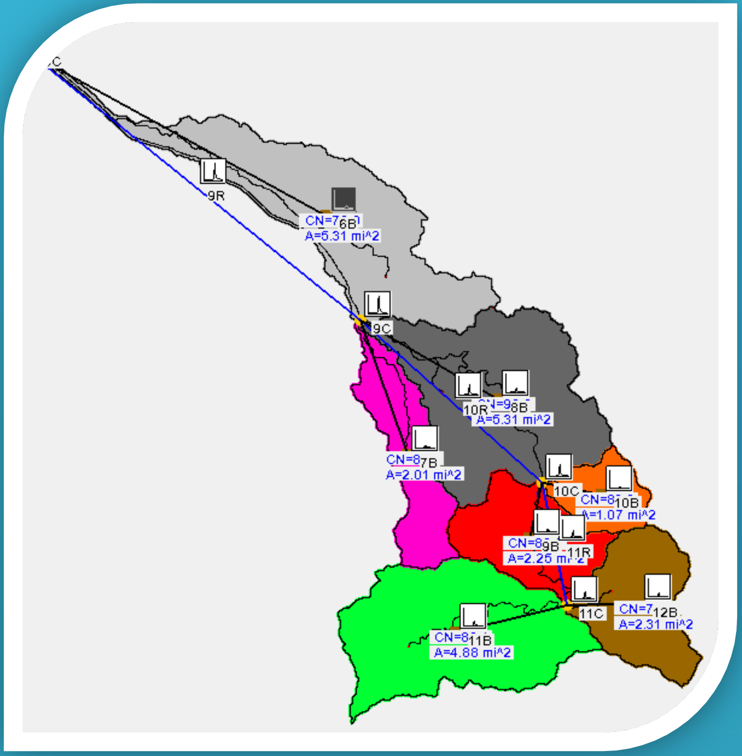
The City College of New York

CE H0700:Advanced Hydraulics

Spring 2013



Evaluation of channel bed stability of Rouyonne River under Hurricane Sandy

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This project aimed at computing bed shear stress for the Leogane's Rouyonne River under the flow conditions imposed by Hurricane Sandy. A 24-hour Rainfall-Runoff simulation estimates a peak flow of 5020.45 cfs at the basin outlet and the sub-basins in upper area of the watershed contributes the most to this flow. Therefore, a special attention needs to be granted to these sub-basins in any watershed management project. A HEC-RAS simulation indicated that shear stress is higher near the inside entrance of a bend and on the outside of the bend toward the bend exit and estimated the lowest shear stress to 0.11 lb/sqft. This value is high enough to move fine gravel particle.

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I. Background

Even though Haiti was not located on the Sandy Storm pathway, over 20 inches of rain dropped for four days on the south and southwest part of the country causing at least 54 deaths, tearing out crops, destroying houses which caused people displacement (New York Times, 2012; USAID, 2013). The rainfall information was confirmed by precipitation data available at the PNAP website http://evigilance.ht .

The objective of this project is to use available meteorological data collected during the Sandy passage and terrain data as input to the Watershed Modeling System (WMS) developed by Aquaveo, LLC., to simulate the potential impacts of the Sandy storms flood waves on sediment particles movement in the Rouyonne River by analyzing the shear forces at several cross-sections. The average velocity of the flow could also be used to characterize the channel bed stability. However, shear stress is a known as a better measure of the fluid force on the channel boundary than is velocity and on top of that, conventional guidelines, including ASTM standards, rely upon the shear stress as a means of assessing the stability of erosion control materials (Fischenich, 2001).

There exist several forces acting on a particle grains. They include hydrodynamic lift, hydrodynamic drag, submerged weight, and a resisting force which depends on the geometry of the particle. Erosion occurs when the hydraulic forces in the flow exceed the resisting forces of the channel boundary (Fischenich, 2001). Hence, critical shear stress has been defined and compared against hydraulic shear stress to determine the tendency of a certain particle to move. Sediment mobility for a given particle size occurs when the hydraulic shear stress exceeds the critical shear stress. Once this condition happens, the given particle is potentially mobile

This work is considered as an initial step in a sediment transport analysis process.

II. Study Area

Leogane is a coastal town located at about 20 miles west from the capital city of Haiti. Its geographic coordinates are 18.51168,-72.633877.

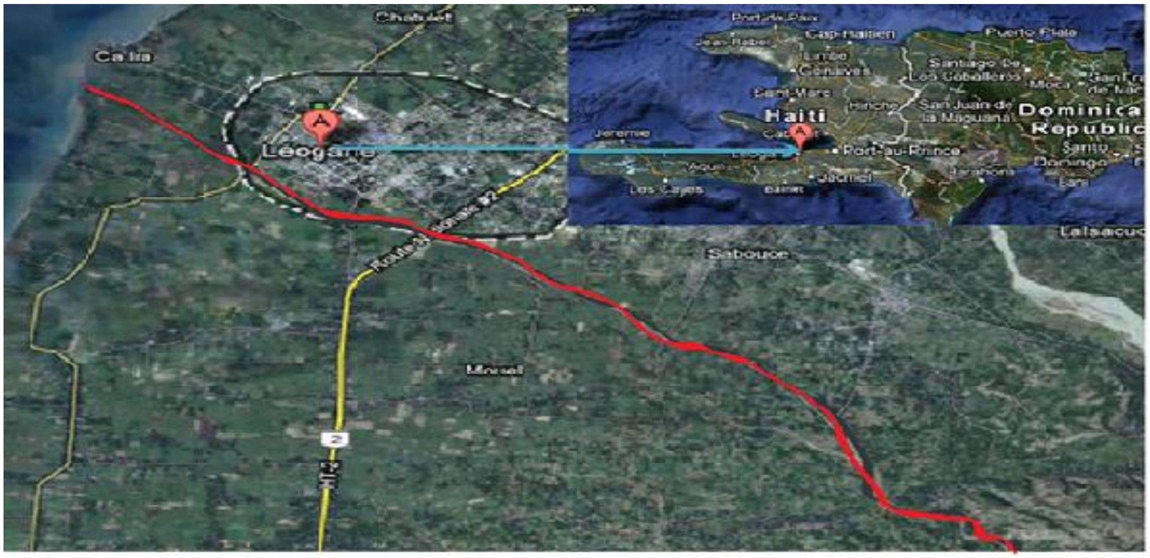


Figure 1: Leogane Map (Google Maps, 2012)

Since before the Sandy Storm sediment deposition and/or erosion due mainly to a mixture of high flows, land degradation and deforestation have been a growing concern in the Leogane region. Soil erosion damage always occurs after a major storm such as Sandy. This has a direct consequence the reduction of channel capacities and ability to pass flood flows (Gibson et al, 2010).

