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Ingeniería

Sensitivity Analysis for Regional Hydrological Modeling Using HEC-HMS Simulation Program and Geographic Information System in Tropical Watersheds

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Abstract *- The flood hydrograph estimation in a catchment is a significant parameter for water resources and conservation of water. Recently, the Geographic Information System (GIS) has become an efficient tool obtaining the watershed's physiographical and hydrological parameters.*

This work presents a sensitivity analysis used as test for the comparison between hydrological studies prepared using the common practice (watershed parameters calculated by hand) and the GIS integration as a newer practice in the water resources industry in tropical regions. The GIS model used was ESRI ArcMap, the ArcHydro tools and HEC-GeoHMS extensions, to determine the hydrologic parameters used in HEC-HMS model.

The investigation have proven that the use of GIS and the hydrologic tools improve the calculations of the Area and Curve Number parameters; in the case of the Lag time many factors influences the formula selection including the analyst expertise and historical equation selection.

Key Terms *- Geographical Information System, HEC-GeoHMS, Sensitivity Analysis, Tropical Watershed.*

INTRODUCTION

New innovation in hydrologic model and the incorporation of the most recent data available [1] in the local and federal agencies are key factors in the development of an up to dated hydrologic study. A combination between the hydrologic models and Geographic Information System (GIS) can offer numerous advantages [2] to the hydrologic studies accuracy [3] and mutual agreement in the delimitation of the hydrological parameters not only saves time and effort, but also improves accuracy over traditional methods. In this research the model used for the GIS analysis was Environmental System Research Institute's, Inc. (ESRI) ArcMap 9.3, the hydrology model used was the Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) version 3.5 and its hydrologic GIS extension, Hydrologic Engineering Center's Geospatial Hydrologic Modeling System (HEC-GeoHMS) version 5.0.

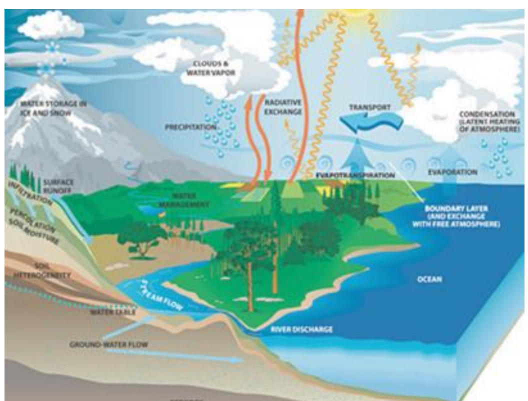


Figure 1 - Hydrologic Cycle

JUSTIFICATION

The digital hydrologic information as well as the available technology, the concern to improve the analysis and to introduce a practice that can be utilized as a standard in Puerto Rico's water resources industry, induced the motivation to present the methodology used in this research.

The GIS tool combined with the hydrologic models is becoming a common practice [4] in some of the states in the U S A, and Puerto Rico can be part of this group if the GIS analysis is recommended to be used in the water resources practice by the federal and the local agencies.

LITERATURE REVIEW

Hydrology is the science that encompasses the properties of the waters of the earth and their relationship with the environment within each phase of the hydrologic cycle (see Figure 1). The hydrological modeling is the representation of these processes using a single or multi-parameter mathematical model. These models can predict and determine hydrological parameters, which allow the good use of water resources [5] and usually are composed of three basic elements, equations that govern the hydrological processes, maps that define the study area and a database of numerical data that describes the study area and its parameters [6].

In the middle of the 1960s, hydrologic modeling involved the development of models and theories of individual components of the hydrological cycle, such as overland flow, infiltration and subsurface flow [7]. The first attempt to model virtually the hydrologic cycle was by the Stanford Watershed Model, a continuous hydrological model, now Hydrological Simulation Program Fortran, by Crawford and Linsley (1966). Another model that became really popular was the HEC-1, an event simulation program, originally developed in 1967 by Leo R. Beard and other members of the Hydrologic Engineering Center (HEC) staff.

The HEC-HMS computation engine draws on over 30 years experience with hydrologic simulation software. Many algorithms from HEC-1 (HEC, 1998), HEC-1F (HEC, 1989), PRECIP (HEC, 1989), and HEC-IFH (HEC, 1992) have been modernized and combined with new algorithms to form a comprehensive library of simulation routines [8].

