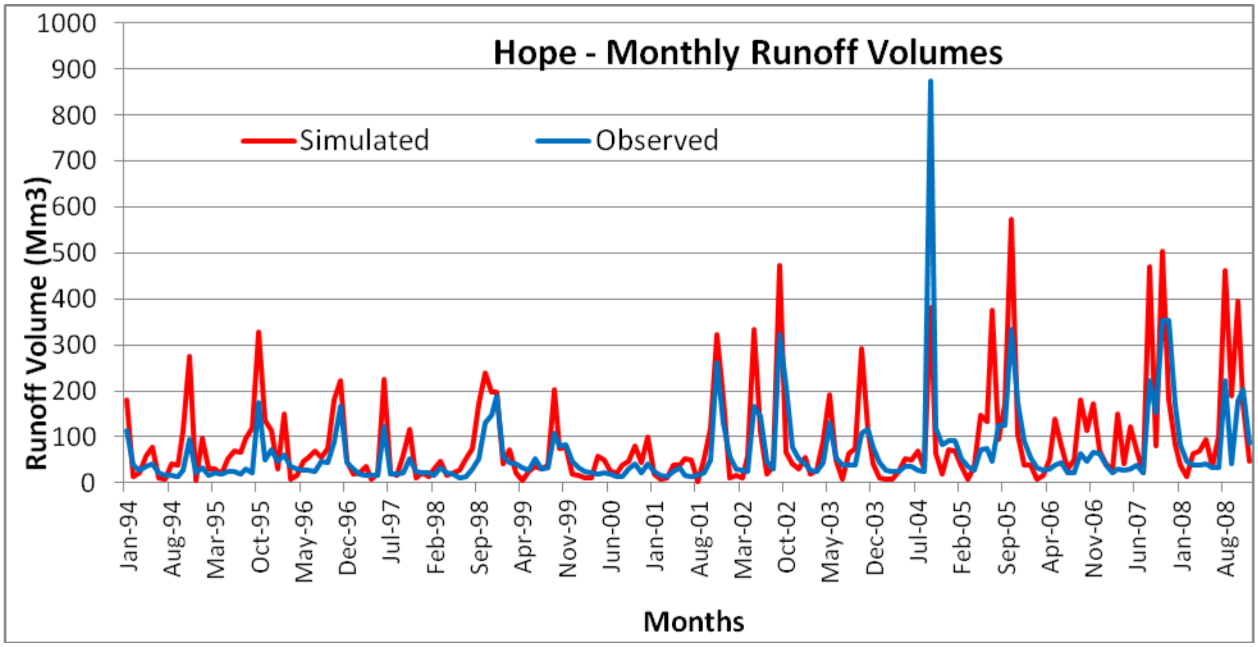

Figure 8: Monthly Runoff Volumes

(c) Daily time-series of flow (m^3/s) (See **Figure 9**)

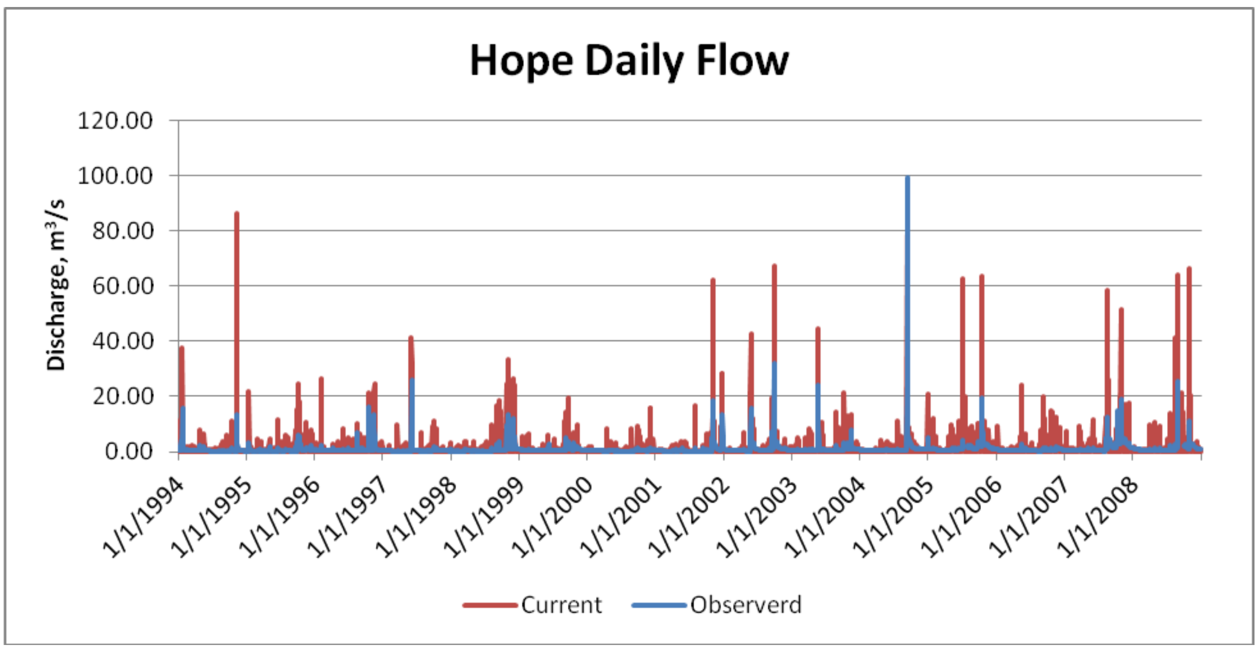

Figure 9: Streamflow time series

(d) Flow-frequency (flow-duration) curves (m^3/s) (See **Figure 10**): Flow duration curves show the percentage of the time the flow exceeds different values. A comparison of observed and simulated flow duration curves shows how well the model captures the flow frequency of exceedance across the entire flow range.

