1. INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The pioneer advection-dispersion equation [ADE; *Taylor*, 1954] remains a support for simulating solute transport along stream reaches. However, the topological discretization of the channel in prismatic elements and the lack of the model to represent transient storage processes, have been highlighted as some of its major shortcomings. The ADE is given by equation (2-1),

$$\frac{\partial c}{\partial t} = -U\frac{\partial c}{\partial x} + D\frac{\partial^2 x}{\partial x^2} \qquad 1\text{-}1$$

where c [ML^{-3}] denotes the solute concentration, U [LT^{-1}] the mean flow velocity in x direction, and t [T] is time. The longitudinal dispersion coefficient D [L^{2}T^{-1}] is responsible in the model to represent dispersion driving by differential advection processes and transient storage. The former is due to irregularities in the velocity field which lead to differential arrival times of solutes particles from a station to another located downstream. Transient storage refers to retention of solutes in stagnant areas arising as a consequence the geometrical and morphological settings along a stream reach, which could be arise as surface and sub-surface zones [*Zarnetske et al.*, 2007; *Camacho*, 2000; *Choi et al.*, 2000; *Kazezyılmaz-Alhan y Medina*, 2006]. The inherent limitations of the *ADE* model implies using high dispersion coefficients to represent reductions of the mean transport properties induced by the stream geometrical irregularities and the water interactions between surface and sub-surface volumes [*Meier y Reichert*, 2005]. This is analogous to use high roughness coefficients in one-dimensional hydraulic models to overcome the lack of detailed geometrical data.

Since these limitations were identifying, a growing interest has been directed towards the knowledge regarding how solutes move along watercourses. The reach-distributed *Transient Storage* model [TS; *Bencala y Walters*, 1983] and the reach-aggregated *Aggregated Dead Zone* model [ADZ, *Beer y Young*, 1983] represent the last three decades' efforts of the research community to have such better understanding. These models allow considering the storage effect of one or more stagnant o dead zones, whose overall effect is displayed as the long tails in the breakthrough curves measured when tracer experiments are carry out.

Nonetheless, the transport parameters for a reach obtained base on tracer experiments are flow dependent and, besides, they cannot be used arbitrary in other stream reaches. This became a limitation issue in a regional context since the variability of spatial and temporal hydrological, sedimentological and geological factors, leads to have large fluvial morphology settings which, in turn, have different geometrical features. Stream morphology determines mechanisms for energy dissipation, sediment transport, hyporheic water exchange and solute transport mechanisms. Moreover, stream bedforms and patterns are underlined by scaling laws which have been studied since the seminal hydraulic geometry relations, today described in terms of statistical formalisms more robust. Based on the latter, as it turns out as the main goal of this research the establishment of solute transport parameters taking into account fluvial morphology and multi-scaling analysis, by combining hydraulic geometry theories, objective stream morphology classification, geospatial information processing, and analyzing tracer data to incorporate the non-linearity induced by streamflow changes.

1.2 JUSTIFICATION

Since the Decree No. 3930 of 2010 was issued, the environmental agencies in Colombia have made advances regarding the monitoring and environmental control of water quality in surface water sources. In this way, the Environmental Wastewater Evaluation (EAV, by its Spanish initials), referred in the Article 43 in the same Decree, defines the main planning tool to establish whether a new punctual spill can be released into a watercourse.

The EAV is focused on the stream segment where an specific pollutant release is projected, which extends downstream a length difficult to define a priori either because the environmental agencies lack of topographic, hydraulic and morphologic information to support the application of some water quality modelling scheme, or because water users not always count with the resources to collect such information. On the other hand, regardless of the possibility of having the mentioned information, users cannot take into account the cumulative pollution effects related with the rest of point sources existing throughout the watershed area.

Without a criteria unification when requiring a new water user, and without taking into account the spatial distribution of pollution spills, an efficient implementation of the management plans (also referred in the Decree No. 3930 of 2010) cannot be made, further because as well as pollution, stream flow along the drainage network may be decline due to water diversions are also spatially distributed.