The GIS tools development for hydrologic and hydraulic modeling at the HEC resulted from many years of interest in geospatial data usage. HEC earliest work was in the mid 1970's when the software concepts development was based on the Harvard University models. That early work culminated with the development of the Spatial Analysis Methodology. HEC and Dr. Maidment formulated a watershed data structure that would connect GIS and hydrologic models. [9]. In 1999 Dodson and Li found the automated floodplain delineation was more efficient and accurate compared to the traditional approach. The availability of the spatial data in digital formats acceptable for GIS analysis from government agencies has significant cost savings in terms of the initial data requirement for the GIS application. Also, many state and local government agencies maintain their own spatial data, which generally is available at higher resolution.

Sensitivity Analysis in Water Resources

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model can be apportioned to different sources of uncertainty in its inputs [10]. This analysis can be useful for a range of purposes [11] including, the testing the robustness of the results of a model in the presence of uncertainty and an increased understanding of the relationships between input parameters and results in a model. It is a common practice in water resources discipline that aids to determine the results variation due to a parameters disturbance associated to a mathematical model [12]. In HEC-HMS, an event hydrological simulation software, there are several parameters needed to set up for the storm simulation.

METHODOLOGY

The following information intends to explain the methodology used in this research.

Local Sensitivity Analysis

The Local Sensitivity Analysis is the simplest form of analysis and consists to simply vary one variable at the time in the model by a given amount, and examine the impact that the change has on the model output results, which can be shown graphically in a chart called the tornado diagram (see Figure 2).

The Relative Sensitivity analysis indicates which parameters are more sensible to model output results. The equation used to compute the relative sensitivity was [13]:

$$R_S = (\Delta O / O_i)/(\Delta P / P_i) \quad (1)$$

where;

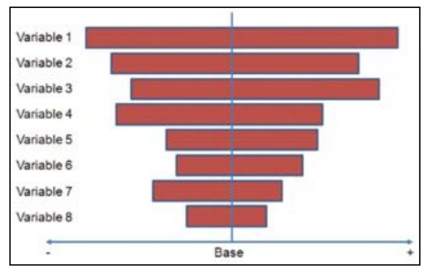
R_S = Relative Sensitivity,

ΔO = Change in Model Output Result;

O_i = Initial Model Output Result;

ΔP = Change in Input Parameter, and

P_i = Initial Input Parameter Value.



The Equation 1 is the numerical approximation of relative sensitivity (R_S) [13] and the result is a dimensionless value. The R_S negative value indicates an inverse correlation between the model output and the parameter input, and a positive value indicates a direct correlation.

Both relative analyses were calculated using the model's output, the peak flow, and three of the most important hydrological parameters, the CN, t_{lag} and watershed area represent a hydrologic characteristic in the analysis and each of them were selected to evaluate the specific effect they produce [14] in the HEC-HMS model. Each analyzed parameter was disturbed by ±10%, ±20% and ±30% while all other parameters were held constant.

Hydrologic Parameters Calculations

In the model development,

the first step involves getting basic watershed properties and delineating stream flows and watersheds. To get accurate results, it is necessary that the Digital Elevation Model (DEM) be preprocessed to take away any misleading elevation values along the main river channel. The DEM grid was processed with the ArcHydro tools, managed by HEC-GeoHMS extension menu, to delineate the watershed and stream network. Figure 3 illustrates the preprocessing in flow chart diagram.

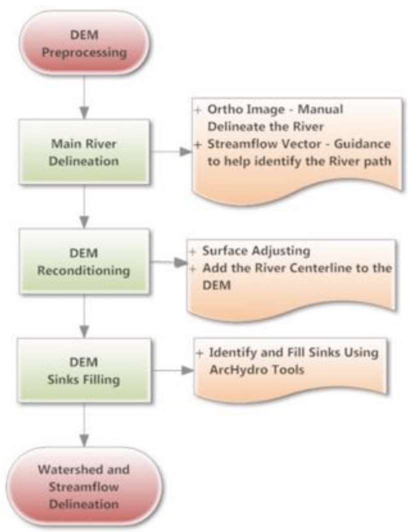


Figure 3 - DEM Preprocessing Flow Diagram

The final step of the process is using the defined points of analysis to delineate the sub-watershed assigned with each design point [15]. The HEC-HMS hydrologic model was used to estimate the peak discharge at the design points. Figure 4 illustrates step by step the hydrologic model development in flow chart diagram. The precipitation data used for the watershed evaluations was the same data used in the study cases. Surface runoff volume was estimated using the SCS CN method and the runoff hydrograph was constructed using the SCS Unit Hydrograph method [15].