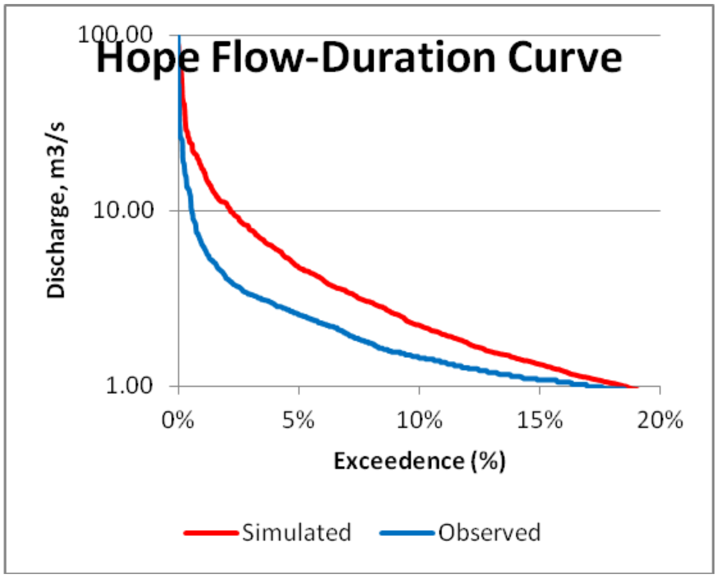

Figure 10: Flow-Duration Curve

We used different statistical tools and tests to measure the goodness of fit of the calibrated parameters by comparing the observed data with the simulated results at daily time step. The Nash-Sutcliffe Coefficient (Eq.1), determination coefficient, and the deviation of runoff volume (Eq.2) are used together with a graphical comparison of observed and simulated data to judge the quality of the calibration.

$$\mathrm{R}^2 = 1 - \frac{\sum (Qi - Qi')^2}{\sum (Qi - Q)^2}$$ (American Society of Civil Engineers, 1993) (Eq.1)

Where: Qi : is measured daily discharge

Qi′ : simulated daily discharge

Q : mean measured discharge

$$Dv = \frac{V - V'}{V}$$ (American Society of Civil Engineers, 1993) (Eq.2)

Where: V : is observed annual or seasonal runoff volume

V` : is simulated annual or seasonal runoff volume

Some researchers have assigned the following qualitative indicators to different values of the performance measures.

R^2 Daily Flow	0.6	0.7	0.8	0.9
Indicator	Poor	Fair	Good	Very Good
Dv	0.1	0.15	0.25	
Indicator	Very Good	Good	Fair Poor	

Graphical methods and statistical tests are qualitatively and quantitatively used to evaluate model performance, calibration, and validation results.

During the numerous calibration runs, the Hope River hydrological model parameters were adjusted within the logical limits of the acceptable parameter values. Our goal was to minimize the difference between observed and simulated values in calibration. We focused on the Curve Number, an important factor in distributing rainfall between surface water and "infiltrated" water.

The flow duration curve and the graphical representation of simulated versus observed data show that the model follows the events; the simulated flow follows the trend of the observed flow but there are differences in the magnitude.

Figure 9 shows flow duration curves comparing the simulated and the observed. Simulated flows show higher values than observed flows. The simulated flows are the total flows generated by the upstream contributing area including the intake volumes; however, because we did not receive the full time series at the intakes, we were unable to include these flows into our estimates of the observed flows.

Results are summarized in **Table 5**. We spent substantial time to calibrate the model. In order to perform a high quality calibration, intake time series are required. We used the precipitation and the streamflow data as they were provided to us by the data consultant, with very limited quality control on the provided data. The determination coefficients show that the calibration is fair for daily simulations and good for monthly simulations. The NSE values are positive indicating that the model is more accurate than the mean of the observed values. The negative values of the average deviation errors mean that the model is over-simulating flows, as expected, because some of the observed flow has not been included and can be reduced when more accurate uptake volumes and flow rates are included in the analysis.

Table 5: Calibration statistics analysis for Hope

Time Step	R2	NSE	Dv
Daily	0.598	0.15	-0.33
Monthly	0.696	0.23	-0.34

We strongly recommend that future projects need to focus on assessing the quality of precipitation data, streamflow data and the intake flow data at different and various locations throughout the watersheds.

In the rest of this report, we focus on the change between each future scenario and the current scenario.

3. Future Land Use Scenarios

The Riverside team worked on developing future land use scenarios using the recommendations provided by the project team. The projections were made using the acreage and the slope factor provided by Hector and David, consultants' leader. We used the slope as the only physical factor/parameter in projecting the changes: pixels with steep slopes were the first to be changed to Forest, for example. Here are the steps that were used in the creation of the future projections of land use maps:

- ***Step-1:*** Start with existing LU layer at the sub-pilot areas.
- ***Step-2:*** Refer to the spreadsheet provided with area criteria under each scenario.
- ***Step-3:*** Calculate existing LU area.
- ***Step 4:*** Manually change existing LU to match spreadsheet area totals. Each scenario was saved as a new separate modeled LU layer. To change area sections, the vector layer was cut and reclassified to an appropriate model class.
- ***Step 5:*** Combine each modeled LU layer with the full LU layer and save as a final-full-extent-modeled-LU. This clip operation replaces only the sub-pilot areas with modeled LU and uses the full LU for the remainder of the Island.
- ***Step 6***: Convert each final-full-extent-modeled-LU was converted form vector to raster.

Table 6 and **Table 7** summarize the future LULC scenarios that we developed. We focused on the year 5 projections as year 15 projections did not have full recommendations and were similar to year 5 projections. In the rest of the analysis, we will compare the 5-year projection scenarios.