It worth mentioning, however, that the national environmental policies are moving towards homologation regarding the methods to assess water quality issues at the reach-scale, by referencing and suggesting the use of solute transport models which takes into account temporal storage processes. Some of these guidelines are given, for instance, through these methodologies:

- Methodology to define the influenced length downstream a spill on surface water courses [*ANLA*, 2013b]
- Methodology to estimate and evaluate the environmental discharge in projects that require environmental license [*ANLA*, 2013c]
- National guidelines for water resources simulation in continental water bodies according with the disposals issued in the Decree No. 3930 of 2010 [*ANLA*, in preparation]

For all those cases the ADZ model is suggested, an approach that will be mentioned throughout this document and defines the selected starting point to explain solute transport processes from the reach-scale to the basin-scale.

1.3 OBJETIVES

1.3.1 General Objective

To study the variability of parameters of one-dimensional models which consider solute transient storage, in terms of stream morphological features and streamflow variation. This, to propose a solute transport framework at the basin scale, and further for cases lacking topographic, hydraulic and morphological data.

1.3.2 Specific Objectives

- To collect tracer experiments data at the reach scale, available in different stream reaches types and carried out at different hydrological stages, in order to explore the invariance behavior of dispersion mechanisms for the morphological types available.

- To establish downstream hydraulic geometry relations at bankfull stage, taking into account the morphological heterogeneity throughout a watershed drainage network.

- To extend the available morphologic classification systems to consider the hydraulic geometry relations derived as well as additional stream corridor features which could be assessed using geospatial information.

- To perform a distributed hydrological model integrated with a solute transport framework which accounts for the morphological channel variations in the drainage network. Besides, to test the model in a region having enough information to validate the obtained results.

1.4 DATA SET GENERALITIES

Throughout this work, it is used a set of information provided by research groups, universities and environmental management's centers, located in the state of Colorado (United States) and the departments of Antioquia and Cundinamarca (Colombia). Figure 1-1 displays the location of these regions.

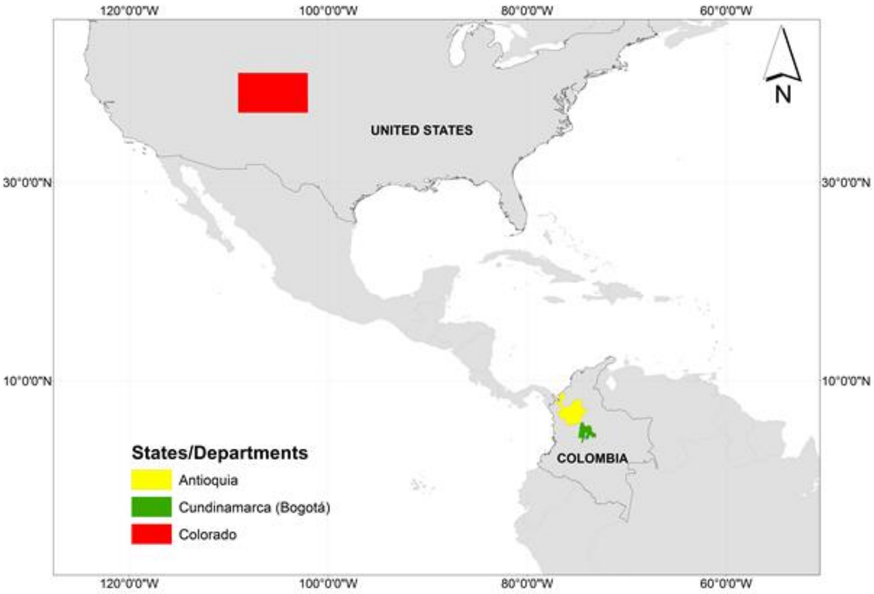

Figure 1-1. General location of regions from which data was provided

According with the aims of this work, such information can be grouped in three categories: tracer data, morphological data and geospatial data. Tracer data was obtained through both the

Department of Geosciences in Colorado State University (*DataColorado*), and the National University of Colombia – Bogotá (*DataBogota*). At Colorado, data consist of rhodamine WT signals measured at the upstream and downstream edges of 15 stream reaches. These channels are located in the Fool Creek and East St. Louis Creek watersheds in the Fraser Experimental Forest in the Colorado Rocky Mountains. The tracer experiments were carried out at four different stages as well as repeated between 3 and 5 times for each of them. Among the surveyed reaches, nine feature step-pool bed forms and five cascades (Table 1-1). This information is referenced in Chapters 2, and is then described in detailed in Chapter 3 for the step-pool morphological type.

