Flood Forecasting – Spring - 2015
Due Friday 05/08/2015

Alfredo Hijar

Term Project

NFIE-River: Cross section approximations for hydraulic channel routing model in the San Antonio and Guadalupe River Basins.

1. Introduction

Flow routing techniques are a key component to understand and forecast environmental impacts as well as hydrological processes, such as reservoir operations, floods, habitat assessments, among others. Flow routing may be classified as either lumped or distributed. Lumped or hydrological flow routing schemes compute flow as a function of time at one location along the watercourse. Distributed or hydraulic flow routing schemes compute flow as a function of time and space along the watercourse.

Data requirements are substantially different for both models. From a practical point of view, hydrological models, which require less information, are more attractive and are widely used in academia and industry. Hydraulic models are based on physical laws and require more detailed information describing river or channel geometry, friction, and lateral fluxes.

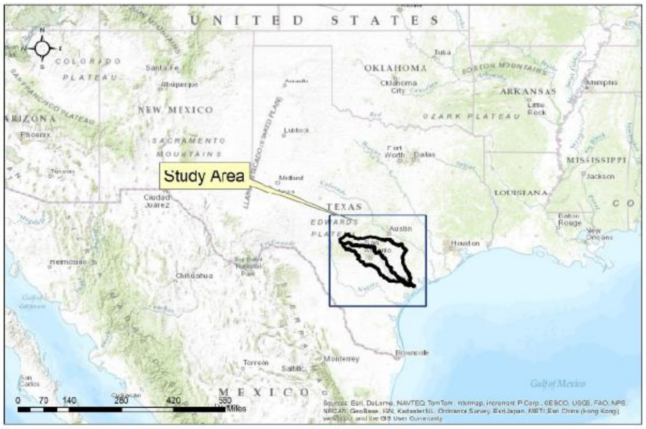
Channel cross section geometry has a controlling influence on the shape of flood waves, velocity and sediment transport capacity in the channel as well as in the floodplain through overbank and subsurface pathways.

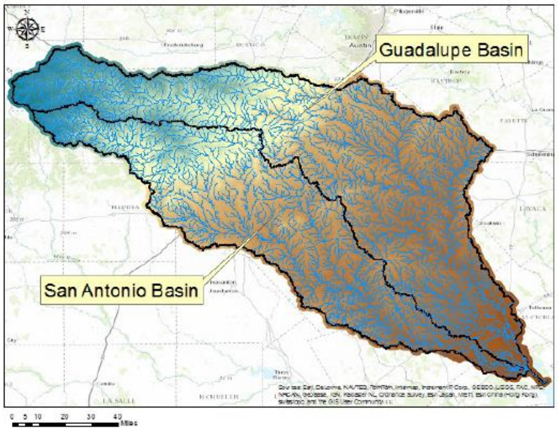
Large-scale flow routing problems involve hundreds of kilometers long reaches or river networks at a regional or continental scale, and the cost of obtaining the necessary information (i.e. channel cross section geometry and its resistance characteristics) over such large distances is considered to be economically and physically unfeasible. Given that channel or river cross section geometry is a prime input for hydraulic models, there is a key importance in obtaining that information.

2. Study Area

The San Antonio and Guadalupe River basins are located in south-central Texas. The Guadalupe River basin has a drainage area of 6,700 square miles as well as about 3,000 river and stream reaches, while the San Antonio River basin has a drainage area of 4,180 square miles and about 2,000 river and stream reaches. These basins are chosen for study because of significant contributions to surface water flow from groundwater sources at Canyon Lake, where the impacts of constructed infrastructure on flow dynamics have to be considered, and because these rivers flow out into an estuarine system at San Antonio Bay.

The San Antonio River basin is a dynamic ecosystem with rivers, creeks and streams that can quickly be impacted by rain events and other weather conditions. This basin is bordered on the west by the Nueces River basin and on the east by the Guadalupe River basin. Most of the San Antonio River basin is rural. The Guadalupe River basin is the fourth largest river basin whose watershed area is entirely within Texas. Figure 1 presents the San Antonio and Guadalupe river networks.