Table 6: Area per Site per LULC type per Scenario (Original and Agro-forestry) (ha)

Site	Original				Agro-Forestry 5years			
	AG	AGRO	FOREST	URBAN	AG	AGRO	FOREST	URBAN
4	179	0	8	0	126	50	9	0
8	295	360	286	0	0	948	0	0
10	39	35	4	0	0	83	0	0
2	185	0	0	0	0	189	0	0
3	285	0	0	0	0	286	0	0
9	24	135	132	0	0	293	0	0
11	138	101	0	0	0	237	0	0
6	95	219	32	0	0	347	0	0
1	77	5	36	0	0	117	0	0
7	27	39	50	2	0	117	0	2
7	1	0	0	0	0	1	0	0

Table 7: Area per Site per LULC type per Scenario (Reforestation and Deforestation) (ha)

Site	Reforestation 5years				Deforestation 5years			
	AG	AGRO	FOREST	URBAN	AG	AGRO	FOREST	URBAN
4	65	0	120	0	186	0	0	0
8	0	365	582	0	425	365	157	0
10	41	37	5	0	56	27	0	0
2	187	2	0	0	189	0	0	0
3	286	1	0	0	286	1	0	0
9	0	96	197	0	68	133	92	0
11	135	102	0	0	180	57	0	0
6	97	218	32	0	193	154	0	0
1	76	5	37	0	113	5	0	0
7	0	0	117	2	45	39	32	2
7	0	0	1	0	1	0	0	0

4. Results Analysis

For the purpose of analyzing the impacts of land use changes on hydrologic regime and sediment yield, we are only looking at the change between each future scenario, focusing on the 5 year projections, and the current LULC scenario. Therefore, we analyzed the water yield, baseflow, sediment yield and flow duration components (Peak flows, medium flows and low flows) for the following scenarios:

- Reforestation
- Deforestation
- Agro-forestry

The final results are presented as the change between the future scenario and the current land use land cover map. The change was computed as:

C_XX_YY5 = [(Current_XX – XX_YY) / (Current_XX)]* 100

Where C_XX_YY5 is the change in percent between the Current scenario and the Scenario of interest. XX is the Hydrological Variable of interest which could be: WY: Water Yield, GW: GroundWater or SY: Sediment Yield. YY is the future Scenario for the 5 Year projection which could be AF: Agro-forestry, DF: Deforestation or RF: Reforestation. A positive change means that the current scenario is ‘producing’ more than the future projection.

4.1 Water Yield

From the maps shown in figure 11, 12 and 13, it is clear that the water yield decreases as additional forestry practices are introduced in the watersheds. Reforestation generates less water than the current scenario which explains the positive change values. On the other hand, deforestation generates more water than the current which explains the negative change values. It is evident that forestry requires more water than other practices, so introducing more forestry decreases water yield.

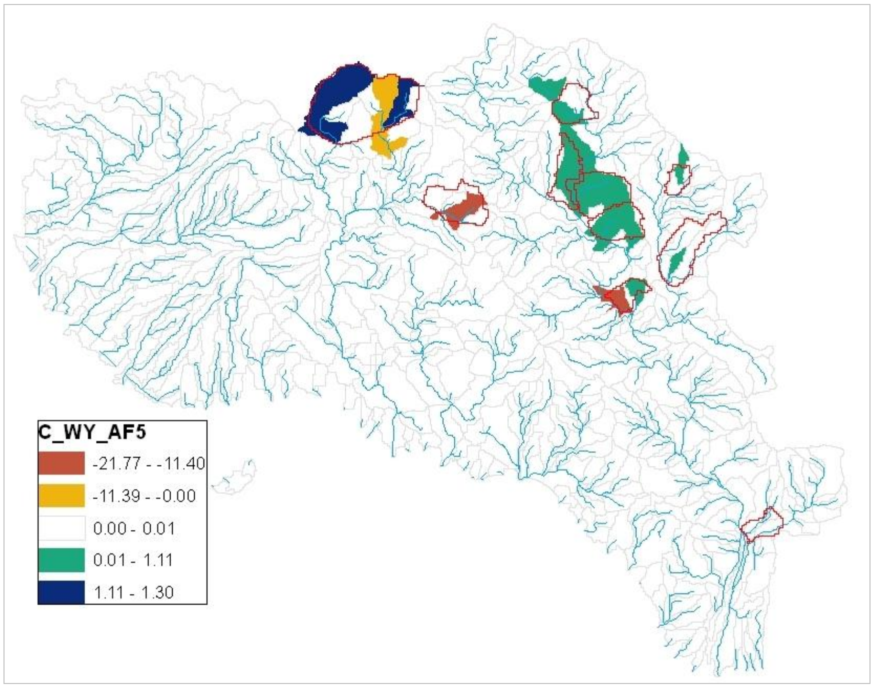

Figure 11: Change in water yield between the current and the Agroforestry scenario

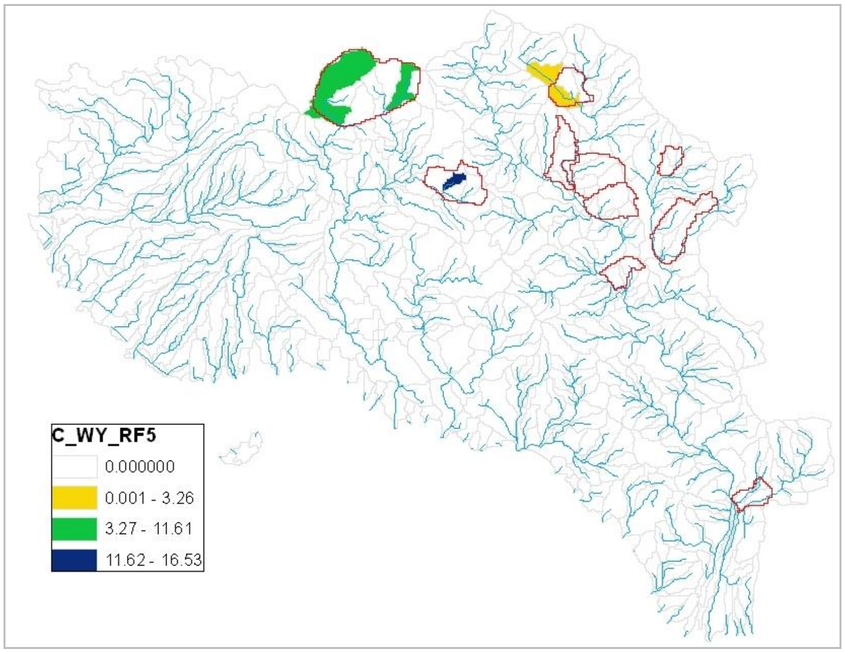

Figure 12: Change in water yield between the current and the Reforestation scenario