After major storms, the Ministry of Public Works (MTPTC) is used to deploy man power along with heavy equipments for a good number of days in this region to desilt stream bed materials deposited in Leogane's major rivers including the Rouyonne River.

The main focus of this project is the Rouyonne River channel (figure 1: painted in red) with a watershed area of about 66 square kilometers and a longest pathway of 31 km crossing the center of the town before reaching the sea. The Rouyonne River watershed extent is Right to Left: 72.6565432105837 to 72.5167842311472 West and Top to Bottom: 18.5245865241068 to 18.3834037266493 North. Its minimum and maximum elevations are respectively -19 m taken the Caribbean Sea as reference which is the basin outlet and 962.114 m. The mean annual rainfall is between 1000 to 1600 mm, the area is covered majorly with sand, clay and silt soil textures (FAO et al, 2012) and its land use includes mainly Agriculture, Forest, Pasture and Urban (CNIGS, 1998).

III. Methodology

a. Software used

The ***Watershed Modeling System (WMS)***, so-called "Complete all-in-one watershed solution", a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics was the primary software used in this project. The package includes powerful tools to automate modeling processes such as automated basin delineation, Hydrologic and geometric parameter calculations, GIS overlay computations (Curve Number, Rainfall-Runoff processes, roughness coefficients, etc.), cross-section extraction from terrain data, etc.

WMS is also considered as a pre and post-processing tools package for ***HEC-RAS***. This latter was also used to simulate geometric and flow data for two reaches and a tributary of the river. A number of parameters were computed on which analysis was done.

Along with WMS, ***Arc Hydro tools*** were used within ***ArcGIS*** to burn the drainage lines of the river onto the 8-m DEM before the watershed delineation processes.

b. Data Acquisition and HEC-1 Model Simulation Preparation

Data necessary for this project comprises the obtention of discharge time series and a Digital Elevation Model (DEM) data. The discharge data were not directly available for the study area. Therefore, a basic HEC-1 model of the watershed was built using an **8-meter DEM** data, a ***1998 Land Use***, a ***2012 Soil Type*** shapefiles downloaded respectively from www.haitidata.org and http://webarchive.iiasa.ac.at and ***Precipitation*** from http://evigilance.ht.

Precipitation data were not complete; there were a lot of gaps over the period of October 24-26, 2012. However, October 25, 2012 was the most complete 24-hour time series available for the Sandy event, the few gaps were filled by taking the average of the rainfall before and after each missing values. Below is the resulting temporal distribution of the total 11.29 inches rainfall data on October 25, 2012. Assuming that the storm produced equal precipitation to each sub-basin, this total value was assigned to each sub-basin.

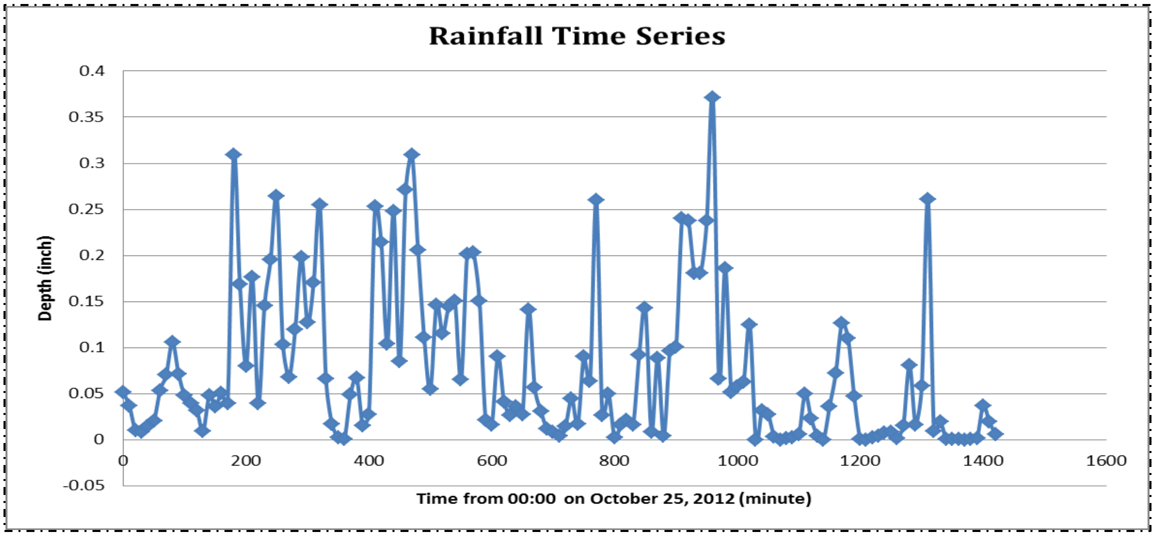
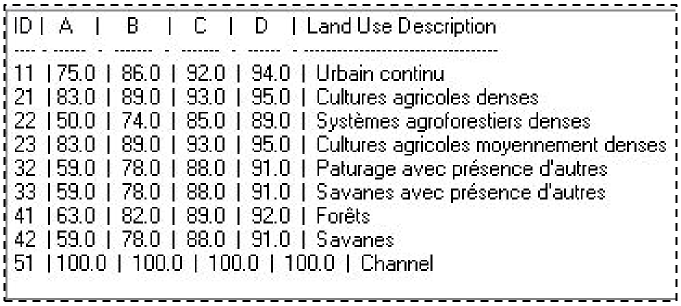