On the other hand, the most complete set of tracer data in Colombia has been surveyed in the department of Cundinamarca. In this region, several researches took place at the Bogotá River watershed and its major tributaries. *González* [2008] made a compilation of information in his work as well as carried out new surveys, and used it to study dispersion mechanisms in mountain rivers. From his work it was taken tracer data at five different reaches as shown in Table 1. These data is used in Chapter 2 for making exploratory analysis of the invariance of dispersion mechanisms. Later, in Chapter 5, it is used for making some verification of the approaches here proposed and to support suggestions for future work.

Table 1-1. General attributes of reaches which feature with tracer data

Study region	River/Creek	Reach code	Reach type	Tracer campaigns	L_r (m)	S_0 (m/m)	W (m)
COLORADO	East St. Louis	ESL1	Step-pool	4	29.4	0.094	2.01 - 2.92
		ESL2	Step-pool	4	13.9	0.092	2.57 – 3.21
		ESL3	Cascade	4	10.7	0.132	2.41 – 3.63
		ESL4	Step-pool	4	16.0	0.115	2.32 – 2.86
		ESL5	Cascade	4	13.8	0.138	3.25 – 4.04
		ESL7	Cascade	4	23.3	0.092	2.46 – 3.02
		ESL8	Step-pool	4	32.5	0.090	2.58 – 3.16
		ESL9	Step-pool	4	16.9	0.110	2.28 – 2.79
	Fool Creek	FC1	Step-pool	4	23.8	0.060	1.28 – 1.97
		FC2	Step-pool	4	14.6	0.074	1.13 – 1.63
		FC3	Step-pool	4	13.1	0.090	1.36 – 2.12
		FC4	Step-pool	4	19.2	0.135	1.25 – 1.65
		FC5	Cascade	4	12.7	0.157	0.74 – 1.15
		FC6	Cascade	4	20.3	0.182	0.67 – 1.07
BOGOTÁ	Teusacá river	TC_s1s2	Pool-Rapids*	5	44	0.009	4 – 6
		TC_s2s3	Pool-Rapids*	3	68.7	0.009	4 – 6
		TC_s1s3	Pool-Rapids*	3	112.7	0.009	4 – 6
		TS_s1s2	Cascade*	4	97	0.011	5 – 8

Study region	River/Creek	Reach code	Reach type	Tracer campaigns	L_r (m)	S_0 (m/m)	W (m)
		TS_s2s3	Cascade*	4	94	0.011	5 – 8
		TS_s1s3	Cascade*	3	191	0.011	5 – 8
	Subachoque river	SU-U_s1s2	Cascade – forced pools*	4	181.3	0.030	5 – 8
		SU-U_s2s3	Cascade – forced pools*	4	106.1	0.030	5 – 8
		SU-U_s1s3	Cascade – forced pools*	6	287.4	0.030	5 – 8
		SU-D_s1s2	Pool-riffle*	4	50	0.0096	4 – 6
		SU-D_s2s3	Pool-riffle*	4	98	0.0096	4 – 6
		SU-D_s1s3	Pool-riffle*	3	148	0.0096	4 – 6
	Lejía creek	QLP	Cascades*	4	274.2	0.048	4 – 7

*L_r denotes reach length, S_0 slope gradiend and W water top width
*Bedforms were inferred based on photographs

Morphological data is related with topographical surveys available for the stream reaches in the *DataColorado* data base. This information includes stream bed and water surface profiles for the overall hydrological stages measured. Additionally, the whole channel geometry was measured by using a ground-mounted LiDAR station. This detailed information is used in Chapter 3 in order to explain solute transport processes in terms of morphological features describing step-pool systems.

Besides, it is included in this category a set of 123 stream reaches for which a plan view digitalization procedure was made. This procedure was carried out using Google Earth satellite images, and it includes margins and downstream mid axis digitalization along distances larger than 15 times the channel width. Chapter 4 compiles this information.