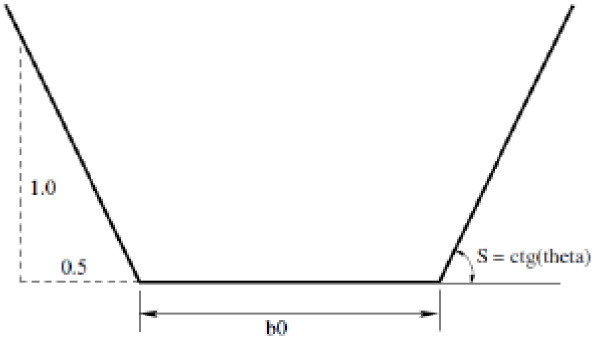


3. Methodology

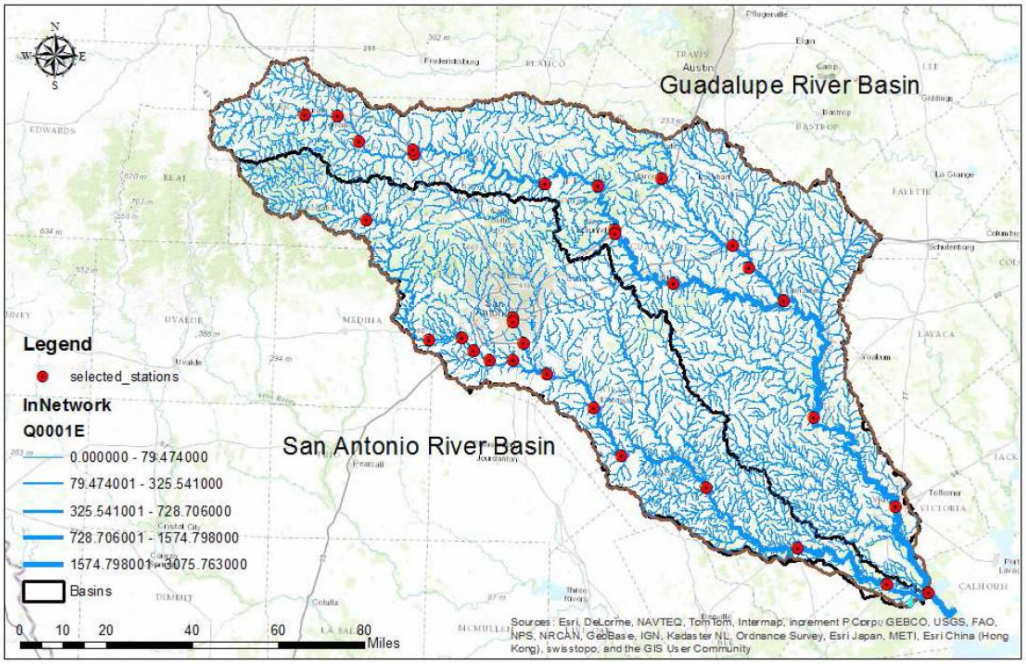
This study presents a statistical approach, which is implemented, simulated, and compared to the results from USGS streamflow measurement stations. To run the hydraulic SPRNT model the following actions were required: (i) the hydrological information from the study area was collected from the National Hydrography Dataset Plus Version 2, (ii) the cross section geometry, as well as the hydrological information, and (iii) the model runoff inputs were fed by the Noah Land Surface Model results for every reach in the study river basin. The SPRNT model solves the full nonlinear Saint-Venant equations for one-dimensional unsteady flow and stage height in river channel networks with non-uniform bathymetry.

In the absence of comprehensive empirical data, it can be argued that simple form (i.e. trapezoidal, rectangular or parabolic) cross-sections are reasonable approximations for many channels. Indeed, prior models have adopted simpler rectangular channels for dynamic routing, and showed that rectangular cross sections, as opposed to rectangular shapes, can lead to considerable improvement in flow simulations.

The hypothesis for this analysis is that river cross sections in the Guadalupe and San Antonio River basins can be approximated as trapezoidal forms with symmetric side walls. Two parameters are required to specify a trapezoidal cross section: the bottom width and the side wall slope. Figure 2 illustrates a trapezoidal cross section and its parameters.



Additionally, the hypothesis considers that the river cross section shape parameters present a relationship with the drainage area of the different streams in the study area. Given these two hypothesis, and knowing the drainage area for every stream in the study area, trapezoidal river cross sections can be approximated for every stream in the study area. Figure 3 presents the active USGS streamflow measurement stations used in this study.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

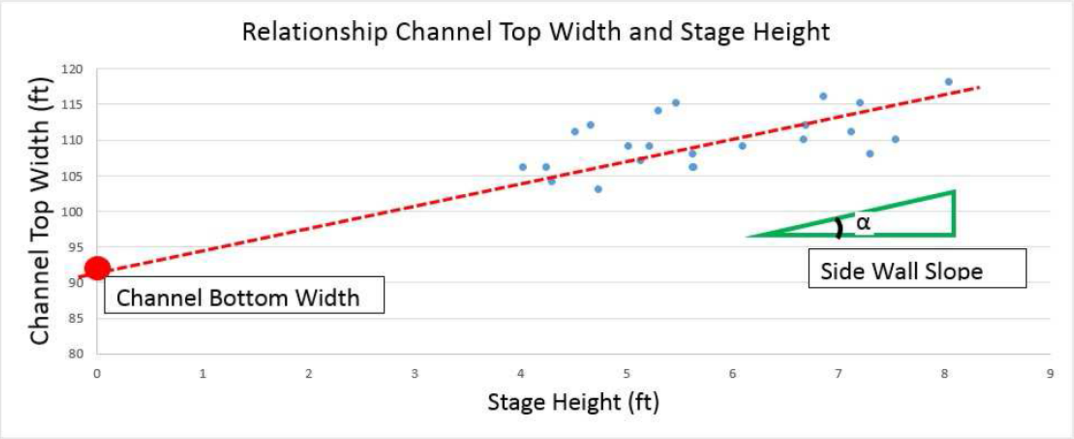
Stage height (h) is plotted vs. channel top width (w) for all the available stations in the study area to analyze the relationship between these two variables. The relationship between h and w provides insight on the cross section geometry.