Figure 2: Temporal Rainfall Distribution

Before running HEC-1, multiple conditions or parameters need to be set. The SCS Loss Method has been selected among several loss methods that could be used in HEC-1 simulation. In order to work with this method, the Antecedent Moisture Condition (AMC) which refers to the wetness of the soil surface had to be defined. Even with the gaps, the rainfall data for October 24, 2012 (the day before the selected day) is greater than 2.26 inches. This value indicates that an AMCIII (when 5-days rainfall before the date considered is greater than 2.1 inches) must be applied to the soil wetness condition through the curve numbers (Singh, 2003). Hence, the curve numbers used to calculate the composite curve numbers (CCN) were selected as follows adjusted from AMCII curve numbers defined according to the SCS Methodology for each land use type and HSG (SCS, 1986).



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ID |  A   |   B   |  C   |   D   | Land Use Description
---- - ------ - ------- - ------- - ------ - --------------------------------
11  | 75.0 | 86.0 | 92.0 | 94.0 | Urbain continu
21  | 83.0 | 89.0 | 93.0 | 95.0 | Cultures agricoles denses
22  | 50.0 | 74.0 | 85.0 | 89.0 | Systèmes agroforestiers denses
23  | 83.0 | 89.0 | 93.0 | 95.0 | Cultures agricoles moyennement denses
32  | 59.0 | 78.0 | 88.0 | 91.0 | Paturage avec présence d'autres
33  | 59.0 | 78.0 | 88.0 | 91.0 | Savanes avec présence d'autres
41  | 63.0 | 82.0 | 89.0 | 92.0 | Forêts
42  | 59.0 | 78.0 | 88.0 | 91.0 | Savanes
51  | 100.0 | 100.0 | 100.0 | 100.0 | Channel
```

Figure 3: Curve Numbers for CCN computations under AMCIII conditions

This method computes the composite curve number which is then used to calculate the initial rainfall abstraction 0.2 * (1000 − 10 * CCN) / CCN when a value of zero is entered for this parameter. On top of this, the percentage of imperviousness has been assigned to each land-use type. An imperviousness value of 5% was used for all land use types while 65% was assigned to the urban land use (SCS, 1986).