CASE STUDIES

Two case studies were selected in order to compare the generated HEC-GeoHMS parameters and the HEC-HMS hydrologic model results. These hydrologic studies were prepared for the Puerto Rico Highway and Transportation Authority (PRHTA). The selected Case Study 1 is the "Hydrologic - Hydraulic study of Rio Bucarabones Substitution of the PR-861 Bridge, Toa Alta, P R", April 2002, prepared by GLMA for PRHTA project AC086112. For the Case Study 2 is "Hydrologic and Hydraulic Study for Culver Structure at Station 181+46 Corredor Del Oeste, PR-2, Phase 5B, Sector El Tuque, Ponce, PR", May 2003, prepared by IVA for PRHTA project AC200219.

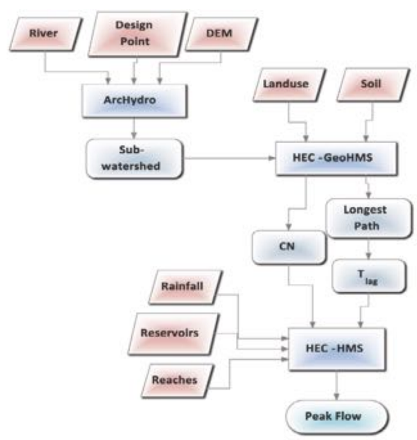


Figure 4 - Hydrologic Model Development Flow Diagram

CASE STUDIES DATA FOR THE ANALYSES

This section describes the data used for the sensitivity analysis, for the HEC-GeoHMS tools and the HEC-HMS model.

Sensitivity Analysis Data for Case Studies

The sensitivity analysis data for the case studies were extracted from the original studies only the flows were recalculated using HEC-HMS hydrological model.

In Case Study 1, two watersheds were delimited and named Watershed 1 and Watershed 2. The parameters of both are presented in Table 1.

Table1

Watersheds Parameters of Case Study 1		
Parameters	**Watershed 1**	**Watershed 2**
Precipitation [in]	11	11
Area [mi²]	1.32	0.704
CN	80.86	78.14
t_{lag} [min]	43.50	30.00
Flow [cfs]	3,577.90	2,395.60

In Case Study 2, a watershed was delimited and named TAREA in the HEC-1 model prepared by the consultant. The parameters of the watershed are presented in Table 2.

Table 2

Watersheds Parameters of Case Study 2	
Parameters	**TAREA**
Precipitation [in]	12
Area [mi²]	1.70
CN	69.00
t_{lag} [min]	55.80
Flow [cfs]	3,578.50

Case Studies-GIS Data for HEC-GeoHMS tools

The case studies GIS data was found, in general, at the United States federal agencies websites. In addition for local information, such as the land use, the Puerto Rico Governmental Geographic Data Portal was used. The horizontal datum of this information is decimal degrees, NAD83.

The data used for the case studies analysis was the following:

- National Elevation Dataset (NED) 30-meters, used as the raw DEM.
- Watershed Boundary Dataset (WBD)
- Soil Survey Spatial and Tabular Data
- Digital Raster Graphic County Mosaic (DRG)
- Land Use Data

Case Studies - Parameters for HEC-HMS Hydrological Model

The HEC-HMS parameters were obtained directly from the results of the HEC-GeoHMS analysis. The tools defined the watersheds areas, the CN, longest path and slopes for the tlag calculation. The lag time calculation methods used for the case studies are the SCS Lag for Case 1 and the Velocity Method for Case 2.

CASE STUDIES SENSITIVITY ANALYSIS

For both studies a local (tornado charts) and relative sensitivity analyses were performed to determine which parameters have the greatest influence on the HEC-HMS hydrologic model results.

Case Study 1: Local and Relative Sensitivity Analysis

The Watershed 1 results for the local sensitivity analysis (Figure 5) shows that the CN is the parameter that produces the greatest flow disturbance values by decreasing the parameters. The Area and t_{lag} produced the second and third greatest disturbance in the decreasing side of the parameters change respectively. The results produced by increasing the parameters shows that the Area is the parameter producing the greatest flow disturbance, in addition the model results react in a linear way in both sides of the parameter change. The CN produced the second and the tlag the third greatest disturbance in the model results. These parameters produce more flow disturbance when they are reduced than increased. In addition the maximum CN value that can be used in HEC-HMS model is 99 that represents the original CN plus a 23% increment for this watershed. Because of the methodology involved in the SCS and in the model as well, a value of 106 representing the original CN with the 30% increment does not exist in the CN range. This situation applies in both the local and relative sensitivity analyses.

