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MEDELLÍN-ABURRÁ RIVER STREAMFLOW AND FLOOD ANALYSIS MODEL FOR ITS STREAM RESTORATION PROPOSAL

Andrés Felipe Marín Muñoz[1]
Juan Fernando Barros Martínez[2]

ABSTRACT

The basin of Aburrá-Medellín River is located at the central range, in the center of the department of Antioquia. The river is born in the Alto de San Miguel at the Caldas municipality and it goes through 10 municipalities until it finally merges with Grande River, where it changes its name to Porce River.

The stretch of Aburrá-Medellín River included between the source and its entrance to the Caldas municipality has suffered severe degradations of its natural conditions due to the exploitation of construction material. It has also affected resource availability and its quality.

The project aims to formulate river restoration alternatives for some stretches of Medellín River that present elevated levels of anthropic affectation. For the hydrologic and hydraulic analyses, HEC-HMS, HEC-RAS and Iber programs were used as technical support to establish the restoration measures. The results of this project will help as support for other major projects such as the POMCA, Bio 2030 project and Medellín River Park..

KEYWORDS: Hydraulic modeling; Hydrologic modeling; River restoration.

MODELACIÓN DE TRÁNSITO DE CRECIENTES EN EL RÍO ABURRÁ-MEDELLÍN PARA UNA PROPUESTA DE SU RESTAURACIÓN

RESUMEN

La cuenca del río Aburrá-Medellín está localizada sobre la cordillera central, en el departamento de Antioquia. El río nace en el Alto de San Miguel en el municipio de Caldas y atraviesa 10 municipios hasta finalmente unirse con el río Grande, donde cambia de nombre a río Porce.

El tramo del río Aburrá-Medellín comprendido entre el nacimiento y su entrada al municipio de Caldas ha sufrido grandes alteraciones en sus condiciones naturales debido a la explotación de materiales para construcción. También se

[1] Ingeniero Civil, Universidad EIA, Joven Investigador Colciencias, MSc (c) en Hidroinformática, Erasmus+ Euroaquae.

[2] Ingeniero Civil, Universidad EIA, MSc en Hidráulica Universidad Nacional de Colombia, PhD en Educación, Universidad de Antioquia.

Author's Mailing Address: Marín Muñoz A.F. (Andrés Felipe): Calle 47 N° 42 – 60 Apt. 2501, Medellín, Colombia: / Tel.: (4) 300 524 90 99
Correo electrónico: anmamun71@gmail.com

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ha visto afectado por la deforestación de su cuenca y la introducción de fauna no nativa que han afectado la disponibilidad del recurso y su calidad.

El proyecto tiene como objetivo formular alternativas de restauración para algunos tramos del río Medellín que presentan un alto grado de afectación antrópica. Para el análisis hidrológico e hidráulico se utilizaron los programas HEC-HMS, HEC-RAS e Iber como soporte técnico para establecer las medidas de restauración. Se espera que los resultados de este proyecto sirvan como apoyo para otros de mayor alcance como el POMCA, el proyecto Bio 2030 y los Parques del Río Medellín.

PALABRAS CLAVES: Modelación hidráulica; modelación hidrológica; restauración de cauces.

MODELAGEM DE TRÂNSITO DE CRESCENTES NO RIO ABURRÁ-MEDELLÍN PARA UMA PROPOSTA DE SUA RESTAURAÇÃO

RESUMO

A bacia do rio Aburrá-Medellín está localizada sobre a cordilheira central, no departamento de Antioquia. O rio nasce no Alto de San Miguel no município de Caldas e atravessa 10 municípios até finalmente juntar – se com o rio Grande, onde muda de nome a rio Porce.

O trecho do rio Aburrá-Medellín compreendido entre o nascimento e sua entrada ao município de Caldas tem sofrido grandes alterações em suas condições naturais devido à exploração de materiais para construção. Também se viu afetado pela desflorestação de sua bacia e a introdução de fauna não nativa que têm afetado a disponibilidade do recurso e sua qualidade.

O projeto tem como objetivo formular alternativas de restauração para alguns trechos do rio Medellín que apresentam um alto grau de afetação antrópica. Para a análise hidrológico e hidráulico utilizaram-se os programas HEC-HMS, HEC-RAS e Iber como suporte técnico para estabelecer as medidas de restauração. Espera-se que os resultados deste projeto sirvam como apoio para outros de maior alcance como o POMCA, o projectoBio 2030 e os Parques do Rio Medellín.

PALAVRAS-CHAVE: Modelagem hidráulica; Modelagem hidrológica; Restauração de canais.

1. INTRODUCTION

The streamflows and floods in a river are studied from hydrologic and hydraulic factors. The river rise introduces a variation in the flow which travels along the natural or artificial channel. In order to represent a flood event, computer information tools have been developed, such as the HEC-HMS model, used to analyze hydrological factors. Meanwhile, models HEC-RAS 5.0 (beta version of the improved model in October 2014) and Iber 2.2 are used to analyze hydraulic factors under one or two-dimensional flow conditions. The hydraulicmodel enables the design of hydraulicworks or modifications in the stream flow in order to improve flow conditions in natural or artificial channels.

Taking into account that until now there has been no development of any research or technical project on the Aburrá-Medellín River for the purpose of streamflow restoration, this current project expects to mark a guideline in the sense of fostering the possibility of management of the river more in tune with the ecological biodiversity and social well-being of the populations near the river. The

SITE (Sustainability, Infrastructure and Territory) research group, subscribed to the EIA University, has developed several international projects oriented toward the restoration of streamflows and has been nourished from international projects developed in other countries.

The restoration of river flowis supported on the results obtained in the hydraulic models for the river rising scenarios in the stretches studied. Restoration methods were designed for a stretch located in the lower part of the basin where the streamflow conditions showed an improvement according to the established reference conditions. Also, analysis alternatives were raised in the remaining stretche.

2. METHODOLOGY

The project was developed in four consecutive processes. The first consisted of a collection of base information, according to its availability and usefulness. Subsequently, the hydrologic and hydraulicmodels were created, based on the extreme events selected. Finally, a design of the restoration methods for the specific needs of the stretch was proposed.