The Kendall's correlation coefficient (τ) and Kendall's test were used to quantify and test the strength of the correlation between the variables in all the USGS stations. Kendall's test allows us to recognize monotonic relationships between the stage height and channel top width.

Additionally, the Pearson correlation coefficient test was performed to assess the linearity of the relationship. The Pearson correlation coefficient (r) measures the linear association between two variables.

Finally, to estimate the parameters that define a trapezoidal cross section and to describe the variation in the dependent variable, the ordinary least squares linear regression model was conducted.

As seen from Figure 4, for a trapezoidal cross section approximation, the intercept can be approximated to the bottom width of the river channel, and the slope can be approximated as two time the side wall slope.

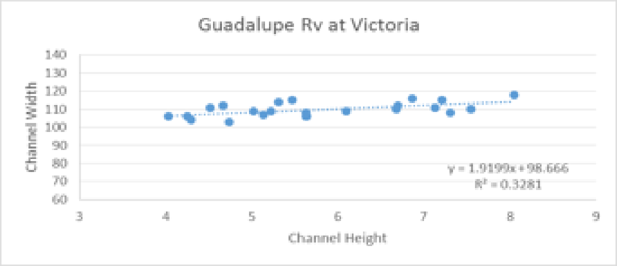


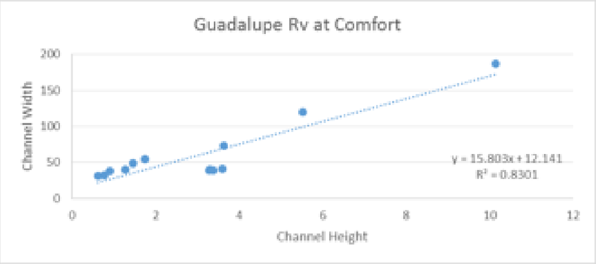
In this study, the NHDPlus dataset or data from NFIE-Geo is used as the land base for the SPRNT model as well as for the Noah LSM. The NHDPlus contains a GIS dataset that links the National Hydrography Dataset description of the mapped streams and water bodies of the nation with small catchments delineated around each stream reach. Each reach and its catchment are assigned a unique identifier, the COMID, and all features and attributes to this reach are labeled similarly. Additionally, the NHDPlus includes diverse attributes such as “FromNode”, “ToNode”, divergence, network connectivity, stream order, slope, length, and mean annual flow.

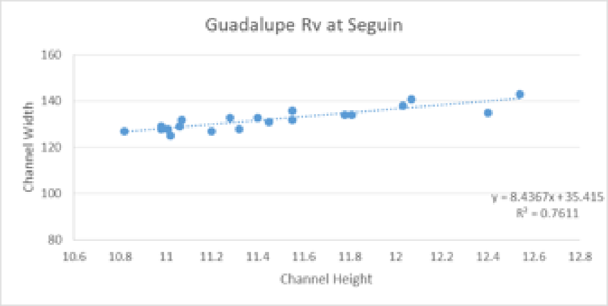
The Noah LSM simulates the overland flow routing as a fully unsteady, explicit, finite difference, one-dimensional diffusive wave flowing over the land surface. Sub-surface flow (down to 2-m depth) is also explicitly modeled using a quasi-steady state saturated flow model. The horizontal flow into a stream network calculated by Noah is the sum of surface and sub-surface runoff. The Noah LSM does not consider flow from the stream back to the landscape or aquifer.

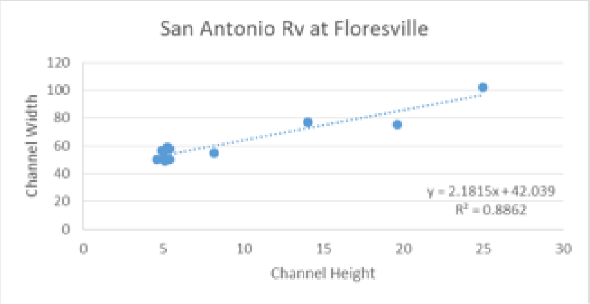
4. Results

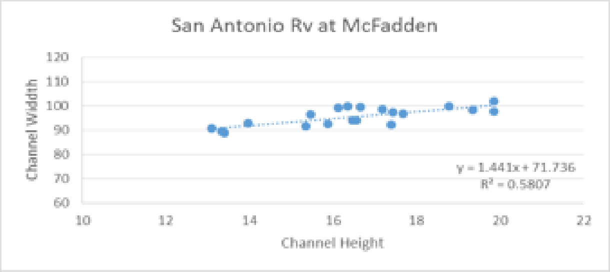
Figure 5 presents different “channel width vs. channel height” plots from the USGS streamflow measurement stations.