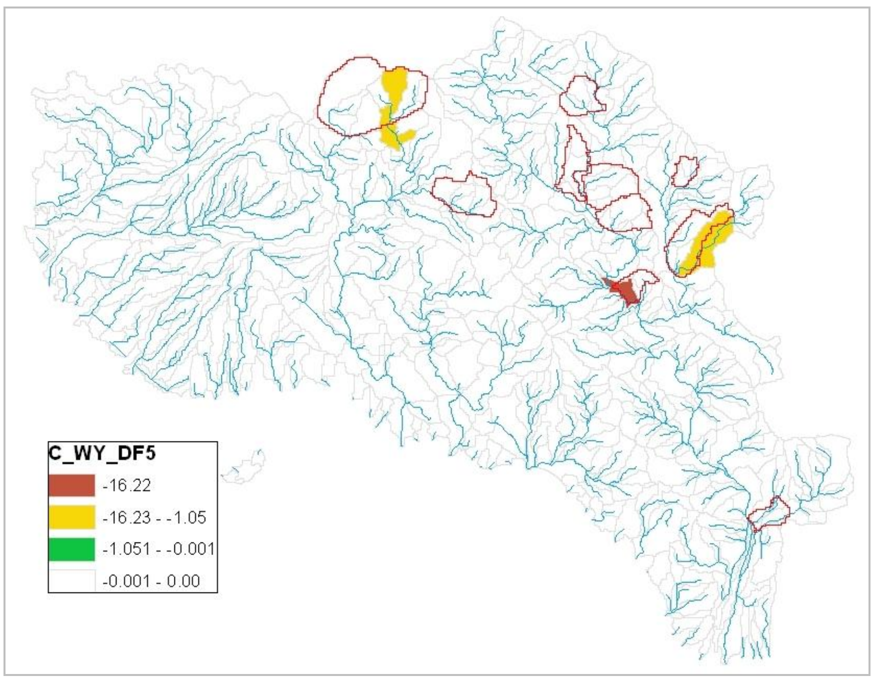

Figure 13: Change in water yield between the current and the Deforestation scenario

4.2 Baseflow

It is clear when comparing the current scenario to the other scenarios, that baseflow decreases as more forestry practices are introduced in the watersheds. However, the difference is not clear among future scenarios from the change maps show in figures 14, 15 and 16. The change maps should show these differences if there are any.

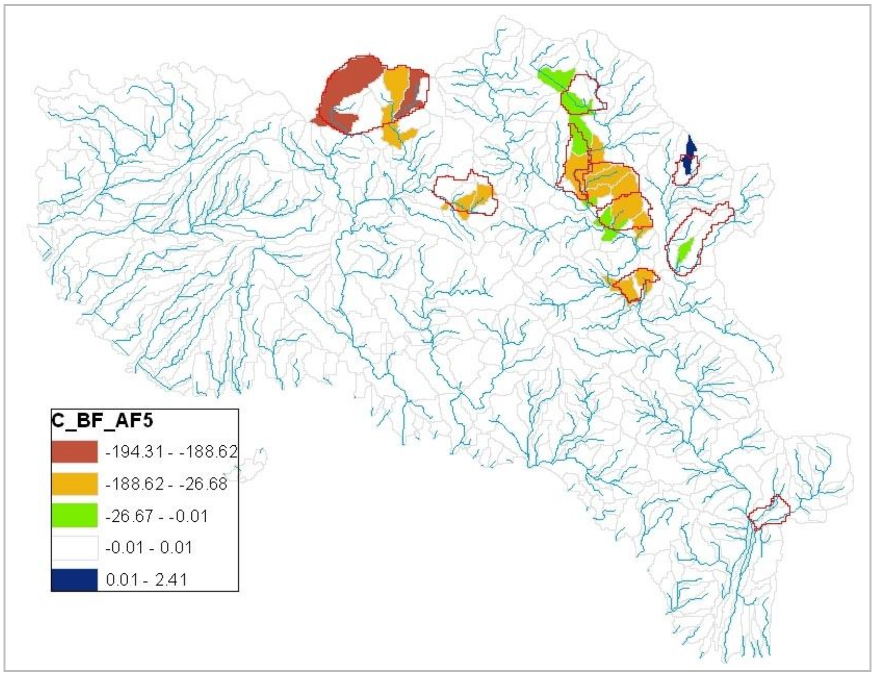

Figure 14: Change in baseflow (groundwater) between the current and the Agroforestry scenario