The project has cartographic, hydrological and hydraulic information available in the environmental corporations affiliated to the Aburrá-Medellín River (Valle de Aburrá Metropolitan Area, Corantioquia and Cornare), as well as secondary information of studies made by Medellín Public Works (Empresas Públicas de Medellín – EPM), Agustín Codazzi Geographical Institution (Instituto Geográfico Agustín Codazzi - IGAC), the Early Alert System of the Aburrá Valley (Sistema de Alerta Temprana del Valle de Aburrá - SIATA) and the Institute of Hydrology, Meteorology and Environmental Studies (Instituto de Hidrología, Meteorología y Estudios Ambientales - IDEAM). The processing of cartographic and hydrologic information available was supported on geographical information programs such as ArcGIS and HidroSIG and the detailed information for the analysis of streamflows of river rising and floods was processed from the AutoCAD Civil 3D drawing tool and the HEC-RAS 5.0 and Iber 2.2 hydraulic models.

The hydrologic model presents two methodologies. The first uses the basic information to obtain the delimitation of the basin and the average flows from the long term hydric balance for each length of the study in the Aburrá-Medellín River. The second model corresponds to obtaining increasing flows though run off-rain methods for the stretches of interest and verified from the secondary information of the Plan for the Management and Organization of the Aburrá River Basin (Plan de Manejo y Ordenación de la Cuenca del río Aburrá - POMCA) and information from the water level recording stations supplied by EPM.

The base information to obtain the flow through long term water balance is a digital elevation model of the terrain of the entire Aburrá-Medellín River basin obtained from the Nasa *Shuttle Radar Topography Mission* (SRTM), a medium precipitation map and an evaporation-transpiration map obtained from POMCA. The digital models' scale is 30 m X 30, pixel size. The results of the delimitation of the stretches of interest and their respective subbasins are shown in **Figure 1**.

Figure 1 shows the delimitation of the Aburrá-Medellín River basin with the 4 zones with similar geomorphological characterization, to the left (flat coordinates system - MAGNA SIRGAS Colombia Bogota central zone) and the delimitation of the micro basins of the stretches studied to the right (spherical coordinates system WGS 1984). **Table 1** shows the point that delimits the stretches studied.

The base information to obtain the flow through long term water balance varies according to the methodology used. Since run off-rain methods were used, the base information corresponds to the Intensity-Duration-Frequency curve (IDF) of 17 pluviograph stations located inside the basin, the morphological characteristics of the basin in order to obtain the time of concentration and the approximate transit time for each of the stretches of interest, the geomorphological characteristics obtained by POMCA and, types and uses of soil from IGAC to obtain response conditions of the basin when facing extreme rainfall events such as infiltration and run off, the curve number and the antecedent humidity of the soil. The detailed hydrological tank model for the calculation of extreme flows of the Aburrá-Medellín River basin is shown in **Figure 2**.

There was a comparison made of the results obtained from the stretches of hydrological floods with HEC-HMS against the recovered information from EPM and POMCA. The latter contained the calculation of extreme flows from statistical methods of 10 water level recording stations in the Aburrá-Medellín River with their respective middle flows and flows of 2,33 and 100-year return period.

Figure 1. Delimitation of the Aburrá-Medellín River basin

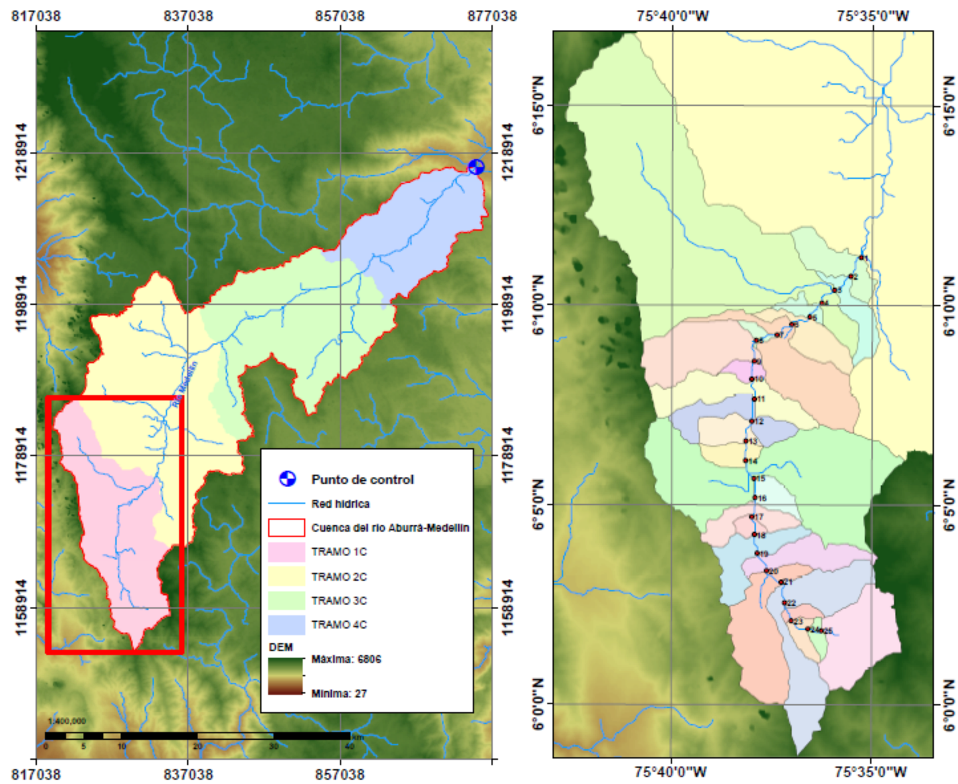
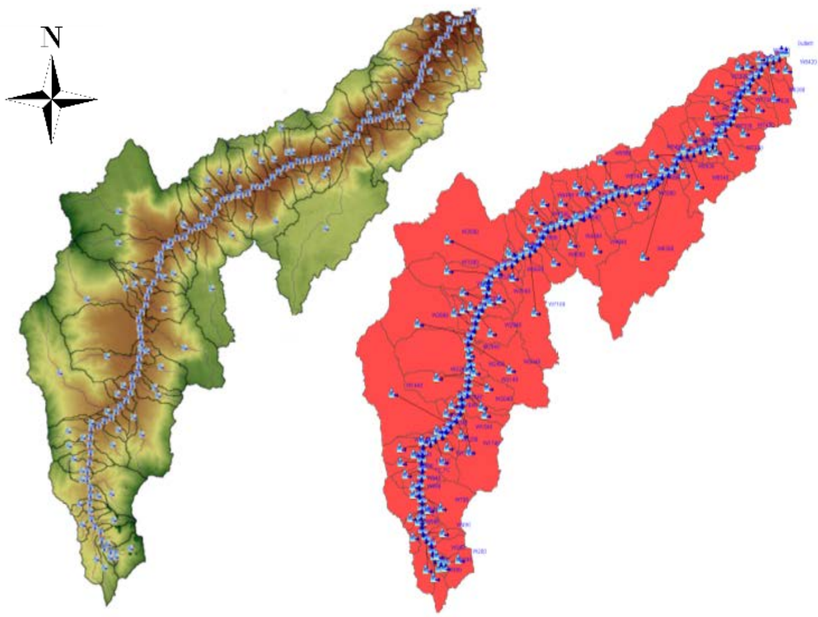