The land use data was modified to include the area occupied by the channel. The channel polygon was created in WMS from the 1-HYD centerline coverage representing the channel banks. The product was then exported to ArcMap 10.0 to modify the land use shapefile.

As for the soil shapefile, a new field was added to the attribute table to represent the Hydrologic Soil Group (HSG) mentioned above. The soil shapefile was downloaded with excel files containing chemical information regarding the soil units. HSG B, C, and D were assigned to soil units according to the National Engineering Handbook (NRCS, 2007) based on the texture of the watershed soil units (Cambisols, Luvisols and Nitrosols).

A Light Detection and Ranging (LiDAR) DEM with a horizontal resolution of 1m downloaded from the website http://waspftp.cis.rit.edu/ was also used. Because it did not cover the entire watershed, it was not used in the delineation process but was used to extract the cross-sections.

All of the raster and shapefile data were projected in Universal Transverse Mercator (UTM Zone 18 Northern Hemisphere) coordinates and vertical datum used was World Geodetic System (WGS) 84.

IV. Results

a. HEC-1 Simulation

The hydrographs show how each sub-basin responds to the peak rainfall that occurred. For example, there was a peak rainfall between 2:30 and 3:40 AM on October 25, 2012 and the hydrographs show a peak flow between 6:40 and 8:20 AM. The effect of the Routing Method attenuating the hydrographs of upper basin before adding them to the lower basin hydrographs was also noted at each outlet. The simulation results show that the peak flows vary from 368.74 to 5020.35 cubic feet per second (cfs).

The Rainfall-Runoff simulations results indicate that the defined sub-basins (see delineated watershed in appendix) located in the upper part of the basin are the primary drivers in flood development. Therefore, these sub-basins must receive special attention in implementation of watershed management projects in the Leogane region. In particular, on a surface area basis, except sub-basin 6B despite its 5.31 Square Miles surface area does not contribute significantly to the total peak flow at the outlet of the basin (see figure 5). Compared with sub-basin 8B which has approximately the same surface area, basin 6B produces roughly 37% less flow. This confirms that the other sub-basins are critical areas to intervene in the context of actions to mitigate floods and erosion.