In a similar way the R_S results in Table 3 have a behavior analogous to the tornado charts in Figure 5. The higher R_S results produced are the ones related to the reduction of the CN. The second and third parameters that produce the greatest values in relative sensitivity are the Area and t_{lag} respectively. The change in Area produce R_S values similar to each other, meaning that the Area is the most important input parameter with the relative sensitivity values not changing significantly with the parameter disturbance [13].

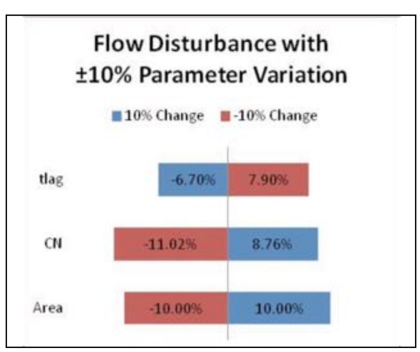
Table 3

Relative Sensitivity Results Case Study 1 - Watershed 1

Parameter Variation %	R_S Area	R_S CN*	R_S tlag
-30%	1.000028	1.299680	-0.959501
-20%	1.000028	1.217991	-0.865033
-10%	1.000028	1.113890	-0.789569
10%	0.999748	0.885349	-0.669946
20%	0.999888	0.684069	-0.623690
30%	0.999935	0.625890	-0.583117

*CN - Parameter variation from -30% to 23%, Max. CN = 99

In addition as confirmed in the calculations of R_S, the analyzed parameters increment the disturbance of the model flow results when the values are reduced. In addition the negative values of the t_{lag} represent an inverse correlation with the model's peak flows results.



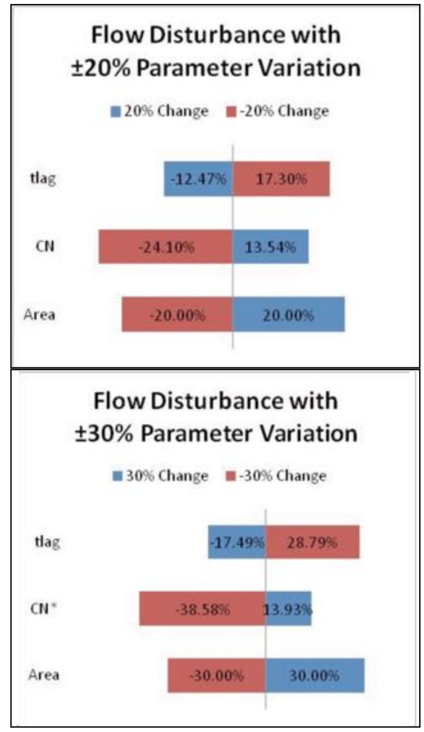


Figure 5 - Sensitivity Analysis Tornado Charts for Case Study 1 - Watershed 1

The Watershed 2 local and relative sensitivity results have the same behavior as the Watershed 1. Figure 6 and Table 4 show the local and relative sensitivity the results.

Table 4

Relative Sensitivity Results Case Study 2 - Watershed 2

Parameter Variation %	R_S Area	R_S CN*	R_S tlag
-30%	1.000028	1.348141	-0.886486
-20%	0.999958	1.272840	-0.811070
-10%	1.000167	1.194930	-0.746368
10%	1.000167	0.951985	-0.641175
20%	0.999958	0.787689	-0.599432
30%	1.000028	0.659712	-0.562698

*CN - Parameter variation from -30% to 27%, Max. CN = 99

Similar to Watershed 1, in Watershed 2 was calculated a maximum increment of 27% in the CN parameter because a value of 102, that represents the CN with the 30% in change in Watershed 2, does not exist in the method and cannot be used in the model.