TABLE 1. LOCATION OF DELIMITATION POINTS OF STRETCHES STUDIED

Point	Abscissa (m)	Coordinates (m)		Location description
		East	North	
1_1C	27.500	832.826	1’176.114	500 m waters above the crossing with the La Ayura ravine
1_2C	52.900	841.000	1’194.000	Entrance to the Copacabana city urban center
1_3C	78.400	859.889	1’203.130	1,5 km water above the Barbosa city urban core
1_4C	95.600	874.887	1’216.960	Crossing with Río Grande – 0,8 km waters above the Gabino Bridge

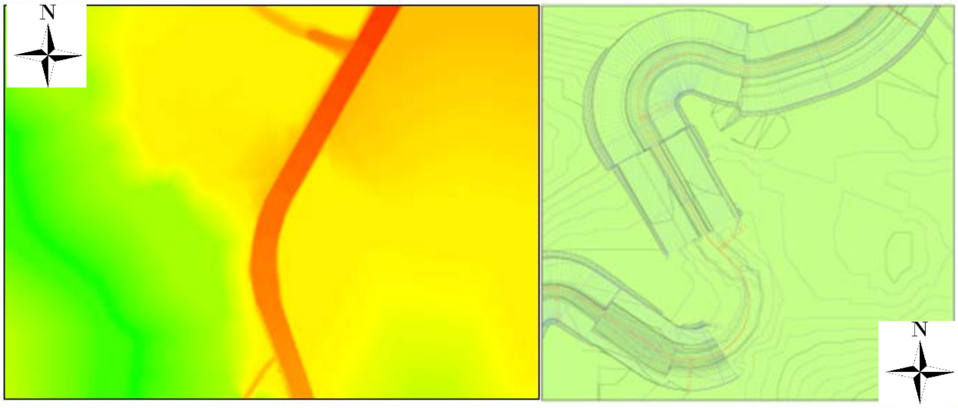
Figure 2. Hydrological Model with the HEC-GEOHMS (left) and HEC-HMS (right)



After obtaining the base flow (hydric balance) and the verified flood flow (run off-rain model), different critical events were modeled using the flows obtained from two tools for the purpose of comparing the results. These were HEC-RAS and Iber, which solve the Saint Venant equation for finite columns to reach a result on each information point. The first solves it implicitly, which speeds processing time, while the second does this explicitly, having to solve the equations for all cells until reaching a convergence point. With these, a one-dimensional (1D) and two-dimensional (2D) analyses were performed, respectively. The base information used in both tools is the same, the only difference being the methodology used to obtain the results. Geomorphology was used to obtain field visits and photographs of the channel. Also, there was use of detailed topography of the riverflow of the Aburrá-Medellín River on a 1:2.000 scale for the stretch between the Ayura ravine and Ancon Sur, as well as some small zones between the Girardota Bridge and the El Hatillo Bridge, transversal sections characteristic of several river points along the entire channel and a detailed digital elevation model of the river between its origin and the township of La Clara in the municipality of Caldas. An example of the available topography is shown in **Figure 3**. Finally, the river's average flow and the hydrograph of the flood were used for the generation of scenarios and the calibration of the model. The stretches calibrated were modeled under permanent flow conditions for the purpose of obtaining values required to design restoration methods.

The hydraulic model was complemented with the AutoCAD Civil 3D drawing tool for the processing of the topography, the generation of the profile and river sections that were later exported to the HEC-RAS in Tiff format (*Tagged Image File Format*), where the Manning coefficient was added, as well as the initial and surrounding conditions.

Figure 3. Topography stretch Channeled in ArcGIS (left) and Girardota in AutoCAD (right)



The hydraulic model with Iber used the same Tiff format image used for HEC-RAS but this time it was exported to an ASCII (*American Standard Code for Information Interchange*) format from ArcGIS, since the format is more stable for data entry on Iber and the creation of the MDT (Digital Model of the Terrain), RTIN *Rectangular Triangulated Irregular Network*) or as a net of information. Upon inputting the topography, it should have been processed and fractioned in different sizes according to the optimum detail for each zone for the purpose of improving processing time. Finally, as with HEC-RAS, the Manning coefficient was added, as well as the initial and surrounding conditions that had to have been identical for both cases for the purpose of enabling the subsequent result comparison.

The comparison of the hydraulic models enabled the selection of the model that would deliver results with greater reliability an under the best processing conditions.

The Hydraulic model was calibrated under non permanent flow conditions along the stretches in which there was enough information from water level recording stations, as well as pluviograph and topography stations. The stretch with the greatest compilation of information was the one between Girardota and El Hatillo, which had transversal sections of the Aburrá-Medellín River. This stretch also had water and flow values which enabled a calibration of the event with 4 extreme historical events between 2007 and 2011.