Finally, the geospatial data in fundamentally related with digital elevation models (DEMs) used for two different purposes. A first utility was to allow the estimation of reach-slope and draining catchment area for those streams digitalized using the Google Earth images gallery. Depending on the watershed and stream size, the Shuttle Radar Topographic Mission (SRTM) or the HydroSHEDS DEMs were incorporated into the analysis (see Figure 1-2), which have pixel size of around 90 m and 450 m, respectively. Secondly, finer DEMs were collected in La Mosca creek watershed, located in the department of Antioquia (Colombia). These data has resolutions of 10 m, 30 m and 90 m. The finer size was provided by the local environmental center CORNARE (Corporación Autónoma Regional de Rionegro-Nare), and the remaining corresponds to the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) mission and the SRTM mission, respectively. This information is also displayed in Figure 1-2, and is capitalized in Chapter 5.

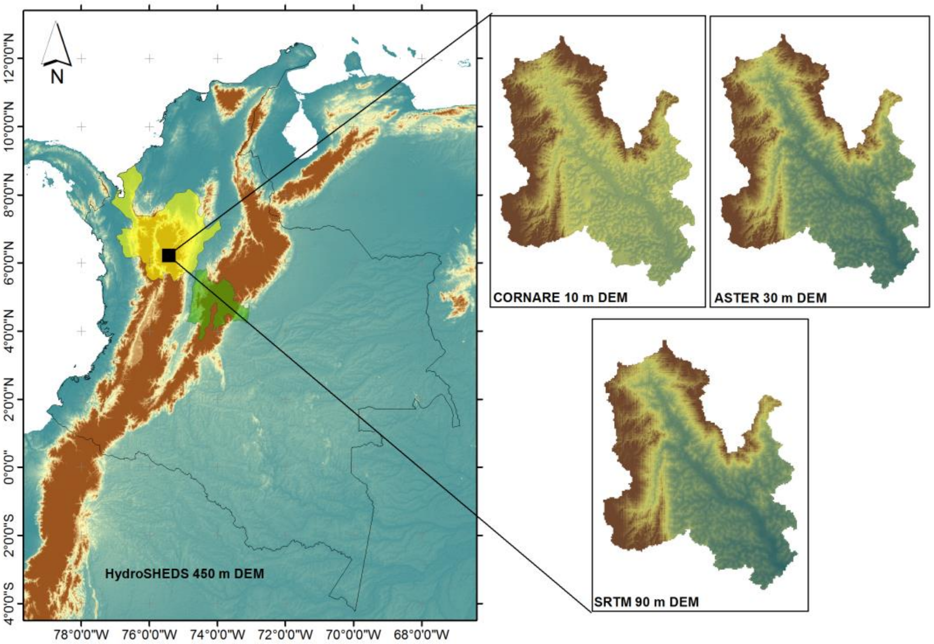

Figure 1-2. Digital elevation models used to infer morphometric and morphologic features

1.5 RESEARCH CONTRIBUTIONS

The major contributions of this work are presented in Chapters 3, 4 and 5, which have been structured such that they could become an independent publication either in national or international journals. Moreover, it is expected these contributions could be used as a starting point for new researches or serving to be replicated as methodological contributions in consulting projects.

Analysis of step-pool channels by processing the *ColoradoData* database, allowed performing an empirical treatment of the dispersion fraction *DF* of the *ADZ* model, taking into account the morphological features of those fluvial systems (Chapter 3). Likewise, the same analysis allows the establishment of dimensionless relations for characteristic travel times of solutes along step-pool reaches. The reach-averaged bankfull width, W_B, and the mean step height, H_s, were included into the normalization procedures. Thus, it is possible to perform downstream solute transport simulations at the reach-scale, when topographical surveys are available to estimate the mean pool length, L_{pool}, the mean step-to-step length, L_{step}, the mean step height, H_s, and the reach-averaged bankfull width, W_B. Nonetheless, having access to such information level is not always possible during a reach survey, and much less at the basin scale. Hence, it was propose a more general simulation strategy based on reach slope S_0 and the reach-averaged bankfull width, W_B , which can readily to estimate by either, low detailed surveys, aerial images, digital elevation models or hydraulic geometry relations. The proposed simulation framework includes the uncertainty contribution coming from the randomness of the bedforms settings, by using probability distribution functions to describe L_{pool} y L_{step}, which were also normalized through bankfull width.