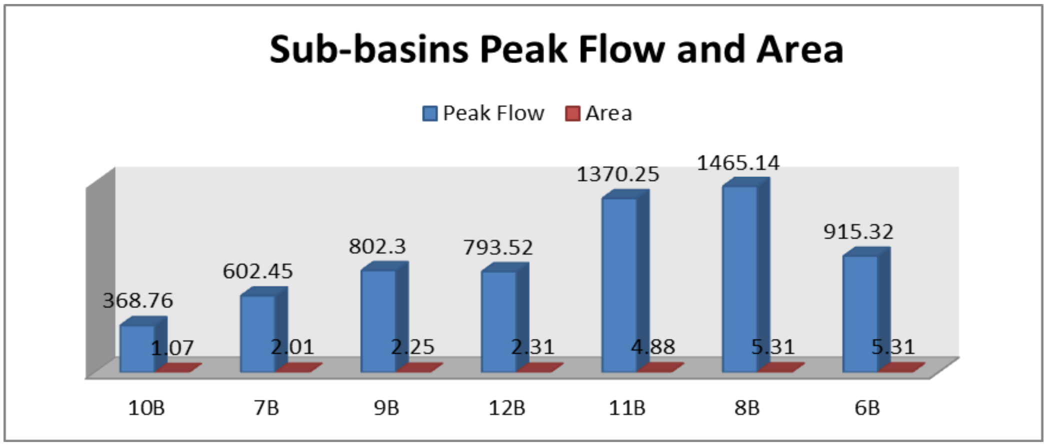
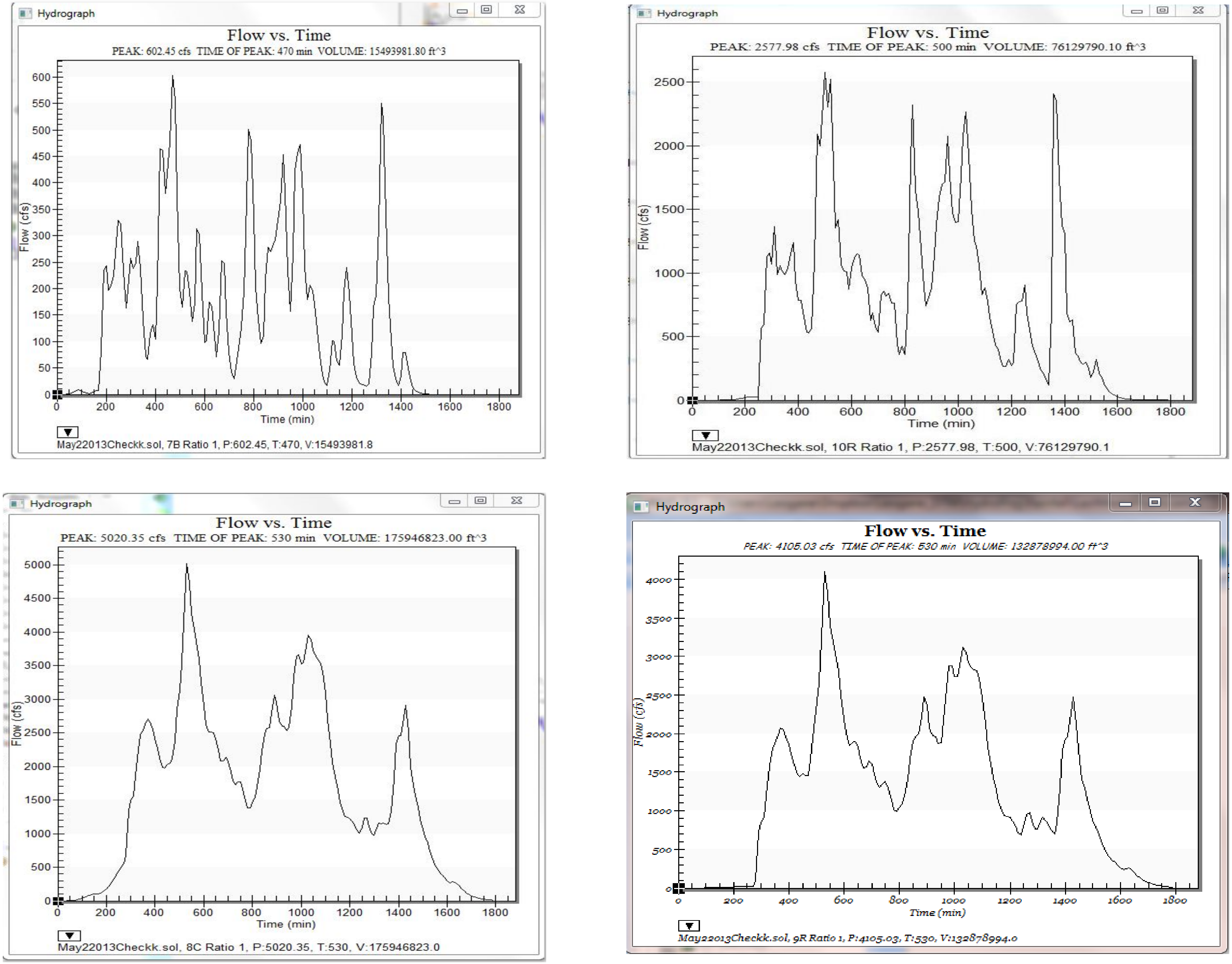


Figure 5: HEC-1 Simulation Results



Flow vs. Time

PEAK: 602.45 cfs TIME OF PEAK: 470 min VOLUME: 15493981.80 ft^3

May22013Checkk.sol, 7B Ratio 1, P:602.45, T:470, V:15493981.8

Flow vs. Time

PEAK: 2577.98 cfs TIME OF PEAK: 500 min VOLUME: 76129790.10 ft^3

May22013Checkk.sol, 10R Ratio 1, P:2577.98, T:500, V:76129790.1

Flow vs. Time

PEAK: 5020.35 cfs TIME OF PEAK: 530 min VOLUME: 175946823.00 ft^3

May22013Checkk.sol, 8C Ratio 1, P:5020.35, T:530, V:175946823.0

Flow vs. Time

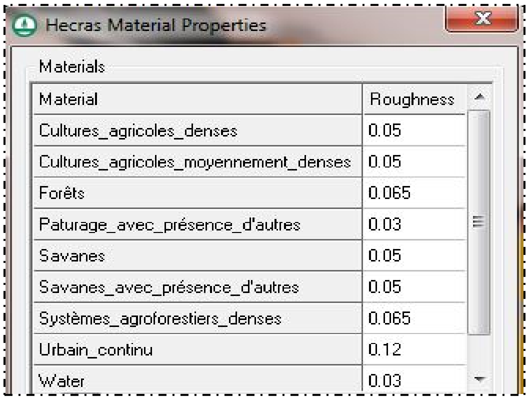
PEAK: 4105.03 cfs TIME OF PEAK: 530 min VOLUME: 132878994.00 ft^3

May22013Checkk.sol, 9R Ratio 1, P:4105.03, T:530, V:132878994.0

Figure 6: Hydrographs of some areas of interest: Basin 7B (Tributary), Upper Reach 10 R, Lower Reach 9R and the Basin outlet 9C.

b. HEC-RAS Simulation

After importing the 1-m DEM into WMS, a nice image of the DEM was generated and used to create the centerline and the banks of the channel under a 1-HYD centerline coverage. Later, the cross-sections were created under a 1-HYD cross-section coverage. Because the 1-meter DEM from which the cross-sections were to be extracted did not cover the entire watershed, two reaches and one of the tributaries covered by the DEM were considered in the HEC-RAS simulation. Manning's Numbers were also assigned to each land use type according to Brunner et al, 2003. The following table shows the values used for each land use type.



Material	Roughness
Cultures_agricoles_denses	0.05
Cultures_agricoles_moyennement_denses	0.05
Forêts	0.065
Paturage_avec_présence_d'autres	0.03
Savanes	0.05
Savanes_avec_présence_d'autres	0.05
Systèmes_agroforestiers_denses	0.065
Urbain_continu	0.12
Water	0.03

Figure 7: Roughness of Materials used in HEC-RAS Simulation