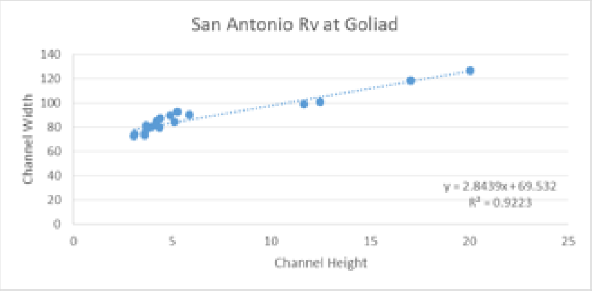


Table 1 presents the data for the USGS streamflow measurement stations.

Table 1. USGS Streamflow Measurement Station – Guadalupe and San Antonio River Basins

Station Code	Station Name	Observations	Time Period	Channel Top Width Average	Channel Stage Height Average	Rating Curve	Drainage Area (km^2)
08188800	Guadalupe Rv nr Tivoli, TX	14	2012 - 2014	126.64	3.79	3	26220.880
08176500	Guadalupe Rv at Victoria, TX	23	2011 - 2014	109.78	5.79	19	13456.240
08175800	Guadalupe Rv at Cuero, TX	18	2010 - 2014	146.76	9.82	8.1	12781.150
08173900	Guadalupe Rv at Gonzales, TX	18	2010 - 2014	120.94	11.93	7	8998.478
08169792	Guadalupe Rv at FM 1117 nr Seguin, TX	20	2011 - 2014	132.15	11.47	3	4873.884
08168500	Guadalupe Rvat New Braunfels, TX	16	2011 - 2014	115.63	1.91	10	3934.607
08167500	Guadalupe Rv nr Spring Branch, TX	19	2011 - 2013	77.42	1.93	16.1	3456.595
08167000	Guadalupe Rv at Comfort, TX	13	2010 - 2014	60.34	3.05	26	2174.374
08166250	Guadalupe Rv nr Center Point, TX	15	2010 - 2014	55.60	3.68	2	1431.016
08166200	Guadalupe Rv at Kerrville, TX	17	2011 - 2014	88.76	1.68	3	1259.104
08165300	N Fk Guadalupe Rv nr Hunt, TX	11	2012 - 2014	39.95	3.37	27	435.992
08188570	San Antonio Rv nr McFaddin, TX	20	2011 - 2014	95.53	16.51	4	10722.330
08188500	San Antonio Rv at Goliad, TX	21	2010 - 2014	87.46	6.30	5	10120.080
08183500	San Antonio Rv nr Falls City, TX	17	2009 - 2014	71.35	1.74	13	5464.457
08183200	San Antonio Rv nr Floresville, TX	18	2011 - 2014	58.87	7.72	5	5091.583
08181800	San Antonio Rv nr Elmendorf, TX	12	2010 - 2013	52.02	12.55	16	4528.458
08178565	San Antonio Loop 410, San Antonio, TX	14	2011 - 2014	68.84	4.90	10	296.773
08178000	San Antonio Rv at San Antonio, TX	11	2011 - 2014	4.46	31.61	22	109.8945

Table 2 presents the results of the Kendall Test for trends and τ values for the different stations.

Table 2. Mann-Kendall Test for trends - Guadalupe and San Antonio River USGS stations

Station Name	N	S	Sigma (σ_s)	Z_s	Z	τ (tau)	P-value	alpha	p-value > a Zs > Z	Trend
Guadalupe Rv nr Tivoli, TX	14	37	18.267	1.971	1.96	0.343	0.048	0.05	YES	TREND
Guadalupe Rv at Victoria, TX	23	103	39.55	2.58		0.407	0.002		YES	TREND
Guadalupe Rv at Cuero, TX	18	61	27.911	2.15		0.399	0.032		YES	TREND
Guadalupe Rv at Gonzales, TX	18	75	26.401	2.803		0.490	0.006		YES	TREND
Guadalupe Rv at FM 1117 nr Seguin, TX	20	130	32.404	3.981		0.684	0.002		YES	TREND
Guadalupe Rv at New Braunfels, TX	16	55	23.646	2.284		0.458	0.022		YES	TREND
Guadalupe Rv nr Spring Branch, TX	19	149	30.129	4.912		0.871	0.002		YES	TREND
Guadalupe Rv at Comfort, TX	13	54	17.704	2.994		0.692	0.002		YES	TREND
Guadalupe Rv nr Center Point, TX	15	88	20.207	4.305		0.838	0.002		YES	TREND
Guadalupe Rv at Kerrville, TX	17	42	24.276	1.689		0.30882	0.092		NO	NO
N Fk Guadalupe Rv nr Hunt, TX	11	42	12.845	3.192		0.76364	0.002		YES	TREND
San Antonio Rv nr McFaddin, TX	20	96	30.822	3.082		0.505	0.002		YES	TREND
San Antonio Rv at Goliad, TX	21	178	33.116	5.345		0.848	0.002		YES	TREND
San Antonio Rv nr Falls City, TX	17	80	20.934	3.774		0.588	0.002		YES	TREND
San Antonio Rv nr Floresville, TX	18	72	26.401	2.689		0.471	0.008		YES	TREND
San Antonio Rv nr Elmendorf, TX	12	29	14.583	1.920		0.439	0.054		NO	NO
San Antonio Rv at Loop 410, San Antonio, TX	14	65	18.267	3.504		0.714	0.002		YES	TREND
San Antonio Rv at San Antonio, TX	11	18	12.845	1.323		0.327	0.186		NO	NO