The calibrated stretch was used to model the average flow stretches, 2,33 and 100 years, for the purpose of obtaining input parameters for the design of restoration measures. The parameters obtained for each flow were flow altitude, wet width, Froude number, flow speed and bottom tension (critical diameter).

Another necessary variable for the design of restoration measures was the D50, which corresponds to the diameter of the average material in weight, that is, the size of the granulometric curve which, in turn, corresponds to 50%. For the case of the Aburrá-Medellín River the area material was gathered for the purpose of obtaining it as primary information. For the greatest part of the Medellín river the D50 EPM values were used for the different river points for the year 2006.

As support for the restoration methods, there was the "Management and restoration of stream flows – A study of cases in the municipalities of La Ceja and Marinilla" report (Zapata et al., 2013), as well as the design guides of the US *Army Corps of Engineers"Hydraulic Design of Stream Restoration Projects"* and *"Channel Restoration Design for Meandering Rivers,"* which serve as a design guide for the different flow conditions and geo-morphological conditions of the stream flow.

The Rosgen methodology seeks to configure the geometric structure and the material as naturally stable stream flow should have so as not to present adverse conditions of erosion or depositions that may affect its dynamic. Despite the fact that stream flows might have been affected, these present an unbalance in their Rosgen classification, demonstrating that its structure does not adjust to the stable flow conditions. By modifying the intervened stream flow, we expect to recover the condition prior to said interventions.

The 3C stretch between the Girardota Bridge and El Hatillo is the stretch with the most interventions at the time of designing restoration measures due to its high grade of anthropic affectation. It also had a greater detail of available information for the calibration of the models and its subsequent design. Several cases were worked on this stretch, the first called "Original," presented the current conditions of the calibrated stretch. The meandering designs and the transversal sections called "Restored" correspond to the restoration alternatives designed to modify the general Rosgen classification of the current.

The restoration conditions were likewise validated according to the geometric information collected in the stretches studied. Among these, we find historic maps or previous orthographies to many interventions of channeling and rectification, although they lack correct characterization and geographical reference that make use difficult. In spite of this, it was possible to adjust the geometry and predict a base restoration condition that sought to take the stream flow to a previous state of negative anthropic intervention.

Finally, the obtained results were analyzed after the design of restoration measures in order to determine their efficiency. With these new results, we redesigned the points at which difficulties continued, as well as reformulated the measures and again designed the stretches studied. The interventions were calculated again with the numeric models of the restoration guides, plotted from the AutoCAD Civil 3D tool and hydraulically modeled with the Iber 2.2 model in order to verify the new flow characteristics. The model for hydraulic behavior verification was carried out under non permanent flow conditions in order to identify the variations in the wave transit along the stretch and the dissipation effects generated by pools in the main stream flow and flood planes.

3. JUSTIFICATION

In general, the ecological and social benefits of the development of restoration methods in a current encompass the following fields: flood control, stabilization of current and sediment transport control, reestablishment of natural conditions for riparian vegetation, native fauna and surrounding ecosystems, enabling the development of the potential for recreation and eco-tourism of the restored stretch and improving water quality. All human intervention on a current affects its flow conditions in the stretch that was intervened, which will equally affect the water flow conditions up and down the current.

Initially, benefits were analyzed, supported by the Aburrá-Medellín River case. Previously, this river had a strong meandering geomorphology in all its stretches, with its bank and flood plane well defined. The changes which generated the greatest impact were the multiple rectifications and channelings in its middle-third, which corresponds to the Valle de Aburrá Urban area, with similar affectations in the upriver stretches, as well as the downriver stretches, although at a smaller scale.

Even though both rural stretches have suffered important rectifications, these still keep natural conditions that can be considered in a Rosgen analysis. Although these stretches have an important affectation and lack quality information, they show the best conditions for intervention and implementation.

The upriver rural waters stretch has been affected by a greater sediment transport and an increase of erosion levels in the bed and bank of the current due to the downriver water conditions that accelerate the flow and a continuous process of extraction in the bed that has accelerated all the negative impacts. The erosion problems are especially noticeable near the rectified and channeled stretch. This generates instability in the normal flow conditions of the current and changes in its shape and capacity to support life.

The downriver water stretch presents affectation with a greater number of floods for return periods lesser than historic values due to the fact the stretches rectification reduces the concentration time toward the downriver water stretch. In addition, since the channel is not completely canalized, it does not have the same hydraulic capacity to transport the volume excess in such a short period of time overflowing the excess in its flood plane. The increase in flow speed has also generated an increase in sediment transport and erosion levels of the bank. The negative effects generated by these events are more harmful than those generated by floods, since even though it generates human affectations, floods cause communities to be displaced toward no flood zones, where these affectations do not present themselves.

The effects of erosions in both stretches has generated instability in the current, detachment in the bank (landslides) and loss of habitat for the species of fish, mammals and plants that settled in the area. The increase in sediment transport has reduced the concentration of oxygen in the water and increased turbidity. The increase in the flow speed has also impeded the settling of fish species and their procreation. The benefits of the physical restoration of the stretch includes flood control, current stabilization and the improvement of natural conditions over time.

Flood control can come about with an adequate design of restoration measures. Previous conditions could be improved by modifying the current, stopping the negative effect caused by changes generated, giving the current a greater capacity to dissipate stream flows that generate floods. An improvement in current stability and sediment transport can be expected by enabling the gradual recovery of the current, generating low speed zones (life zones), where the inhabitants can establish themselves again. All this can be achieved by the appropriate restoration methods for erosion control and sediment transport.

The reestablishment of natural conditions for the threatened native animal and vegetation species enable the establishment of a control over flow conditions, thereby enabling the displaced species to recover those spaces gradually. In case the damage is so extensive that these cannot return naturally, they could be introduced artificially.

The reestablishment of natural conditions also allows for the development of the potential for recreation and ecotourism of the restored stretch for the economic contribution of the necessary works to implement the proposed restoration measures. Additionally, the economic benefits will help the community to have a greater consciousness of the value of conservation and restoration. Finally, water quality of the restored sectors would improve, largely because of the growing biodiversity. The project would also aid the development of new restoration plans in currents with similar problems. Likewise, it would serve as support for intervention projects such as Bio 2030 and Parks of the Medellín River.