According with the outcomes of Chapter 3, bankfull width showed to be an appropriate scale factor to create synthetic step-pool sequences as well as to take solute transport parameters to dimensionless forms. This issue motivates the analysis in Chapter 4, with the aim to provide insights to pass from the reach-scale to the basin scale. This lead to propose reach-hydraulic geometry relations (*DHG*) for the bankfull width for the listed considerations below:

- Watershed area was used as surrogate of discharge, taking into account the lack of this type of information in Colombia. Thus, by using DEMs and appropriate processing techniques, it is possible to assess W_B throughout a drainage network.
- Those relations are reach-averaged, which reduces uncertainty when compared with traditional downstream hydraulic geometry relations based on cross sectional values.
- To derive the *DHG* relations, different morphological classes were defined by using morphologic classification systems. By this method, it was possible the distinguished four quasi-universal morphological classes for braiding, suppy-limited, transport-limited and migrating systems.

Outcomes in Chapter 4 have a significant relevance on the national context since they can be used to support hydrologic simulation, delimitation of environmental zones and performing distributed models as the presented in Chapter 5. The distributed solute transport model *MDTS* (for the Spanish stands) combines the findings of this work with those previously posed by other researchers, by taking the reach-scale solute transport conceptualizations to the basin scale, with the intention that this model could be used to support surface water quality simulations, monitoring programs design and morphometric and morphologic characterization of watersheds.

1.6 DOCUMENT CONTENTS

The document is divided in six chapters. Chapter 2 presents a general state of the art regarding one-dimensional solute transport models to perform simulations along a reach or a cluster of reaches. The *Transient Storage* (TS) model and the *Aggregated Dead Zone* (ADZ) model are described whereby they consider as a dispersion mechanism the temporal retention of solutes in stagnant zones. Moreover, a general description of probabilistic extensions of the TS and ADZ model are described, which make possible to do uncertainty analysis in applications related with long stream segments, reaches different than those from which transport parameters were derived and stream flow conditions lacking tracer data and therefore the corresponding solute transport parameters. This chapter also describes some methods to classify streams morphologically, and the role of hydraulic geometry theories to implement them. Finally, insights from the state of the art are collected and summarized, around which the contributions of this work are build.

In Chapter 3, it is presented one of three papers drafts, named *Solute transport modeling using morphological parameters of step-pool reaches*, already published in the journal Water Resources Research on 2013. This chapter arises to attend the first specific objective of this research, and it is focused specifically on step-pool channels taking into account not only the availability of the complete database *ColoradoData*, but also the growing attention this stream morphology has received on the last 10 years. This chapter effectively allowed finding out the invariance in the dispersion mechanisms taking place in this type of natural channels.

The bankfull widh, adopted in this work as scale parameter, was analyzed in Chapter 4 in terms of its relation with watershed area, which corresponds with the scale parameter at the basin scale. In this chapter, satellite images, raster data and vector data, are put and processed together to derive hydraulic geometry relations. This chapter is titled *Stream morphology and downstream hydraulic geometry relations for bankfull width*.

Chapter 5 presents an integration of the outcomes from Chapter 3 and the contributions by *Camacho* [2000] and *González* [2008]. These contributions allow considering the representation of dispersion mechanisms in the channel types *cascade*, *plane bed* and *pool-riffle*, did not consider in detail in this work. On the other hand, the proposed model in this chapter represents the strategy to jump from the reach-scale to the basin-scale through the application of the stream classification system by *Flores et al.* [2006], the hydraulic geometry relations derived in Chapter 4, and the treatment of digital elevation models looking for an appropriate topological representation of the drainage network for solute transport modelling. This chapter also accounts for such DEM's treatment.

Finally, Chapter 6 articulates the conclusions did along the previous chapters, and highlights the shortcomings of this work in order to motivate complementary future work and, definitively, enhanced contributions.