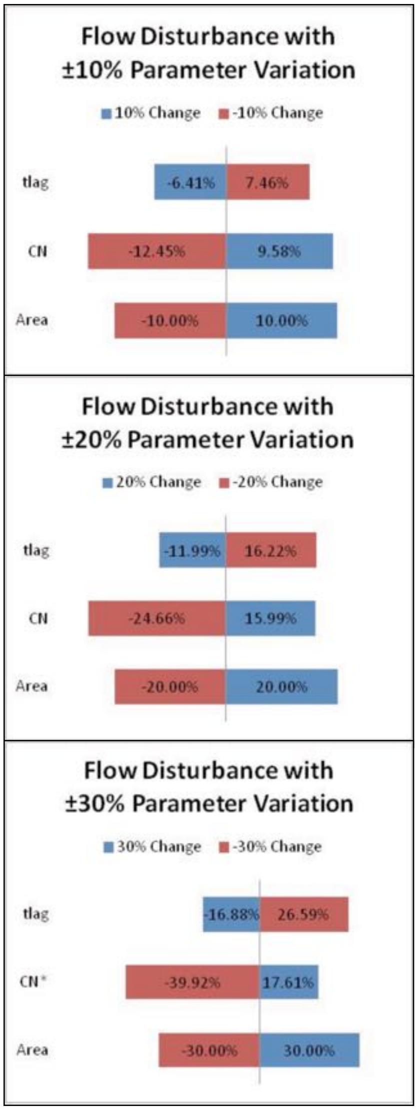


Figure 6 - Sensitivity Analysis Tornado Charts for Case Study 1 - Watershed 2

Case Study 2: Local and Relative Sensitivity Analysis

The results of the local sensitivity analysis using the tornado charts in Figure 7 illustrate that the CN is the parameter that produces the greatest flow disturbance values by reducing the parameters. The Area and t_{lag} produced the second and third greatest disturbance in the model's results in the decreasing side of the parameters change respectively. The results produced by increasing the parameters shows that the CN is the parameter producing the greatest flow disturbance until the 30% parameter variation where the Area is the parameter which produces the greatest flow disturbance. The Area produced the second greatest disturbance at the 10% and 20% of parameter variation and the t_{lag} the third. The CN and the t_{lag} parameters produce more flow disturbance when reduced than increased. In addition the model results react in a linear way in both sides of the Area parameter variation.

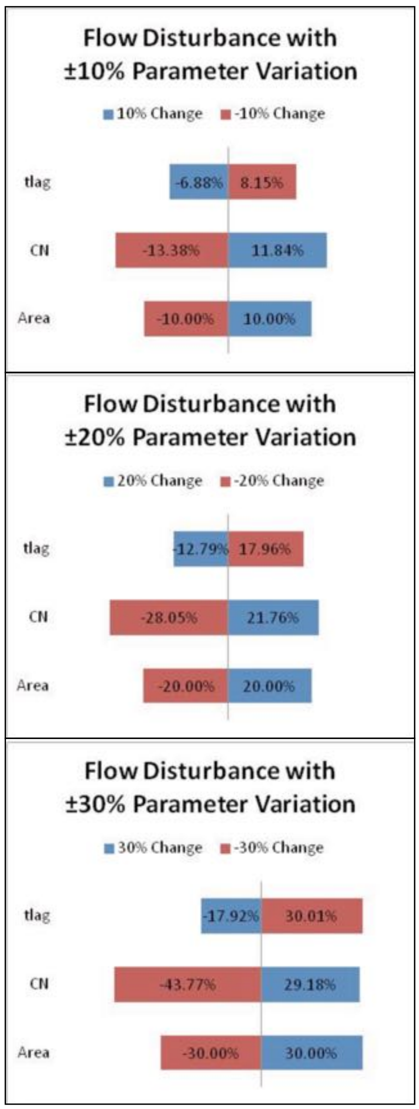


Figure 7 - Sensitivity Analysis Tornado Charts for Case Study 2

The R_S results in Table 5 have a behavior analogous to the tornado charts in Figure 4.3. The higher R_S values produced are the ones related with the reduction of the CN and its increment until the 30% of the parameter variation. The Area is the second and the tlag is the third parameter that produces the greatest values in relative sensitivity. The change in Area produce R_S values similar to each other, meaning that the Area is the most important input parameter with the relative sensitivity values not changing significantly with a change in Area [13], but in this case the parameter producing the higher disturbance in most of the parameter variation percentages is the CN.

As confirmed in the calculations of R_S, the CN and tlag parameters increment the disturbance of the model's results when the values are reduced, but in the case of the Area the parameter produces a constant effect in the R_S behavior in both sides of the parameter variation.

Table 5
Relative Sensitivity Results Case Study 2

Parameter Variation %	R_S Area	R_S CN	R_S tlag
-30%	0.999935	1.438171	-1.000214
-20%	1.000028	1.382628	-0.898041
-10%	1.000028	1.319280	-0.815334
10%	1.000028	1.167522	-0.688480
20%	1.000028	1.072225	-0.639582
30%	1.000028	0.958750	-0.597204

CASE STUDIES HEC-GEOHMS AND HEC-HMS RESULTS COMPARISON

The parameters compared in the analysis were the Area, CN and tlag from the original hydrologic studies and the ones calculated with HEC-GeoHMS tools and the flow results associated with each set of parameters in HEC-HMS models.