The "River Tools" option was used to extract the cross-sections from the 1-m DEM. It is noteworthy to mention that no actual field surveys were available for the study area. Therefore, the topographic accuracy of the DEM generated data could not be improved prior to exporting to HEC-RAS using the "HEC-RAS→Export GIS file" option.

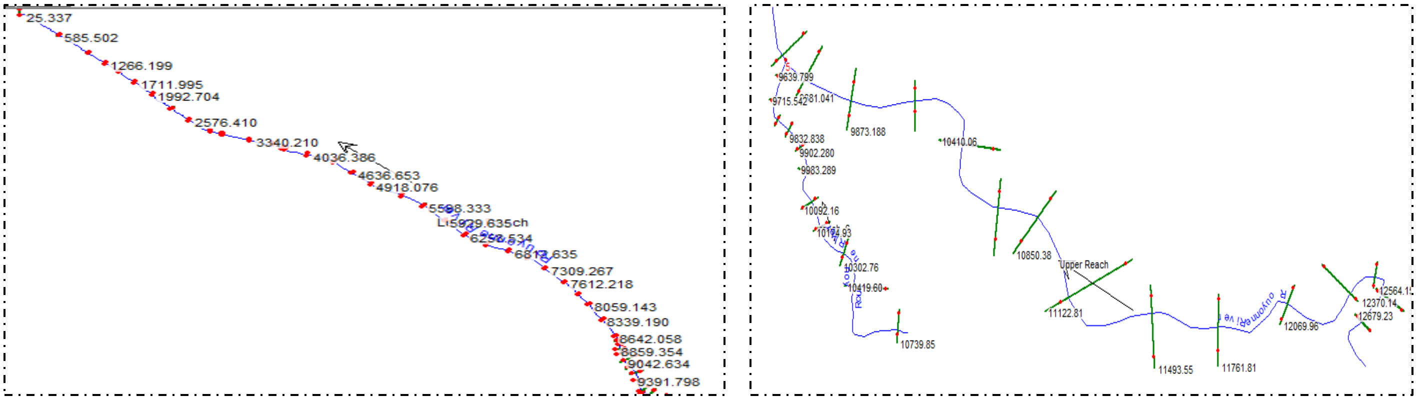


Figure 8: Lower Reach Cross-section stations (Left Image), Upper Reach (Right and Longer) and Tributary (Left and Shorter) cross-sections

A total of 66 cross-sections were considered in the simulation. The upper figures show a schematic of them.

Boundary conditions were taken as the average slope of the upper or lower sub-basins which respectively feed each reach and tributary or to which a reach or tributary drains. The following tables show the sub-basins average slopes and boundary conditions values used.

Basin	12B	11B	9B	7B	8B	10B	6B
Slope	0.6384	0.4892	0.5848	0.4534	0.4606	0.5596	0.0999

Figure 9:Sub-basins average slopes

Upper	Lower	Reach/Basin	Peak Flow rate (cfs)	Upper/Lower Basins
0.568	Junction	10R	2257.98	9B,10B,11B,12B
0.4534	Junction	7B	602.45	7B
Junction	0.0999	9R	40105.03	6B

Figure 10: Boundary conditions (slopes) used in the HEC-RAS simulation

The flow values mentioned above for the reaches and tributary, 602.45, 2577.98 and 4105.03 cfs, were used in the simulation. HEC-RAS computes a number of variables, but the one that is of interest is the shear stress. These values were recuperated and input to an excel file to visualize the location where sediment transport is more likely to occur. Below are the plots of the shear stress values versus cross-section station. The simulation was also run for 50% and 25% of the reaches and the tributary peak flow in order to compare how shear stress evolves with flow.

The following figures demonstrate that the shear stress is exaggerated at the first upstream cross-section for both the tributary and the upper reach and also at the end of the lower reach. This is illustrated in figures 12 and 13 where values are circled in red. This may be associated to the fact that HEC-RAS does not know that the river continues upstream and consider these locations as end points in the analysis.