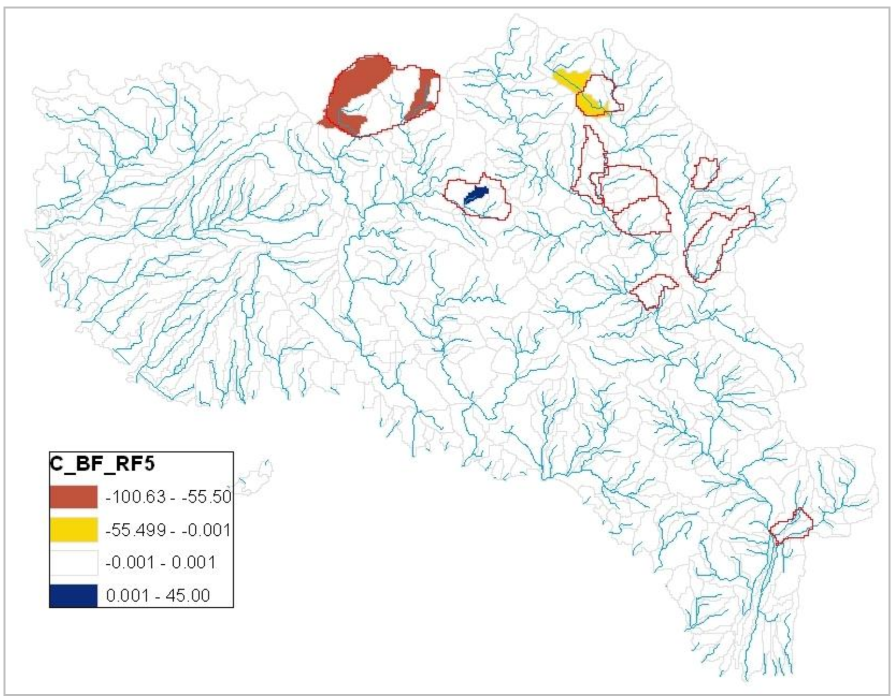

Figure 15: Change in baseflow between the current and the Reforestation scenario

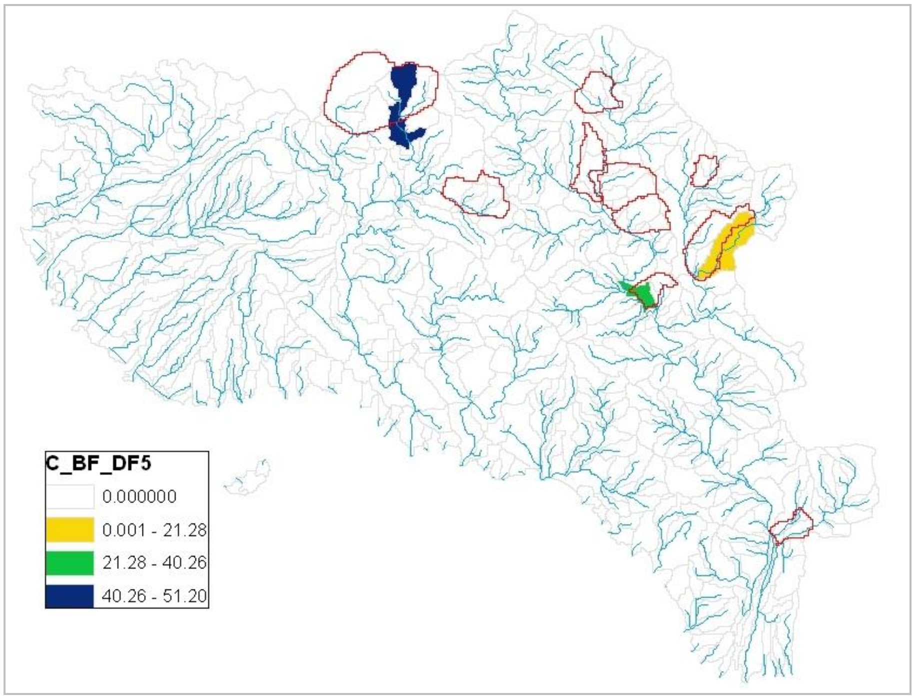

Figure 16: Change in baseflow between the current and the Deforestation scenario

4.3 Sediment Yield

When the sediment yield is compared for different scenarios, the impact of forestry practices in retaining sediment is evident. Sediment yields are lower for forestry scenarios.

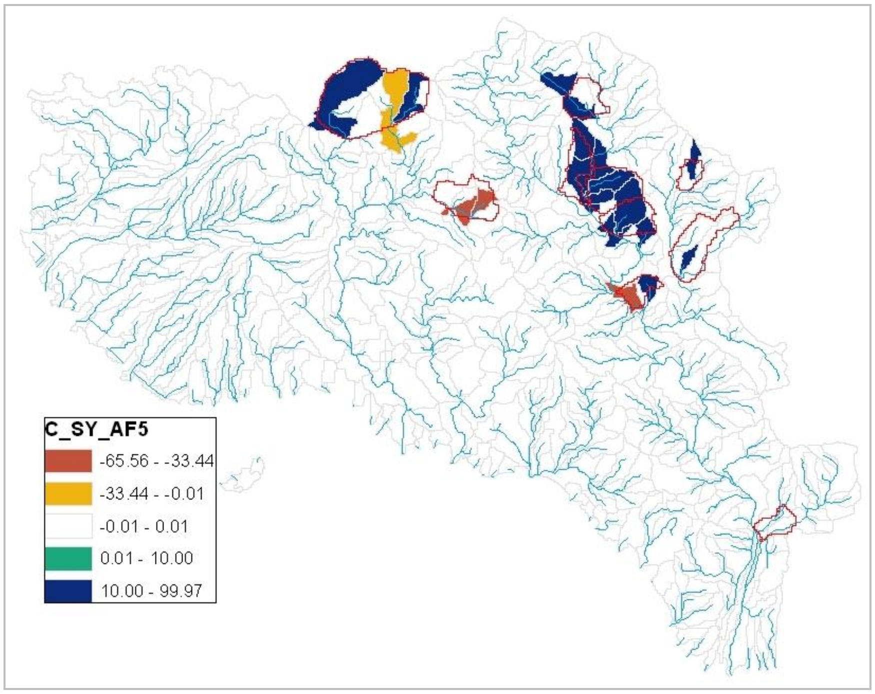

Figure 17: Change in sediment yield between the current and the Agroforestry scenario