Definitively, the Medellín River is a natural element that structures the urban development of the Aburrá Valley. However, it was mistakenly viewed before as an obstacle for the urbanization of useful areas, which generated the proliferation of the canalizations and a collective belief that the only way to develop was close to a fluvial current. This project looks to change the way people view the river and present development alternatives in accordance with the current needs of conservation and restoration of the ecosystems.

4. RESULTS

The river stretch between 500 m upriver and the mouth of the Ayurá ravine in the Aburrá-Medellín River and the La Aguacatala bridge has a concrete covered channel with a natural bed. The flow regimen is markedly mixed, with a supercritical predominance under normal conditions and presents a wide flood plane which is highly inhabited by construction and urban infrastructure, as shown in **Figure 5**.

Figure 4. Hydrological modeling of rain-runoff in section 25_2C

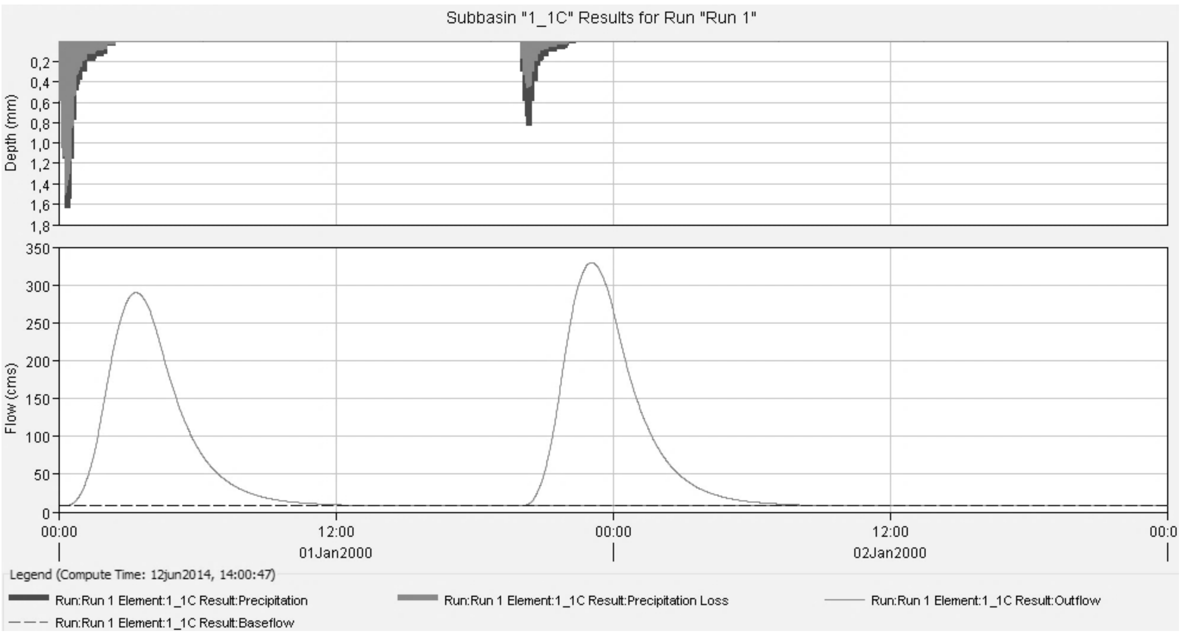


Figure 5. Hydraulic model 25_2C stretch for a100-year return period river flow

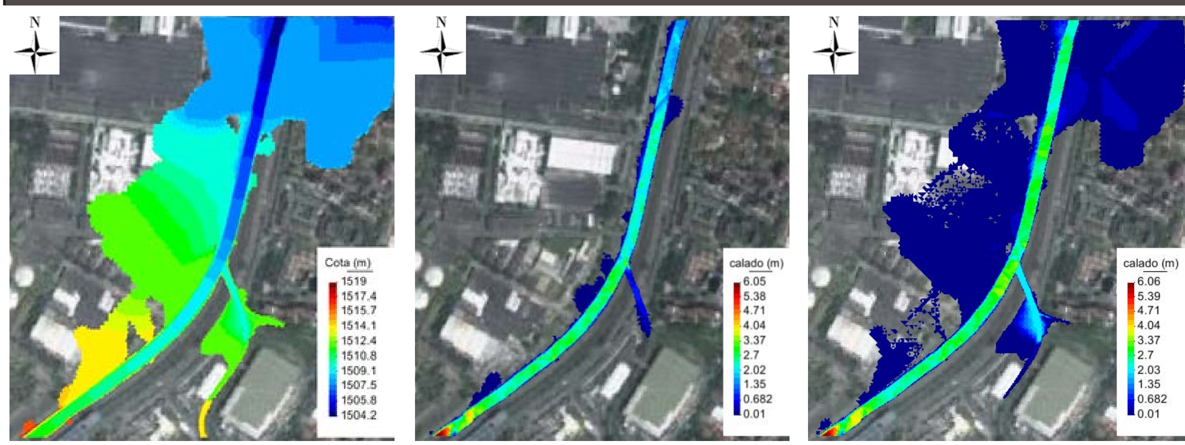


Figure 5 shows the hydraulic model of a hydrologic flood for a 100-year return period in the 25_2C stretch. The first image presents the digital elevation map used in the model. The center image presents the water stain in the main channel when it begins to overflow the channel in the flood plain. The image on the right shows the flood stain for the permanent flow of the riverbed for a 100-year return period.

In the 25_2C stretch, the stream flow and river rising for both the 1D and 2D models was similar for normal flow conditions. The flow regimen was supercritical, while for the extreme river courses, the flow regimen was mixed, with very noticeable changes along the route, flooding a vast plane both along the left margin and right one. The 1D model presented more unfavorable flooding conditions since it overdimensioned the passing of water in the flood plane. It also had difficulties in presenting the stain due to the border conditions the model generates and didn't present conditions that the 2D model did show in two important points for the results: the first in the flood plane and the second at the mouth of the La Ayura ravine. In both zones, there were conditions of counterflow at the streamflow and river rising, causing problems and affectation in the areas closeby, as shown in **Figure 6**.