The results confirmed that maximums of shear stress are found near the inside entrance of a bend and on the outside of the bend toward the bend exit where it persists further downstream (FWHA, 2005). The picture shows the location of the maximum shear stress (7.8 lb/sqft) of figure 11. This also happens in the lower reach in the region comprised between 4000 ft from the Darbonne Road going downstream where several moderate bends in the channel exist (reach stations between 4000 to 8500 ft).

Figure 11: A location of a maximum shear stress (upper reach)

Shear stress is generally reduced on the channel sides compared with the channel bottom (FHWA, 2005). The results prove this is generally true.

On top of that, comparison with allowable or critical shear stress values (Fischenich, 2001) lets to pretend that the channel was quite unstable under this storm event. The minimum shear stress in the channel was 0.11 lb/sqft at station 9042.634 ft; it is enough to move uniform fine gravel**.** The soil texture of the watershed is mainly composed of gravels, sands and clays (FAO et al, 2012).

Two bridges are constructed over the channel, but they do not have piers in the channel. Therefore, they were not included in the analysis. However, the most downstream bridge which is much lower than the upstream and almost touches the stream bed shows high shear stress (3.71 to 5.3 lb/sqft) compared to the other.

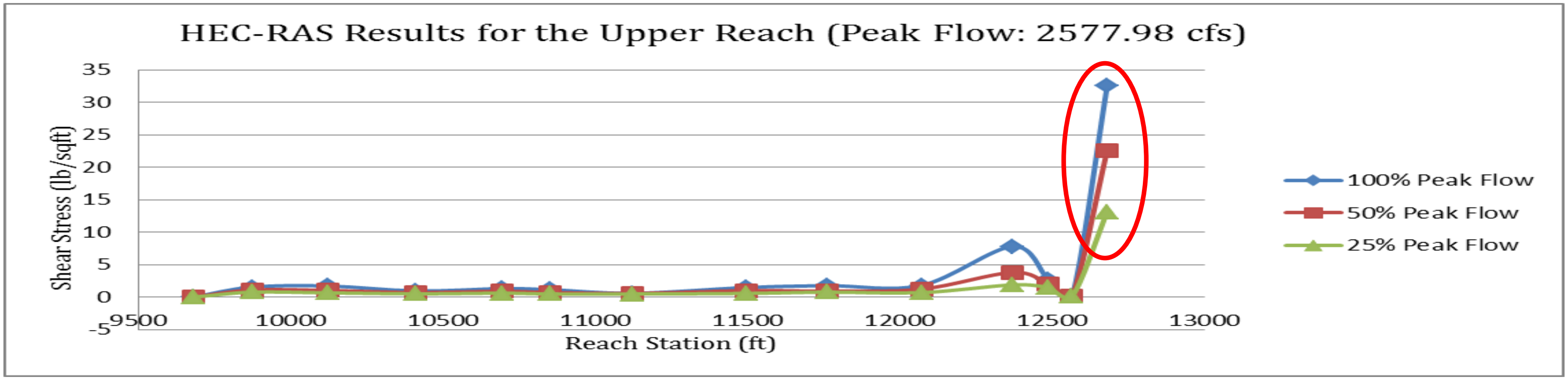


Figure 12: Shear Stress versus Reach Station (Upper Reach)

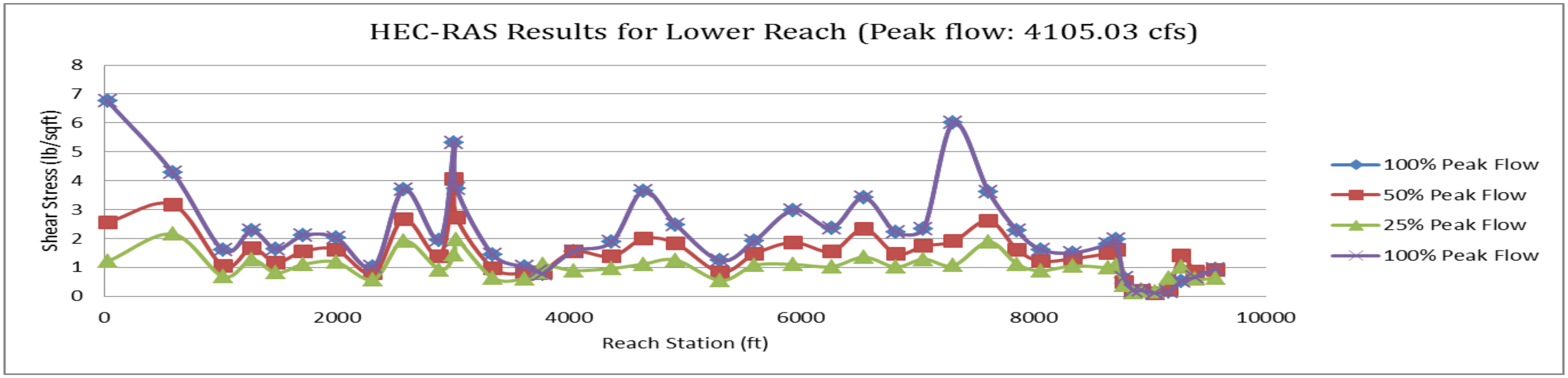


Figure 14: Shear Stress versus Reach Station (Lower Reach)

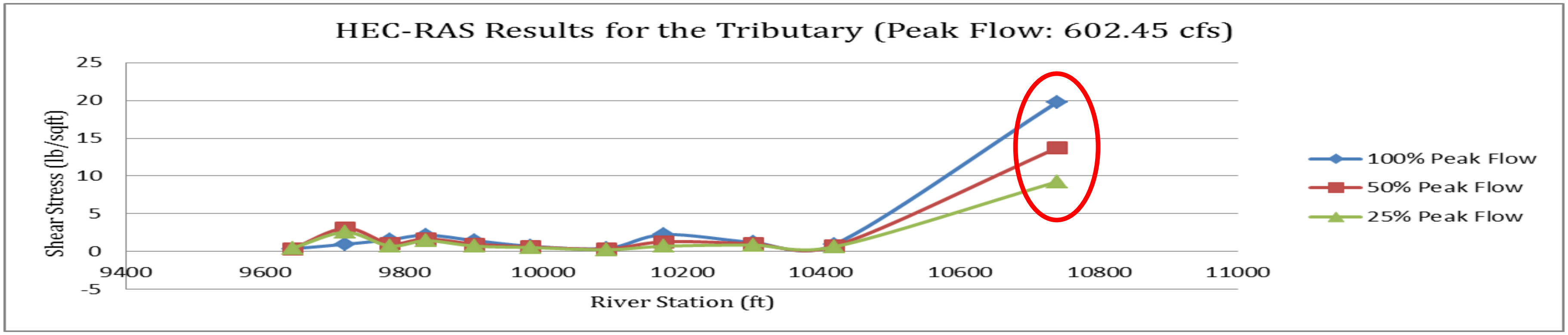


Figure 13: Shear Stress versus Reach Station (Tributary)

V. Conclusion

Several models have been developed to predict bed load sediment transport. However, shear stress is a required input to any of these sediment transport models (Nielsen, 2001). This project has shown the capability of WMS in general and HEC-RAS in particular in computing bed and overbanks shear stress, wetted perimeter and stream power.