Case Study 1: Results Comparison

Comparing Watershed 1 results in Table 6, the greatest parameter difference produced is in the t_{lag}; the second and third greatest differences are the Area and the CN respectively. All of these parameters presented an increment from the original study parameters. The HEC-HMS flow produced with the HEC-GeoHMS parameter is 4.18% less than the original study flow result. In this case the combination of the HEC-GeoHMS parameters variation produced a small effect in the flow comparing the result to the original study. The negative sign presented in the variation column of the table is to identify a reduction from the original study results.

Table 6

Parameters and Results of Case Study 1: Watershed 1

Parameters	Original Study	HEC-GeoHMS	Variation
Area [mi^2]	1.32	1.5265	15.64%
CN	80.86	82.78	2.37%
T_{lag} [min]	43.50	57.866	33.03%
Flow* [cfs]	3,577.90	3,428.40	-4.18%

*Flow was calculated using HEC-HMS hydrologic model.

For the Watershed 2 results in Table 7, the greatest parameter difference produced is in the t_{lag}; the second and third greatest differences are the Area and the CN respectively. The Area and tlag presented an increment and the CN presented a reduction from the original study parameter. In addition the HEC-HMS flow produced with the HEC-GeoHMS parameter is 21.88% less than the original study flow result, representing a significant change with respect to the original output. In this case the effect of the t_{lag} increment in the HEC-GeoHMS parameters produced a significant reduction in the HEC-HMS result.

Table 7

Parameters and Results of Case Study 1: Watershed 2

Parameters	Original Study	HEC-GeoHMS	Variation
Area [mi^2]	0.704	0.7179	1.98%
CN	78.14	75.50	-3.38%
T_{lag} [min]	30.00	41.683	38.94%
Flow* [cfs]	2,395.60	1,871.40	-21.88%

*Flow was calculated using HEC-HMS hydrologic model.

Illustrated in Figure 8 are Watershed 1 and Watershed 2 areas delimitation from the Original study (top) and the HEC-GeoHMS tools (bottom). In the figure it can be seen that the Watershed 1 area from the HEC-GeoHMS analysis extend more to the south than the Original study area making it 15.64% bigger as presented in Table 6. In the case of Watershed 2 the areas are almost the same size with an incremented difference of 1.98% between the HEC-GeoHMS analysis and the original study.

Case Study 2: Results Comparison

Comparing the results for TAREA watershed in Table 8, the greatest parameter difference produced is in the t_{lag}; the second and third greatest differences are the CN and the Area respectively. All of these parameters presented a reduction from the original study parameters. In addition HEC-HMS flow produced with the HEC-GeoHMS parameter is 38.00% more than the original study result. Comparable to the Case 1: Watershed 2 the increment in the HEC-GeoHMS's t_{lag} in this case produced a significant reduction in the HEC-HMS result.

Table 8
Parameters and Results of Case Study 2: TAREA Watershed

Parameters	Original Study	HEC-GeoHMS	Variation
Area [mi^2]	1.70	1.6548	-2.66%
CN	69.00	62.60	-9.28%
T_{lag} [min]	55.80	30.017	-46.21%
Flow* [cfs]	3,578.90	4,939.00	38.00%

*Flow was calculated using HEC-HMS hydrologic model.

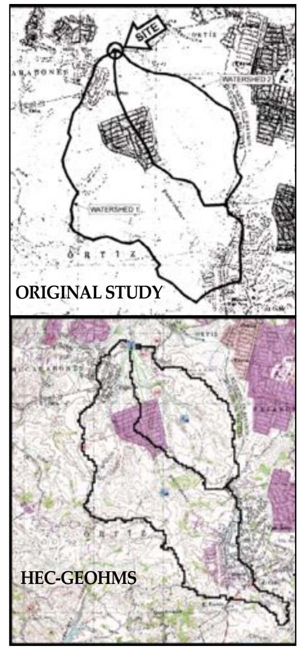


Figure 8 - Case Study 1: Original Study and HEC-GeoHMS Watershed 1 and Watershed 2 Area Delimitation

Figure 9 illustrates the TAREA watershed area delimitation from the Original study (top) and the HEC-GeoHMS tools (bottom). The figure can be seen that the watershed area delimitation is similar to each other with only a 2.66% reduction between the HEC-GeoHMS analysis and the original study.

Figure 9 - Case Study 2: Original Study and HEC-GeoHMS Watershed Area Delimitation.