Figure 6. Hydraulic model with HEC-RAS (1D) vs Iber (2D) in the 25_2C stretch

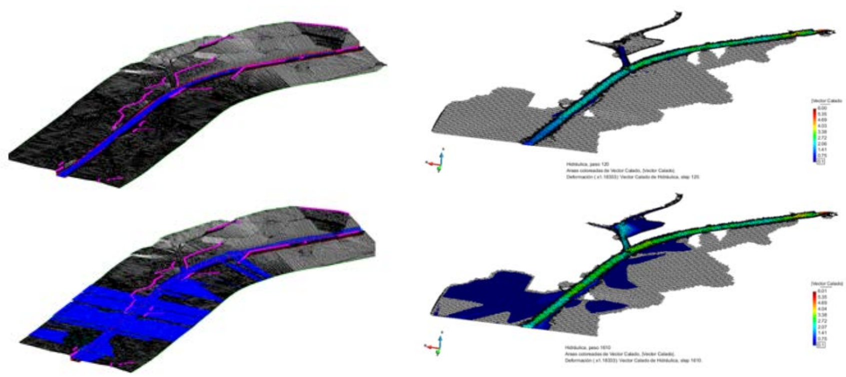


Figure 7. Hydraulic model with HEC-RAS (2D) vs Iber (2D) in the 25_2C stretch

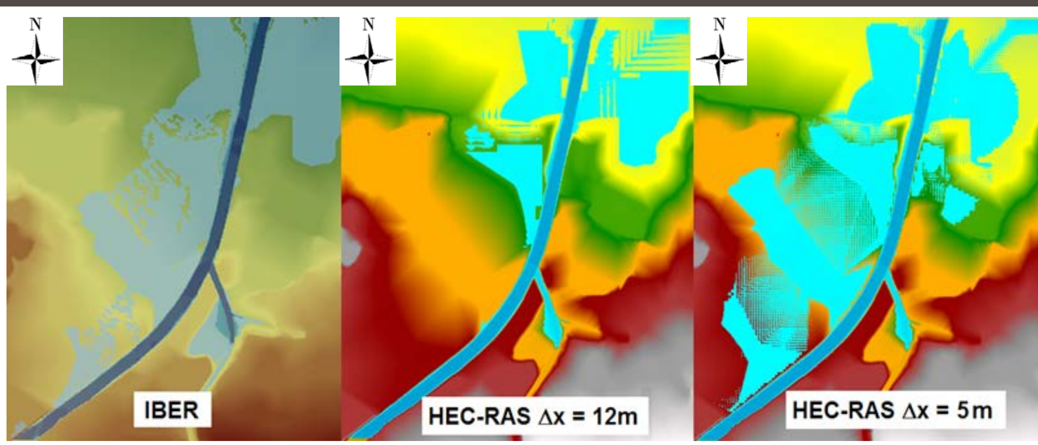


Figure 8. Hydraulic model10_3C stretch – Girardota zone

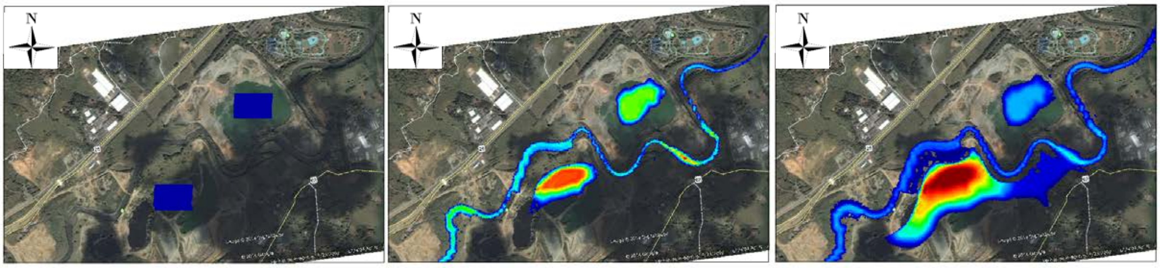


Figure 6 shows, on the top, a stain generated by the approximate transit of the average rivercourse along the stretch studied. On the bottom, we can see the stain generated at the moment it reaches the peak streamflow and river rising of the 100-year return period for that point of the river. Both figures on the left are the results of the model in HEC-RAS, while those on the right are the results of the Iber model.

The new HEC-RAS 5.0 version, beta test version at the time the study was carried out, allows for the two-dimensional hydraulic calculation, making it possible to compare the results to the Iber model, as seen in **Figure 7**.

Figure 7 shows the results of two-dimensional modeling for permanent flow with Iber and HEC-RAS with a net size of 12 m and 5 m. We can see the similarity between the Iber stain and that of the 5 m HEC-RAS, due to the topography detail which is improved using a smaller sized cell. For a case under permanent flow conditions, the stain presents similar conditions in HEC-RAS and Iber. However, analyzing the stretch under non-permanent flow conditions, the flow conditions that most adjust to the wave propagation in the stretch corresponds to the size of the 12 m net.

For the Iber model, in stretches in which the length of circulation is extensive or there are wells that retain flow, while these fill up, problems arose at the time of modeling the flood event of any streamflow regardless of its peak river rising, since at the time of reaching a well, it presented a nonexistent dissipation. In order to avoid this effect from occurring, the model needs to be preheated in order to approximate it to the previously expected conditions at the moment of the flood. A base river course was modeled during a delay period of the wave in order to fill those spaces in the channel, and for the wells, an Iber tool was used which enables filling at a known level at the information cells **(Figure 8)**.

Figure 8 shows the sequence of what was described in the previous paragraph. The first image shows step 0 of the model. This one shows only the squares with topography information which were assigned the condition of initial flow altitude. The second image depicts the base stream flow in step 15 of the model, which is equivalent to 75 minutes of water circulation. This, in turn, represents the time the base flow takes to reach the entrance section until the end of the stretch. Finally, step 87 of the model shows a stain generated after 7 hours and 15 minutes of the stream flow and river rising.