As seen in Table 2, 15 stations for the Guadalupe and San Antonio River present a trend or correlation between the channel width and channel height (only 3 stations do not show a trend for α = 0.05). Moreover, almost all the stations present a Kendall's correlation coefficient (tau) greater than 0.4, which demonstrate a strong correlation between the two variables.

Table 3 presents the results for the ordinary least squares linear regression model.

Table 3. Ordinary Least Squares Linear Regression

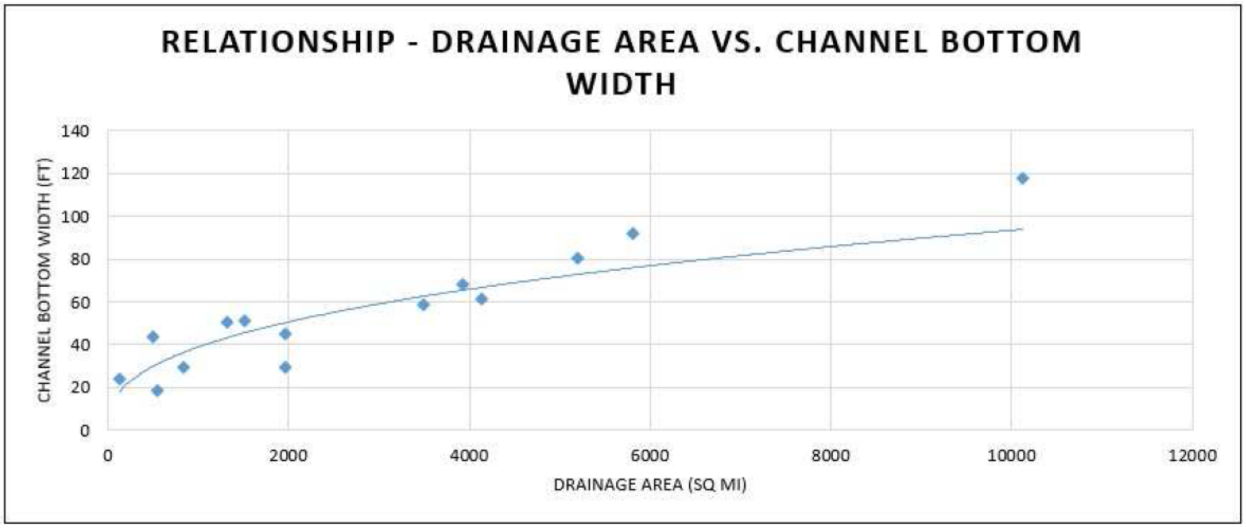
Station Name	N	Linear	S_{xx}	S_{xy}	S_{yy}	b_1	$\overline{X}$	$\overline{Y}$	b_o	r	t	t_{crit}	Statistical Relationship
Guadalupe Rv nr Tivoli	14	Yes	0.23	0.72	5.94	3.15	3.79	126.64	114.71	0.62	2.72	2.179	Yes
Guadalupe Rv at Victoria	23	Yes	1.39	2.67	15.63	1.92	5.79	109.78	98.67	0.57	3.20	2.08	Yes
Guadalupe Rv at Cuero	18	Yes	21.36	121.38	1392.61	5.68	9.82	146.76	90.92	0.70	3.96	2.1	Yes
Guadalupe Rv at Gonzales	18	Yes	4.34	38.77	388.41	8.93	11.93	120.94	14.42	0.94	11.47	2.1	Yes
Guadalupe Rv nr Seguin	20	Yes	0.25	2.08	23.08	8.44	11.47	132.15	35.41	0.87	7.57	2.1	Yes
Guadalupe Rv at New Braunfels	16	Yes	0.17	4.23	135.45	25.25	1.91	115.63	67.33	0.89	7.21	2.15	Yes
Guadalupe Rv nr Spring Branch	19	Yes	0.12	2.69	65.56	22.71	1.93	77.42	33.65	0.97	15.33	2.1	Yes
Guadalupe Rv at Comfort	13	Yes	6.70	105.84	2014.96	15.80	3.05	60.34	12.14	0.91	7.33	2.2	Yes
Guadalupe Rv nr Center Point	15	Yes	0.13	0.91	10.40	7.17	3.68	55.60	29.21	0.79	4.65	2.16	Yes
Guadalupe Rv at Kerrville	17	Yes	0.11	4.15	185.32	36.97	1.68	88.76	26.73	0.91	8.47	2.13	Yes
Guadalupe Rv nr Hunt	11	Yes	0.03	0.24	2.84	8.52	3.37	39.95	11.19	0.85	4.84	2.26	Yes
San Antonio Rv nr McFaddin	20	Yes	4.21	6.06	15.05	1.44	16.51	95.53	71.74	0.76	4.99	2.1	Yes
SA Rv at Goliad	21	Yes	22.84	64.94	200.23	2.84	6.30	87.46	69.53	0.96	15.02	2.1	Yes
SA Rv nr Falls City	17	Yes	2.60	23.82	222.33	9.17	1.74	71.35	55.39	0.99	28.58	2.13	Yes
SA Rv nr Floresville	18	Yes	33.66	73.43	180.78	2.18	7.72	58.87	42.04	0.94	11.16	2.12	Yes
SA Rv nr Elmendorf	12	Yes	14.52	40.50	132.67	2.79	12.55	52.02	16.99	0.92	7.59	2.23	Yes
SA Rv at Loop 410	14	Yes	4.73	51.94	602.26	10.98	4.90	68.84	14.98	0.97	14.67	2.18	Yes
SA Rv at San Antonio	11	Yes	0.32	1.18	6.29	3.72	31.61	4.46	15.01	0.84	4.57	2.262	Yes