PARAMETERS VARIATION ANALYSIS IN HEC-HMS MODEL BEHAVIOR

The Area, CN and t_{lag} parameters local variations modify the HEC-HMS behavior in different ways. This section intends to explain how each analyzed parameter affects the model results.

Variations in Area

The parameter variation, as illustrated in the tornado charts in Figures 5, 6 and 7, produces a linear effect in the model results in the watersheds analyzed. The percentage of change in flow produced in the model results, as presented in the Case Studies Sensitivity Analysis section, is equivalent to the percentage of variation in the parameter. For example, if the Area increases 20% from its original value, the flow will have an increment of 20% from its original value, meaning that the change in percentage of the model flow results have a relationship directly proportional to the percentage of variation in Area. The Area R_S results presented in Tables 3, 4, and 5 confirms that with every change in the Area will be a change in the flow results similar or equal to the percentage of change in the parameter. The results of Area's R_S for the watershed analyzed are close or equal to 1 meaning that the percent of change in Area ($\Delta P/Pi$), as presented in the Equation (1), and the resulting change in flow percentage ($\Delta O/O_i$) are equal or similar.

Variations in CN

The CN variation produces a relationship directly proportional to the HEC-HMS model result but not as linear as the variation in Area. As illustrated in Figures 5, 6 and 7, the parameter increments produce an increment in the flow results and a flow reduction when the parameter is reduced. But in the case of the CN, the parameter variations in the reducing perturbation present more disturbances in the flow results with respect to the incrementing perturbation and the more the reduction, the more is the disturbance; meaning that underestimating the CN causes further reduction in the model's results.

As presented in Tables 3, 4, and 5, the Curve Number R_S values affirm that the more the parameter is reduced the more disturbance in the flow results occurs. In the analyzed cases the RS resulting values are greater than 1 at the CN reduction side, meaning that the resulting flows percentage of change are greater than the percentage of change of the CN ($\Delta O/O_i > \Delta P/P_i$). In the other hand at the increasing side of the CN, in most of the analyzed cases, the flow result has an inverse behavior, with values less than 1 meaning that the resulting flows percentage of change are less than the percentage of change of the CN ($\Delta O/O_i < \Delta P/P_i$).

In Case 2 the CN presented a variation different from the Case 1 sensitivity analysis. At the 10% and 20% of the positive variation of the parameter the CN dominates the flow disturbance over the Area. It was found that in the cases where the CN is in the lowest sixties (<65) the parameter dominating the results disturbance in the model is the CN. In addition when the CN tends to be over the eighties (80 >), the parameter dominating the flow disturbance in the positive side of the variations is the Area.

Variations in t_{lag}

The variation in the t_{lag} produces an inverse proportional relationship proportional to the HEC-HMS model results. As illustrated in Figures 5, 6 and 7, the parameter increment produces a reduction in the flow results and a flow increment when the parameter is reduced. This relationship can be identified in the tornado charts by the negative flow percentages in the incrementing side of the parameter and the positive percentages in the reducing side of the parameter variation. The t_{lag} produces more disturbances in the flow results when the parameter is reduced than when is increased and underestimating the t_{lag} causes further increment in the model's results.

The Lag time R_S values, in Tables 3, 4, and 5, confirms that the more the parameter is reduced, the more disturbance in the flows results. In most of the analyzed cases the RS resulting values are less than 1 at both sides of the parameter variation, meaning that the resulting flows percentage of change are less than the percentage of change of the t_{lag} ($\Delta O/O_i < \Delta P/P_i$). Only in Case 1: Watershed 1 and in Case 2 at the 30% reduction of the parameter the R_S value is similar to 1, meaning that for these cases that variation percentage in the t_{lag} and the resulting change in flow percentage are equal or similar to each other ($\Delta P/P_i \approx \Delta O/O_i$).

It is important to mention that the tlag was the parameter presenting the greatest difference between the original study and the ones calculated using HEC-GeoHMS tools and this parameter influences the results significantly. In common practice, the t_{lag} computation methodology is defined by the water resources engineer, who decides which formula will use to calculate it. Is for this reason that available information and tools as well as professional criteria helps the engineers to make the right decision.

CONCLUSIONS AND FUTURE WORK

Recent works to determine the hydrologic parameters of a watershed using the GIS have proven to be a useful help to the water resources discipline that can be used for more efficient and accurate results. This research use the GIS hydrologic tools in tropical watersheds in order to provide results comparable to the common practice currently used. Also the sensitivity analyses performed provided important feedback in the model's behavior, in how the parameters variations can affect the results. In this research two hydrologic and hydraulic studies from the PRHTA were selected as study cases to be analyzed using ArcMap 9.3, HEC-GeoHMS (ver. 5.0) and HEC-HMS (ver. 3.5), paying particular attention to the watersheds Area, CN and tlag parameters produced with the GIS tools.