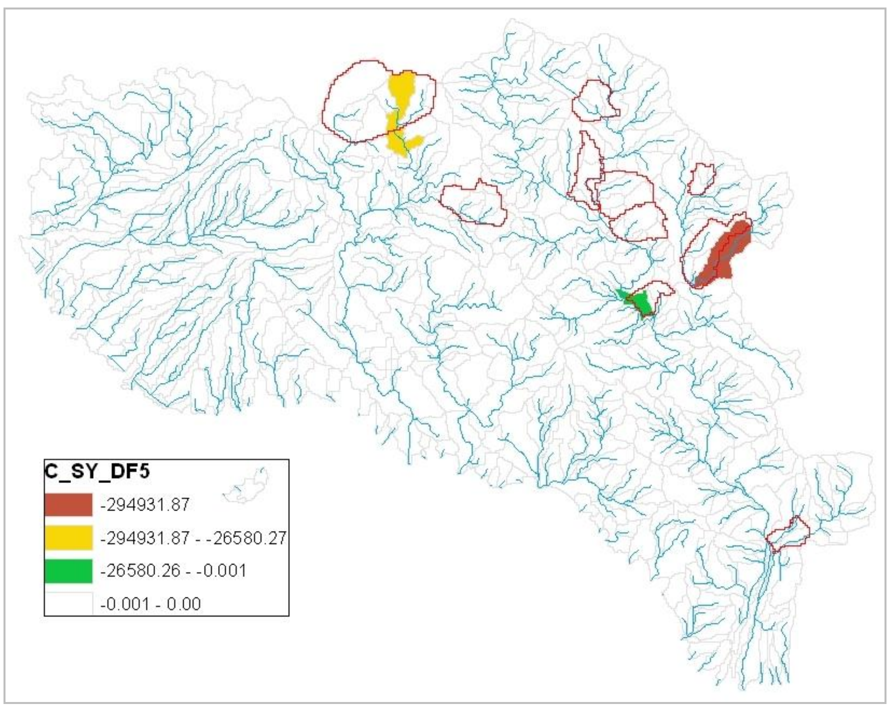

Figure 18: Change in sediment yield between the current and the Deforestation scenario

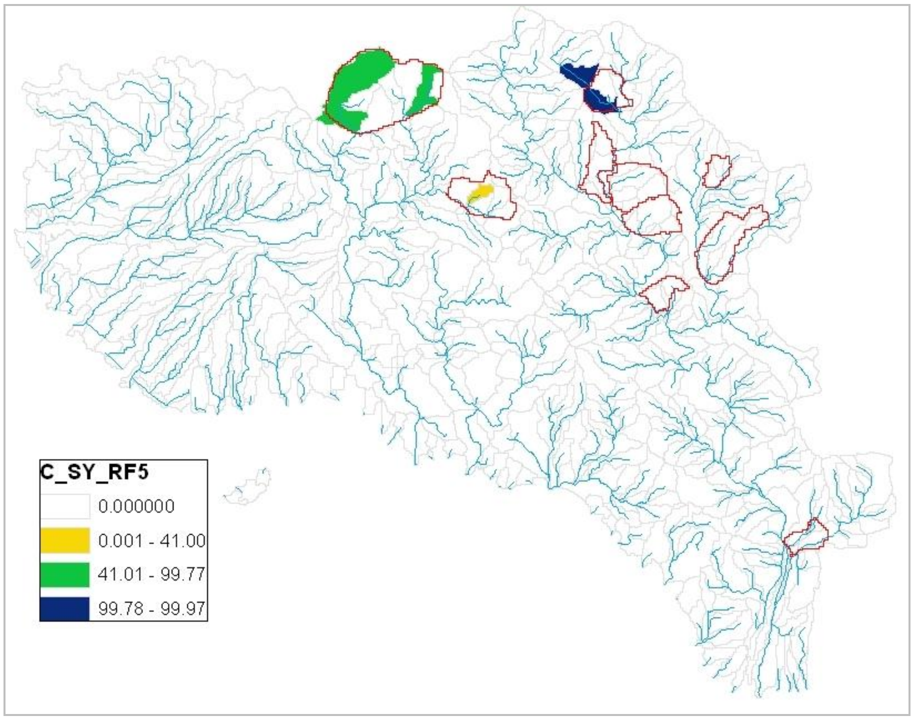

Figure 19: Change in sediment yield between the current and the Reforestation scenario

4.4 Duration Curves

In the process of analyzing the impacts of future land use scenarios on hydrologic regime and sediment loads at specific points of interest (See **Figure 20**), the full period of simulated flows was used for the four scenarios; current, agro-forestry 5 years, reforestation 5 years and deforestation 5 years. The analysis focused at the outlets of the basins where changes are projected. At each point, duration curves were produced for both the simulated streamflow and sediment loading.

4.4.1 Streamflow duration curves

The relative change between the current scenario and the scenario of interest for different probabilities of exceedance at different points of interest are shown in **Table 8**. The goal is to highlight the impacts of future LULC on peak flows, medium flows and low flows.

Table 8: Percent change at different probability of exceedance levels at different points of interest

Probability	2%			25%			50%		
Reach	AF5	DF5	RF5	AF5	DF5	RF5	AF5	DF5	RF5
R408	-0.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R393	-0.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R391	-0.7%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
R327	0.9%	0.0%	-0.2%	2.1%	0.2%	-0.5%	5.5%	-0.6%	2.1%
R229	-0.2%	1.2%	0.0%	0.2%	-2.3%	0.0%	0.4%	-0.9%	0.0%

Table 8: Percent change at different probability of exceedance levels at different points of interest