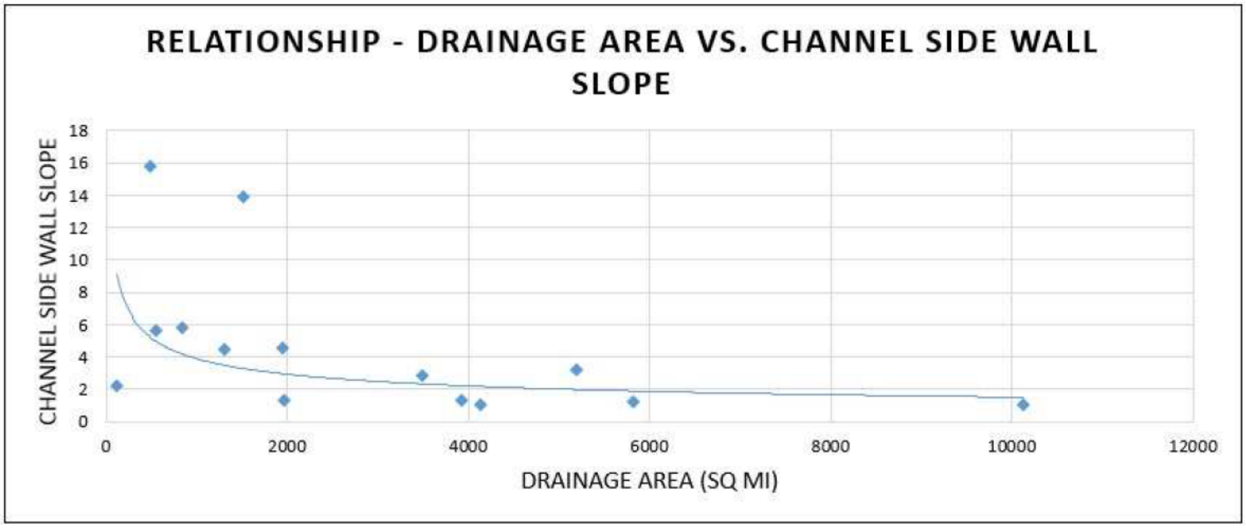
As seen in Table 3, for all the USGS the “t” statistic is greater than the critical “t”. Therefore, we reject the initial hypothesis ($b1 = 0$) and we can say that there is a linear relationship between the channel width and channel height for the studied USGS stations. Moreover, the Pearson correlation coefficient “r” is above 0.8 in most cases.

As discussed in previous sections, one of the goals of this study is to be able to estimate reliable river cross sections. Table 4 and Figures 6 and 7 present the data to assess the linear relationship between stream drainage area and channel cross section parameters (bottom width and side wall slope).