This work is aimed to be just an initial step towards a complete channel bed stability analysis. Therefore, long-term data collection and assessment measures such as surveying cross-sections, particle size distributions, installation of bed hooks and water level and flow sensors, getting an Aerial Photography or Satellite Imagery of the area to digitize the channel centerline and banks lines would important if a complete analysis is to be conducted. It must be noted that WMS had failed to import such imagery. These will provide a quite accurate estimation of the threshold of hydraulic and critical shear stress using several theoretical approximations.

VI. Acknowledgements

Special thanks go to Mr. **Dwinel Belizaire** for his generosity regarding the sharing of the rainfall data.

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VIII. Appendix

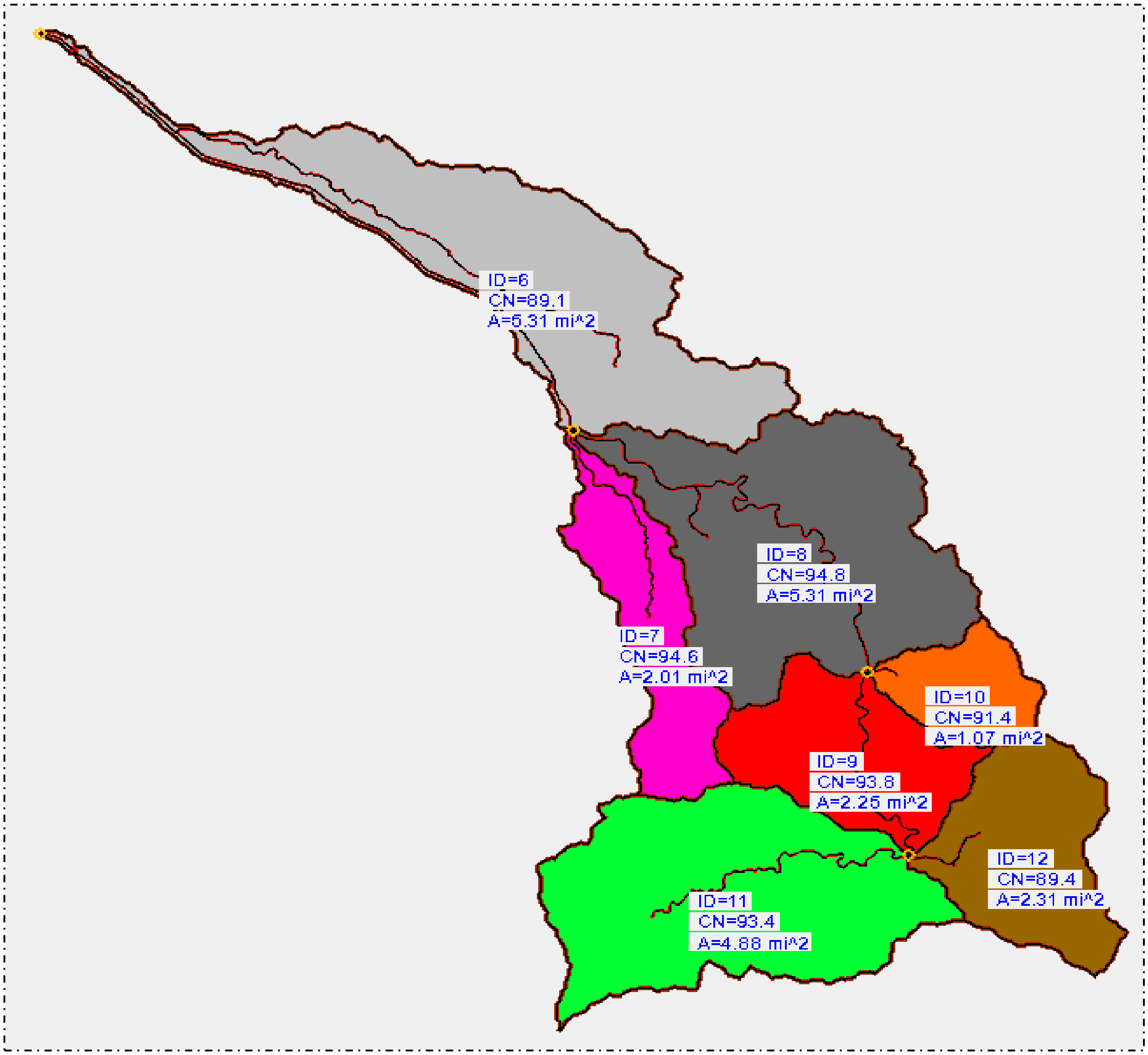


Figure 15: Delineated Watershed and Stream Network

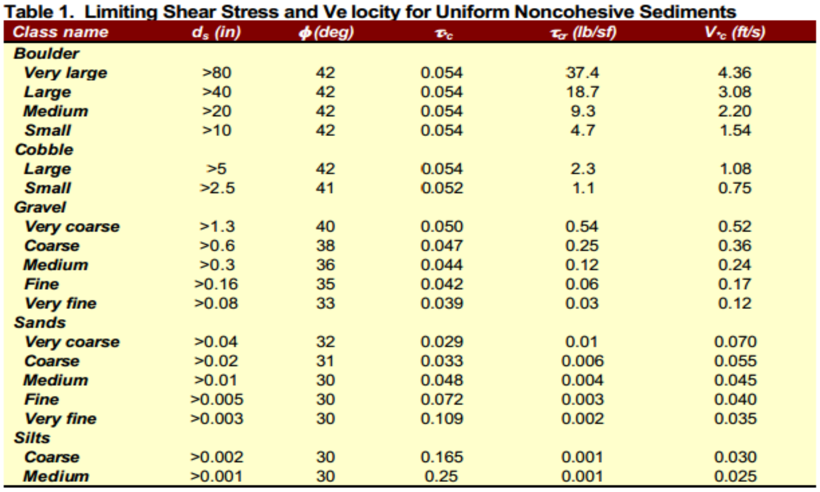
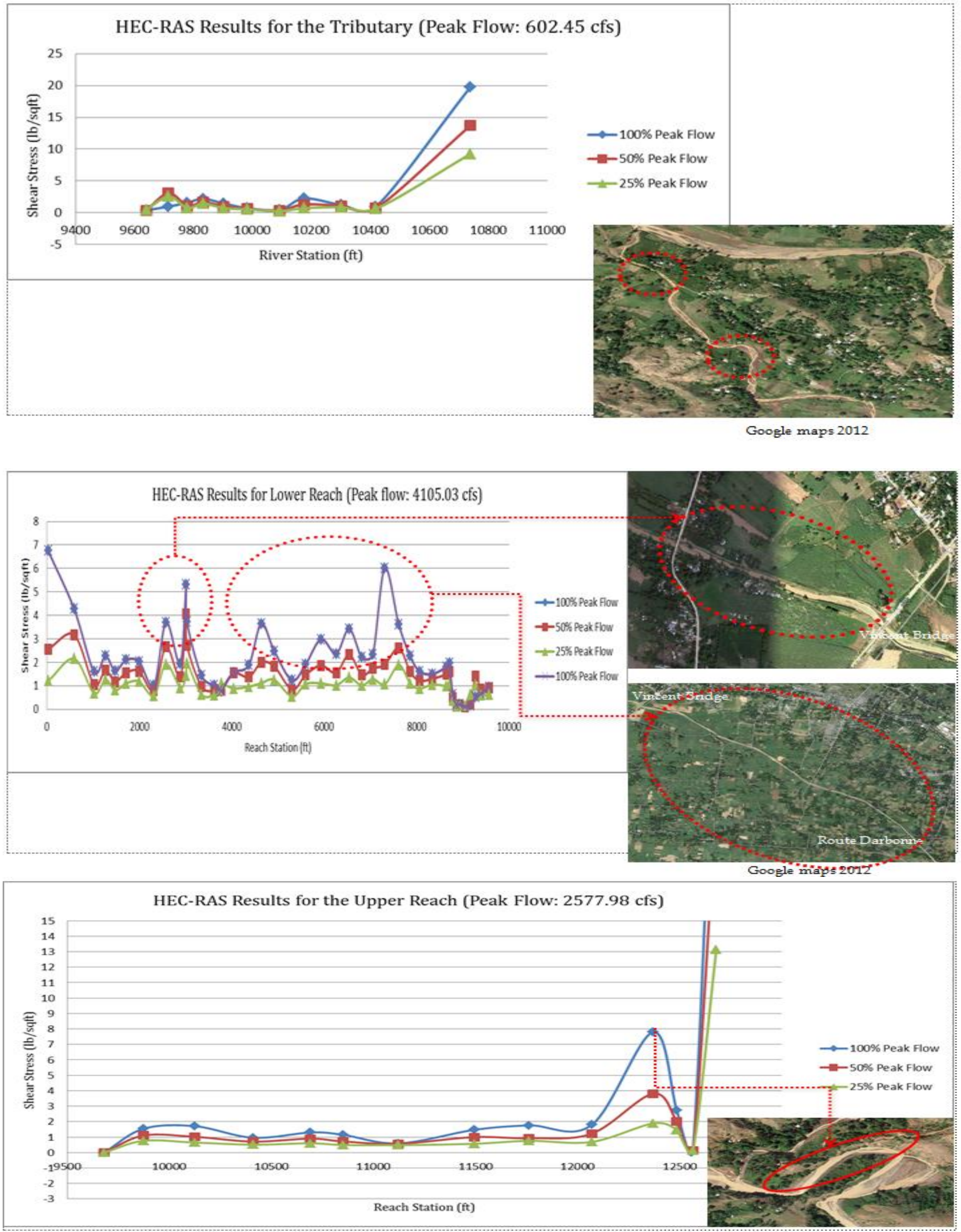


Table 1. Limiting Shear Stress and Velocity for Uniform Noncohesive Sediments

Class name	d_s (in)	ϕ (deg)	τ_c	τ_{cr} (lb/sf)	V_{*c} (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	4.36
Large	>40	42	0.054	18.7	3.08
Medium	>20	42	0.054	9.3	2.20
Small	>10	42	0.054	4.7	1.54
Cobble					
Large	>5	42	0.054	2.3	1.08
Small	>2.5	41	0.052	1.1	0.75
Gravel					
Very coarse	>1.3	40	0.050	0.54	0.52
Coarse	>0.6	38	0.047	0.25	0.36
Medium	>0.3	36	0.044	0.12	0.24
Fine	>0.16	35	0.042	0.06	0.17
Very fine	>0.08	33	0.039	0.03	0.12
Sands					
Very coarse	>0.04	32	0.029	0.01	0.070
Coarse	>0.02	31	0.033	0.006	0.055
Medium	>0.01	30	0.048	0.004	0.045
Fine	>0.005	30	0.072	0.003	0.040
Very fine	>0.003	30	0.109	0.002	0.035
Silts					
Coarse	>0.002	30	0.165	0.001	0.030
Medium	>0.001	30	0.25	0.001	0.025

Figure 16: Limiting Shear Stress for Uniform Noncohesive Sediments (Fischenich, 2001)



Google maps 2012

Google maps 2012

Google maps 2012

Figure 17: some locations with high shear stress