The ArcMap/HEC-GeoHMS GIS tools exhibit a great performance in the Area and CN parameters extraction for the studied cases. The lowest and highest difference between the original studies and the GIS tools parameters of the analyzed cases were the Area in Case 1: Watershed 2 with a parameter increment of 1.98% and 15.64% in Case 1: Watershed 1 respectively; for the CN in Case 1: Watershed 2 with a parameter increment of 2.37% and a reduction of 9.28% in Case 2: TAREA watershed respectively.

The t_{lag} parameter presented its lowest difference in Case 1: Watershed 1, with a parameter increment of 33.03% and its highest difference in Case 2: TAREA watershed, a reduction of 46.21%. The t_{lag} showed considerable variations from the original studies values, in which this variation are directly dependent of the methodology and formulae selected for its calculations.

Future work ideas emerged during the research that can improve the hydrologic analyses An idea that arose as part of the t_{lag} results variations is the development of a research methodology that focuses in the best selection of that formulae used to determine the lag time. The proposed research could be applied to the different areas of the island of Puerto Rico where hydrological conditions are different in order to create a database that can provide better parameter estimation. Another future work that sprang when the GIS layers were selected was to update the land use database of the Island for the hydrologic studies to come.

REFERENCES

[1] Maidment, D. R. (2002). Arc hydro: GIS for water resources. Redlands, Calif.: ESRI Press.

[2] Ogden, Fred L.; Garbrecht, Jurgen; DeBarry, Paul A.; and Johnson, Lynn E., "GIS and Distributed Watershed Models II" (2001). Publications from USDA-ARS / UNL Faculty. Paper 461.

[3] Charnock, T. (1996). Linking Multiple Process Level Models with GIS. Application of geographic information systems in hydrology and water resources management: proceedings of the HydroGIS'96 conference held in Vienna, Austria, from 16 to 19 April 1996 (pp. 29-36). Wallingford, Oxfordshire: International Association of Hydrological Sciences.

[4] Li, Z., & Zhang, K. (2008). Comparison Of Three GIS-Based Hydrological Models. Journal of Hydrologic Engineering, 13(5), 364.

[5] McCulloch, J. (1984). Hydrologic Modeling Of Small Watersheds Haan, C. T., Johnson, H. P. And Brakensiek, D. L. (Eds). ASAE Monograph No. 5, American Society Of Agricultural Engineers, Michigan, 1982, 533 Pp. Agricultural Systems, 13(2), 123-124.

[6] Maidment, D.R., 1993. "GIS and Hydrologic Modeling". An: Environmental Modeling with GIS. Ed. Goodchild, M.F., Parks, B.O., Steyaert, L. New York: Oxford University Press

[7] Singh, V. P., & Woolhiser, D. A. (2002). Mathematical Modeling Of Watershed Hydrology. Journal of Hydrologic Engineering, 7(4), 270.

[8] U.S. Army Corp of Engineering (USACE), HEC-HMS technical reference manual, 2010.

[9] U.S. Army Corp of Engineering (USACE), HEC-GeoHMS user's manual, 2010.

[10] Saltelli, A. (2008). Global sensitivity analysis: the primer. Chichester, England: John Wiley.

[11] Pannell, D. (1997). Sensitivity Analysis Of Normative Economic Models: Theoretical Framework And Practical Strategies. Agricultural Economics, 16(2), 139-152.

[12] Crosetto, M. (2001). Uncertainty and sensitivity analysis : tools for GIS-based model, 15(5), 415–437.

[13] McCuen, R. H., 2002. "Modeling Hydrologic Change". Lewis Publishers, Florida, USA.

[14] Chang, Chi-Wen, "Application of SCS CN Method in HEC-HMS in ShihMen Watershed - Simulation of Rainfall-Runoff Hydrologic Model" (2009). Electronic Theses, Treatises and Dissertations. Paper 3900.

[15] Baumann, C.A., Halaseh, A.A., P.E, (2011). Utilizing Interfacing Tools for GIS, HEC-GeoHMS, HEC-GeoRAS, and ArcHydro. World Environmental and Water Resources Congress 2011 Bearing Knowledge for Sustainability R. Edward Beighley II & Mark W. Killgore, Editors, (p. 1953 – 1962). Reston: American Society of Civil Engineers.