Table 4. Information for drainage area and cross section parameters of the USGS stations

Station Code	Station Name	Drainage Area (km^2)	Side Wall Slope (b1)	Bottom width (bo)
08188800	Guadalupe Rv nr Tivoli, TX	26220.880	3.15	114.71
08176500	Guadalupe Rv at Victoria, TX	13456.240	1.92	98.67
08175800	Guadalupe Rv at Cuero, TX	12781.150	5.68	90.92
08173900	Guadalupe Rv at Gonzales, TX	8998.478	8.93	14.42
08169792	Guadalupe Rv nr Seguin, TX	4873.884	8.44	35.41
08168500	Guadalupe Rv at New Braunfels, TX	3934.607	25.25	67.33
08167500	Guadalupe Rv nr Spring Branch, TX	3456.595	22.71	33.65
08167000	Guadalupe Rv at Comfort, TX	2174.374	15.80	12.14
08166250	Guadalupe Rv nr Center Point, TX	1431.016	7.17	29.21
08166200	Guadalupe Rv at Kerrville, TX	1259.104	36.97	26.73
08165300	N Fk Guadalupe Rv nr Hunt, TX	435.992	8.52	11.19
08188570	San Antonio Rv nr McFaddin, TX	10722.330	1.44	71.74
08188500	San Antonio Rv at Goliad, TX	10120.080	2.84	69.53
08183500	San Antonio Rv nr Falls City, TX	5464.457	9.17	55.39
08183200	San Antonio Rv nr Floresville, TX	5091.583	2.18	42.04
08181800	San Antonio Rv nr Elmendorf, TX	4528.458	2.79	16.99
08178565	San Antonio Rv at Loop 410, TX	296.773	10.98	14.98
08178000	San Antonio Rv at San Antonio, TX	109.8945	3.72	15.01



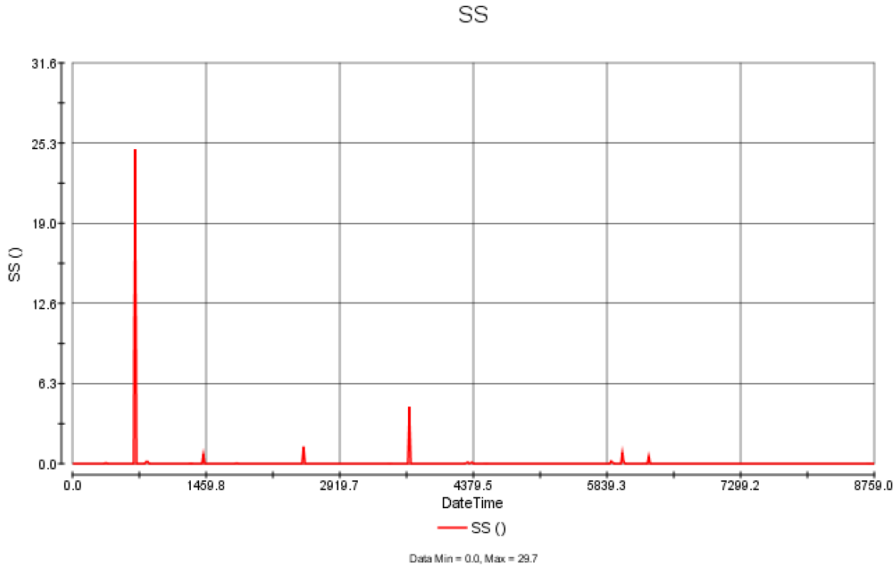


Then, the equations for determining the channel bottom width and channel side wall slope for the Guadalupe and San Antonio River basins are:

$$b_0 = 2.7\ DA^{0.382}$$
$$b_1 = 50\ DA^{-0.41}$$

where DA is the drainage area for the stream, and b_0 as well as b_1 are the trapezoidal cross section approximation parameters.

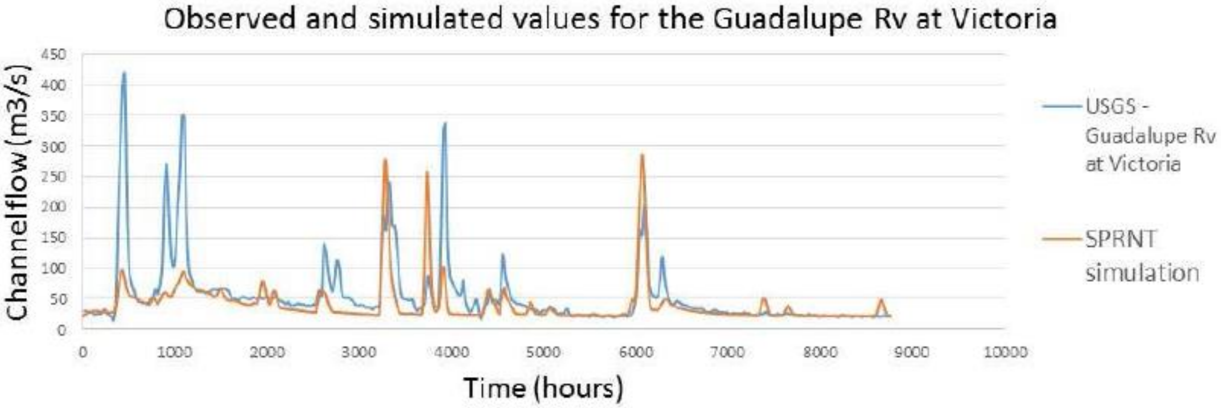
For our river network, the principal boundary conditions are surface and sub-surface runoff that occur both at the ultimate headwater and along all the streams in the study area. The surface and sub-surface runoff is collected from the Noah LSM in units of mm/hr. The multiplication of the individual catchment area, in units of km^2, and the values of the LSM provide the discharge value along the stream in that particular catchment area. Table 5 and Figure 8 show the surface and subsurface values for a particular catchment area.