Probability	2%			25%			50%		
R228	-1.1%	0.3%	-0.2%	1.9%	-0.7%	0.1%	2.0%	-0.7%	0.0%
R214	-1.5%	0.1%	-0.3%	2.1%	-0.2%	0.0%	3.0%	0.0%	0.3%
R185	-1.8%	0.0%	-0.3%	2.2%	0.0%	0.1%	2.5%	0.0%	0.0%
R129	1.0%	0.0%	-0.3%	4.0%	0.0%	0.5%	27.6%	-8.2%	18.1%
R122	0.1%	0.0%	0.0%	-0.4%	0.0%	0.0%	-0.3%	0.0%	0.0%
R115	-2.9%	0.0%	-0.8%	3.0%	0.0%	0.5%	4.6%	0.0%	0.1%
R99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R93	4.1%	0.0%	-1.1%	14.6%	0.0%	-3.7%	54.1%	0.0%	-9.1%
R91	3.7%	1.9%	-0.8%	7.0%	-1.3%	0.5%	20.2%	-12.2%	12.6%
R80	1.6%	0.0%	-2.8%	8.9%	0.0%	2.1%	44.2%	0.0%	31.6%
R56	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R48	-1.2%	0.0%	-1.3%	0.7%	0.0%	0.3%	0.6%	0.0%	-0.2%

Table 8 (continued): Probability of exceedance at different points of interest

Probability	75%			99%		
Reach	AF5	DF5	RF5	AF5	DF5	RF5
R408	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R393	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R391	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R327	10.3%	-8.8%	9.7%	0.0%	0.0%	0.0%
R229	-0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
R228	0.2%	0.1%	-0.1%	0.0%	0.0%	0.0%
R214	2.4%	0.1%	0.0%	0.0%	0.0%	0.0%
R185	1.8%	0.0%	-0.1%	0.0%	0.0%	0.0%
R129	0.1%	-0.2%	0.8%	0.0%	0.0%	0.0%
R122	-0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
R115	0.6%	0.0%	-0.5%	0.0%	0.0%	0.0%
R99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R93	2.0%	0.0%	-0.7%	0.0%	0.0%	0.0%
R91	-5.4%	5.2%	3.7%	0.0%	0.0%	0.0%
R80	-9.9%	0.0%	14.5%	0.0%	0.0%	0.0%
R56	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R48	0.4%	0.0%	-0.7%	0.0%	0.0%	0.0%

These tables show that agroforestry and reforestation scenarios provide reduction in high flows at the majority of these points of interest. For some points, agroforestry and reforestation scenarios could provide and sustain higher medium flows compared to current and deforestation scenarios. No effects on low flows were observed for these scenarios. It is also clear that the impacts of the contributing area and the positioning of the reach and points of interest affect the magnitude of the change. Reaches close to the project sites record 'significant' changes, while reaches far away from the project sites record lesser changes. This effect was considered in the monitoring proposed in a later section.

4.4.2 Sediment loading 'duration curves'

As shown in **Table 9**, we adopted the same approach to investigate the impacts of future land use on sediment loadings at points of interest.

Table 9: Sediment loading probability of exceedance at different points of interest

Probability	2%			25%			50%		
Reaches	**AF5**	**DF5**	**RF5**	**AF5**	**DF5**	**RF5**	**AF5**	**DF5**	**RF5**
R408	-6.0%	2.6%	-0.1%	0.0%	0.1%	0.0%	-0.4%	0.0%	0.0%
R393	-6.1%	2.6%	-0.1%	0.0%	0.2%	0.0%	0.2%	0.6%	0.0%
R391	-8.0%	3.5%	-0.1%	0.0%	0.1%	0.0%	0.0%	0.7%	0.0%
R327	0.0%	0.0%	0.0%	-16.5%	0.9%	-16.5%	5.9%	0.0%	0.1%
R229	-4.2%	45.6%	0.0%	-0.6%	9.8%	0.0%	-1.4%	24.3%	0.0%
R228	-14.4%	9.3%	0.0%	-4.1%	3.2%	-2.2%	-1.9%	2.6%	-1.8%
R214	-16.2%	4.4%	0.0%	-4.9%	5.1%	-2.9%	-1.7%	0.0%	-2.1%
R185	-23.5%	0.0%	0.0%	-11.5%	0.0%	-4.7%	-7.6%	0.0%	-4.3%
R129	0.0%	0.0%	0.0%	1.3%	-0.2%	-3.8%	38.4%	-5.8%	27.7%
R122	-17.9%	0.0%	0.0%	-100.0%	0.0%	0.0%	-100.0%	0.0%	0.0%
R115	-69.1%	0.0%	-1.2%	-29.6%	0.0%	-11.9%	-30.9%	0.0%	-14.7%
R99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R93	0.0%	0.0%	0.0%	3982900.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R91	0.0%	71.8%	0.0%	35.5%	-2.2%	5.3%	-91.2%	54.1%	69.9%
R80	-81.0%	0.0%	-81.0%	-100.0%	0.0%	-100.0%	-100.0%	0.0%	-100.0%
R56	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R48	-53.0%	0.0%	-53.0%	-66.8%	0.0%	-66.4%	-80.0%	0.0%	-79.9%

Table 9 (continued): Probability of exceedance at different points of interest

Probability	75%			99%		
Reaches	AF5	DF5	RF5	AF5	DF5	RF5
R408	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R393	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R391	-0.1%	0.1%	-0.1%	0.0%	0.0%	0.0%
R327	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R229	-4.8%	19.2%	0.0%	0.0%	0.0%	0.0%
R228	-5.0%	2.1%	-2.5%	0.0%	0.0%	0.0%
R214	-5.7%	-0.1%	-4.3%	0.0%	0.0%	0.0%
R185	-10.8%	0.0%	-5.1%	0.0%	0.0%	0.0%
R129	0.3%	-1.0%	0.3%	0.0%	0.0%	0.0%
R122	-99.9%	0.0%	0.0%	0.0%	0.0%	0.0%
R115	-54.9%	0.0%	-18.0%	0.0%	0.0%	0.0%
R99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R93	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R91	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R80	-50.0%	0.0%	-50.0%	0.0%	0.0%	0.0%
R56	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R48	-84.8%	0.0%	-84.8%	0.0%	0.0%	0.0%

From the tables above, it is clear that agroforestry and reforestation scenarios generate less sediment loadings at these different points of interest. The magnitude of change varies depending on the proximity of the point of interest to the project site. The deforestation scenario generates more sediment loading that the current scenario. It is important to mention that the SWAT model sediment parameters were provided by Hector and David, and no sediment parameter calibration was performed.