The geomorphological characterization for the Girardota – El Hatillo stretch under the current flow conditions showed that the riverbed presents a type F and B predominance, which do not represent the natural conditions of the riverbed, since Type F represents a highly eroded and held up channel, while Type B corresponds to a river with a high incline (greater than 2%), with no meandering and a moderately held up channel. All the aforementioned is shown in **Table 1**. Likewise, the flood stain for the 100-yearreturn period is shown in **Figure 9**. This figure details the great affectations due to flooding along the stretch, mainly in its mid zone.

The flow conditions for the Girardota – El Hatillo stretch after designing restoration methods are shown on **Table 2**, in which you can observe the improvement of geomorphological conditions, adjusting to conditions most closely approximated to those expected in the stretch, according to the meandering curve designs and transversal sections of the guides from the *US Army Corps of Engineers, Channel Restoration Design for Meandering Rivers* (2001) *and Hydraulic Design of Stream Restoration Projects* (2001). Upon improving flow conditions in the stretch, flood risk is also decreased in non designated flood plain areas, as shown in **Figure 10**.

Comparing flood stains shown in **Figure 9** and **Figure 10**, we can appreciate the magnitude of the required intervention in the stretch.

TABLE 2. GEOMORPHOLOGICAL CHARACTERIZATION OF ROSGEN IN GIRARDOTA UNDER CURRENT CONDITIONS

	1	2	3	4	5	6	7	8	TOTAL
Incision	2,77	1,24	2,32	1,12	1,15	2,13	1,87	2,16	1,85
W/D Pr 2,33	33,80	29,28	31,48	31,01	35,11	23,59	24,25	24,12	29,08
W/D Pr 100	93,52	36,30	72,96	34,76	40,46	50,27	45,31	52,20	53,22
Sinuosity	1,96	2,15	1,80	1,56	1,81	1,88	1,83	2,16	1,89
Type	C	F	C	F	F	B	B	B	B
Incline	-0,054	0,025	0,021	0,021	0,051	0,040	0,002	-0,224	-0,015

Figure 9. Flood stain in Girardota for a 100-year return period flow under current conditions

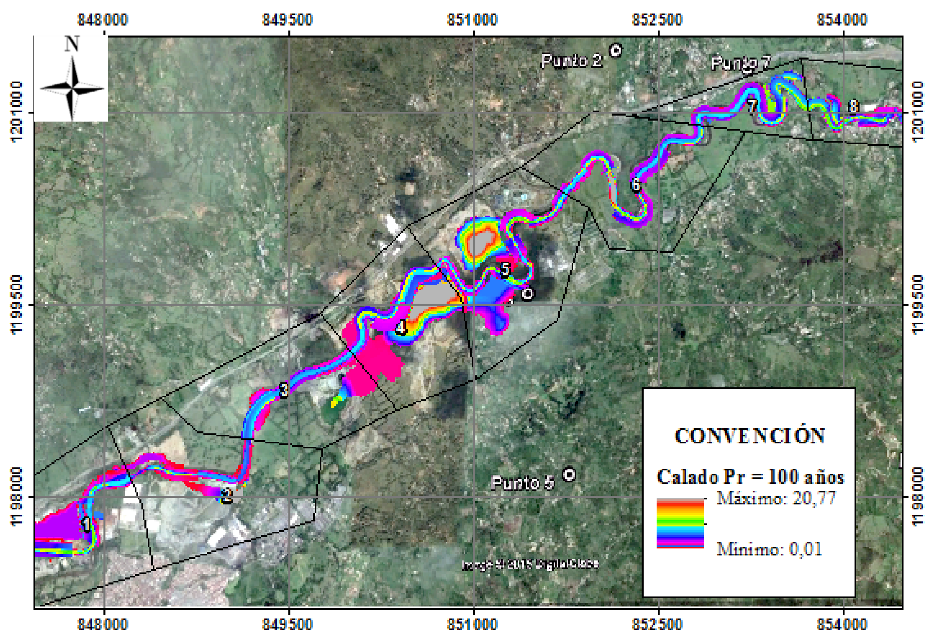
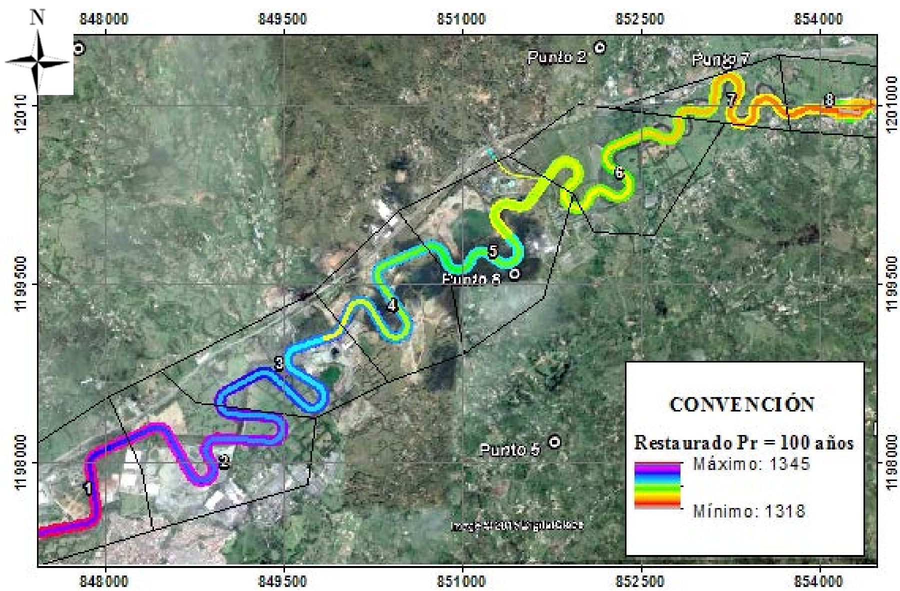