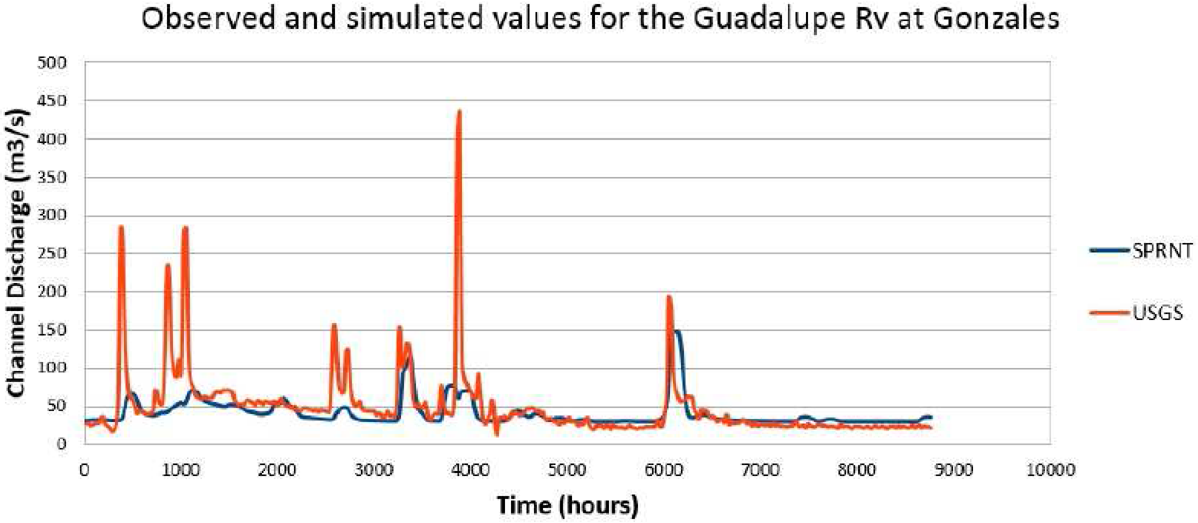


The initial conditions for the water surface level (related to the area by the cross sectional shape) and flow rate are calculated from the steady state from the Saint-Venant equations and the Chezy-Maning equation.

The information from the cross section, boundary conditions, initial conditions, channel roughness, and stream's bottom slopes is collected in the netlist, a set of defined block with river channel information as well as boundary and initial conditions.

Figures 9 and 10 show observed and simulated daily flow from January 2010 to December 2010 at the USGS streamflow measurement stations. In these figures, one can see the baseflow for each station as well as the peak flows generated by the lateral inflows/precipitation.





Due to use of initial values from the steady state Saint-Venant equations, the simulated results present a spin-up time, which is the time that requires the model to be no longer affected by the initial values or initial conditions. As seen from figures 9 and 10 the spin-up time is approximately from 3-4 months, where the peak flows are not well simulated. However, after the spin-up time, one can see a close agreement between peaks flows as well as baseflow for the USGS stations. Seasonal precipitation in this region causes alternated high and low water periods. Hydrographs of the upper part of the basin are noisy, with several peaks related to intense rainfall events. As the flood wave travels to the lower part of San Antonio and Guadalupe river basins, it is attenuated and delayed due to the storage of high volumes of water on the floodplain.

5. Conclusions

This work describes the development of a methodology to approximate channel cross sections for large scale hydraulic modeling. Additionally, this research present a validation for the physically based large-scale hydraulic SPRNT model in the San Antonio and Guadalupe river basins. The model results are able to reproduce observed hydrographs at different spatial scale from the USGS streamflow measurement stations in the study area.

However, while our cross section approximation for flow propagation in rivers is relatively complete, the description of floodplain dynamics is a continuation of the river description. Our approach does not fully reproduce what is actually happening in the floodplains

Finally, sources of model errors, which can be extrapolated to other similar large-scale models, were investigated by using model validation results. These errors may be related to input data (i.e. lateral inflows from the LSM, approximations in cross sections), and limitations of the hydraulic model itself. Nevertheless, results show that it is possible to employ fully dynamic hydraulic models within large-scale river networks even using limited data for river geometry.