5. Monitoring Protocol

Based on the results discussed in previous sections, it is recommended that the project invests in acquiring and installing a number of meteorological stations to increase the density of the weather stations in both watersheds. It is also recommended that, in collaboration with different stakeholders, a number of continuous gaging stations are needed throughout the hydrographic network. The difficulties we encountered during the execution, set up, development and calibration of the SWAT model were largely due to the lack of data in some parts of the watersheds and to the quality of climatic and hydrologic data.

In order to monitor the proposed changes in the watershed, it is also recommended that the project monitor the outlets of the sub-basins within the project sites. It is proposed that monitoring consider both water volumes (flows) and water quality. Because the basins have steep slopes and poor vegetation cover and experience flashy rains and wet conditions, it is recommended to sediment loadings be monitored more frequently in space and time. Monitoring should be done at the following locations (See **Table 10** and **Figure 20**):

Table 10: Geographic coordinates of monitoring points

Point	Latitude	Longitude
R48	18.06502119790	-76.64319627490
R80	18.05790291950	-76.73573328910
R93	18.03399578590	-76.69817830670
R115	18.03458538590	-76.64645671180
R122	18.04314693160	-76.60698077600
R185	18.02279577470	-76.63387021290
R212	18.00846140250	-76.61239921970
R228	17.99446577780	-76.62707917960
R327	17.96248292540	-76.71322352590
R393	17.91734256400	-76.58168252690
R408	17.89388232350	-76.59052867700

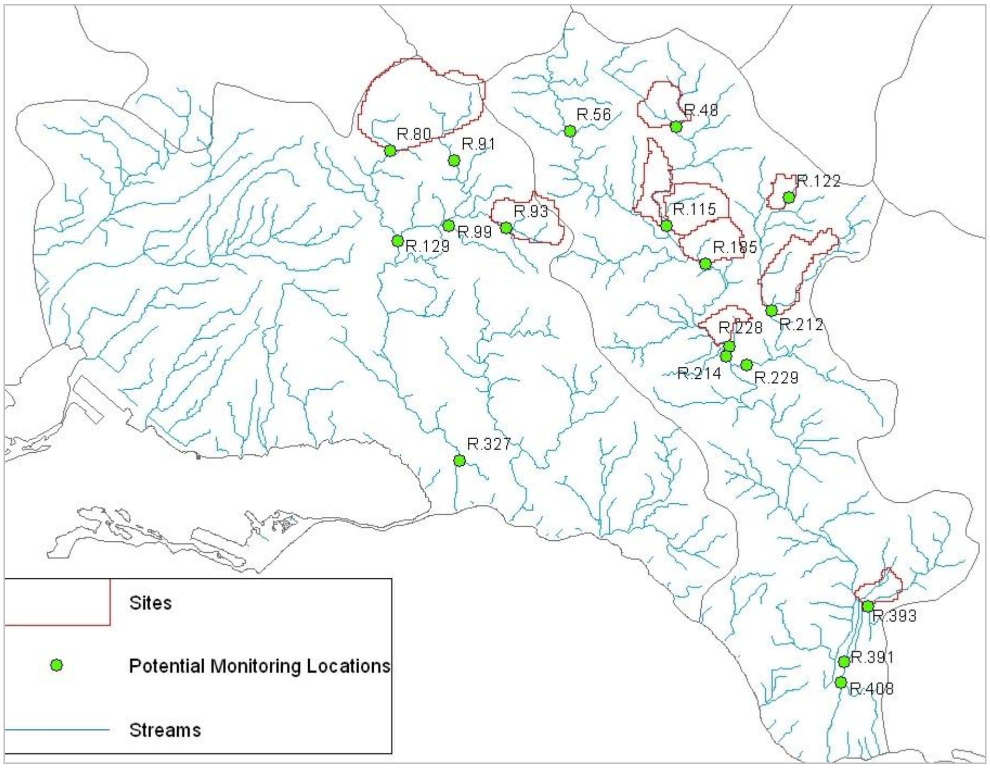

Figure 20: Map of monitoring points

In its first stage, it is recommended that the project acquires Portable Turbidity Meters and Flow Meters, equip and train personnel to monitor turbidity and flow frequently in the rainy season and after rain events and periodically (every week) in the dry season. Each location should have a turbidity meter and flow meter. Turbidity meter costs about $750.00 USD and the flow meter costs about $775.00 USD. The total cost for the necessary portable equipments are 16,775.00 USD (11 sites x (750 + 775)). This is considered the minimum that the project needs for equipment costs. It is also recommended that the project establishs cross sections at different points of interest with the help of surveyors to improve the gaging station performance to provide more accurate streamflow information.

6. Conclusions and next steps

Promoting hydrologic stability and preventing water quality degradation in streams within the Yallahs River and Hope River watersheds will require changes in land use and land cover combined with improvements in agricultural and watershed best management practices. The changes projected in 5 years in the selected sites substantially affect water production and sediment production in different sub-basins. The modeling exercise shows that in general, and in most sub-basins where forestry and forestation practices are projected to increase, water yield, baseflow, and sediment production are expected to decrease.

It is important to highlight the data issues encountered during this project. The limited data availability and poor data quality caused substantial delays and excess time spent in executing this project. For future projects, it is recommended that the following actions need to take place:

- LULC classification and update of the LULC map: For future studies and projects and especially for the implementation phase of this project, it is necessary to generate a fine resolution map of land use land cover for the whole watersheds. This will allow the model to use the right parameters for each land use class and type.
- Precipitation Data: A detailed analysis of precipitation is necessary to quality control data sets for all different weather stations in the region.
- Streamflow Data: It is strongly recommended that the streamflow data is obtained for all gaging stations available in the region, and that all intake flows be collected and quality controlled.