TABLE 3. GEOMORPHOLOGICAL CHARACTERIZATION OF ROSGEN IN RESTORED GIRARDOTA

	1	2	3	4	5	6	7	8	TOTAL
Incision	2,66	2,63	2,66	2,71	2,50	2,71	2,53	2,56	2,71
W/D Pr 2,33	12,38	12,25	12,38	12,38	12,00	12,75	12,25	13,00	12,13
W/D Pr 100	33,26	31,96	32,61	31,30	33,91	31,30	33,91	33,59	30,98
Sinuosity	2,47	2,44	2,47	2,31	2,36	2,31	2,44	2,50	2,41
Type	C	C	C	C	C	C	C	C	C
Incline	0,089	0,099	0,081	0,087	0,089	0,086	0,097	0,085	0,085

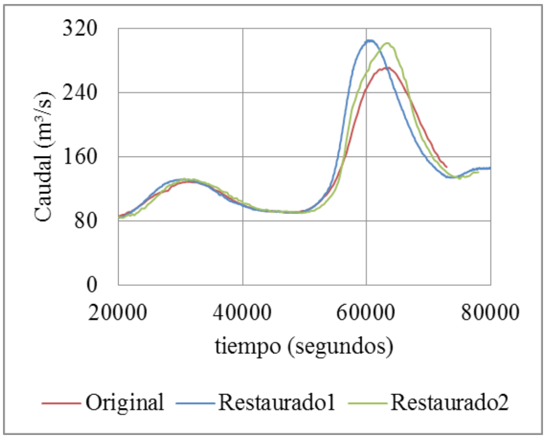
Figure 10. Flood stain in Girardota for a flow of a 100-year restored return period



After implementing restoration measures for the study stretch Girardota – El Hatillo, the hydraulic model gave unexpected results of the wave transit along the stretch, mainly for the travel time of the wave between both the control point and the expected dissipation level. All this can be seen in **Figure 11**. The Original case represents down river current conditions. Restoration Case 1 represents the intervention of the first third of the river, adding 1,5 km meandering. Finally, Restoration Case 2 represents a total intervention of the river, adding more than 4 km of extra meandering.

Figure 11 shows streamflow and floods registered on October 18, 2007 for the current "Original" channel and for the channels of two restoration proposals. Analyzing the results of the models, we saw that the river flow corresponding to that flood is found very close to the 2,33-year flow of the return period, also known as "trainer flow." This is why, at the of the floods for the cases in which the river flow was restored, the river flow was at the maximum level necessary to begin pouring toward the flood plain. For this reason, despite the fact the streamflow needs to travel more to reach the downriver point, the difference between the dissipation levels after establishing restoration measures is not so significant.

Figure 11. Hydrographs of the 2007/10/18 flood –El Hatillo Station



5. CONCLUSIONS AND RECOMMENDATIONS

The use of 1D models is not recommended for zones where the water flow is markedly two-dimensional, since the generated results would notprecisely represent the reality of the flow conditions in the modeled stretch. For this case, the use of 2D models enables obtaining better quality results.

The urban stretch in the middle part of the basin is mostly channeled but, for extreme cases in which the protection of the riverbank is not sufficient, the production of the flood is two-dimensional. In this case, an adjusted 1D-2D would be better recommended. However, this type of model requires a greater detail of information and greater time for the generation of the model.

The case between Girardota and Barbosa, despite the basin being strongly altered and rectified in many zones, might be considered two-dimensional because it maintains a meandering composition which generates recirculation areas and high speed areas in the same transversal section, considerably affecting the flow conditions and the hydraulic results; likewise, for extreme cases the generation of the flood stain is markedly two-dimensional.

The time saved between a 1D-2D model and a 2D model under under conditions of similar detailed information, is considerably better. This is why, in order to achieve a 2D hydraulic model, we must analyze the information processing capacity of the machine used. We must take into account that this relationship might vary depending on the processed area, its detail, processing time and the interval between steps in the process. Also, to optimize processing time, we need to sacrifice the quality of one or some of these processes, which will negatively affect the quality of the results. Comparing processing time between HEC-RAS and Iber, the former lasted between 2% and 3% of the time it took Iber to obtain results.

The results of the river stream flow and flood analysis model, in addition to serving as input for the design of adequate measures of restoration, enables making decisions in key environments such as urban planning and of uses of soil, risk control and mitigation, harnessing of water resources and intervention plans of a river stretch.

In spite of the fact the Aburrá Valley has a network of good quality topographic measuring and information stations, the free and accessible availability of this information and the space variability of this information limit the reach of a great quantity of projects in the urban area between Envigado and Bello, since it has a wider scale and distribution of information. In general, the topography is the greatest lack in rural areas where the river detail is easily lost. The stretch between Girardota and Barbosa had information from transversal sections which eased their characterization, while other stretches with less information were not correctly characterized.

Prior to initiating the hydraulic model, the entry data must be verified, as well as the geometry, structures, Manning coefficient, border conditions and interval of calculation time. This because any error in data can generate instability in the model, making the running of the data stop, or continue generating results which will not correctly represent the intended event to model.

Sediment transport was not analyzed in any of the hydraulic models developed because this parameter requires a wide number of variables which are impossible to obtain for the area and so its calibration would not be sufficient. The Iber model includes a sediment transport model but it is very sensitive to changes in its entry variables and requires greater calibration and quantity of variables measured. The D10 and D50 were used to calibrate the Manning number and as an entry parameter of empirical equations of restoration of flows presented the design guides.

The restoration measures suppose that the size of the D10 and D50 particles in the restored stretches will remain over time after implementation and only geometric conditions will be modified, which will alter flow conditions along the riverbed until finding a condition of balance. It is expected that changes in flow conditions will alter sediment transport and the particle size in each area. This change can lead to other projects focused on a greater collection of information of the non hydraulic conditions and possible changes generated.

The hydraulic model of the stretches studied after establishing the interventions in the riverbed is fundamental to determine possible direct or indirect affectation that can be generated due to the modifications made in the alignment of the river or its shape. The main affectation found in the stretch studied of Girardota – El Hatillo was the increase of the peak flow due to the elimination of several wells and because, for the analyzed flood flow the effect of the flood plain was null. Meanwhile, under current conditions, this streamflow floods a great quantity of terrain that could be considered flood plains.

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