6. CONCLUSIONS A SUGGESTIONS

This research was carried out having as north the specific objectives defined in Chapter 1, which were mostly cover in the contents of chapters 3, 4 and 5. Although conclusions regarding the outcomes corresponding to each chapter were included in their ending part, this chapter compiles the most important findings in order to connect them as a whole and highlight, in turn, their underlain shortcomings. Additionally, insights for further work are mentioned to overcome such limitations.

6.1 GENERAL ASPECTS AND METHODS

- The reach-aggregated structure of the ADZ model as well as its parsimony were the main reasons taken into account to select this model in order to find out a parameterization based on morphological features of stream reaches. Besides, it has be shown that the parameters of the model, t_m and τ , not only keep a strong relationship with discharge within the same stream reach, but also they are always identifiable, thus giving them physical meaning. Since the focus of the work was to study dispersion mechanisms taking place superficially, it was used only one aggregated dead zone in the model structure. Further, given that the analyzed reaches in Chapter 3 had a dominant and common morphology, it was also expected that a dominant time scale be enough to represent the solute storage within the reaches, in agreement with the selection of one lumped dead zone.

  It must be taken into account that analyses were always related with in-stream solute transport processes and flow conditions lower than the bankfull stage. Hence, solute interactions with floodplains or solute movement along multiple-thread channels cannot be treated with the methods here presented.

- Tracer data is a key experimental tool to assess dispersion driven by superficially and hyporheic mechanisms in streams. Once data is collected, it is common to have several inconsistencies relying on factors such as the tracer type and how this interact with water and sediment, the sampling method as well as the number and differences in probes, and the measuring periods that not always allow to recover the entire tracer mass. The *ADZ* model in calibration mode provided an interesting alternative to obtain transport parameters even under the influence of such inconsistencies, as carried in Chapter 3 to process data from the Colorado database. The *ADZparameter* tool was developed to process tracer signals and obtains, by Monte Carlo simulations, the parameters t_m, τ and *DF*. In the application, signals are first filtered using a median filter with a user-fixed windows size depending on how noisy are the signals. In this step, the backward and forward tails of the signals are identified in order to calculate the mean base concentration upstream and downstream, whose difference, in turn, are used to adjust both signals at the same level. Using a truncation threshold of 10% of the measured concentration range for each signal, these are truncated to calculate geometrically the first arrival time and mean travel time (measured to the center of mass). Those values are use as seeds on the Monte Carlo simulations of the ADZ model from which t_m, τ and *DF* are finally estimated.

The alternative *Solute Transport Tool v1.0* developed by *Gonzalez* [2008] allows calibrating the ADZ model for serial arrangements, a special functionality did not included in the *ADZparameter* tool. Nonetheless, it worth making extensions far beyond the capabilities of both, that also let parallel arrangements to be included, in advanced to the treatment of more complex stream morphologies as braided channels.

- Analysis in Chapter 4 and Chapter 5 were preconditioned to the stream classification method posed by *Flores et al.* [2006]. Selection of this method was made based on the possibilities to apply it by using geospatial data (specifically digital elevation models), and also because of the consideration of the specific stream power into the classification framework. Inclusion of this metric, account for sediment transport capacity, while allowing making distinctions between morphological classes that cannot be distinguished only by using the longitudinal slope as a discriminatory variable. However, as pointed out by *Flores et al.* [2006], the scheme does not account for additional forcing factors including the geological or lithological setup along the stream corridor, interactions with sediment coming from adjacent hillslopes, nor sediment supply rates and sediment size. Besides, the longitudinal slope, in which the method is mainly supported, is sensitive to DEMs' resolution as well as their sample techniques, as shown in Chapter 5.

  It also worth underscore the limitations of the classification method regarding the impossibility to identify, based upon slope a watershed area, braided systems as those treated in Chapter 4. Figure 6-1 recalls from Chapter 4 the wide variation of slope for the analyzed braided reaches overlapping both supply-limited and transport-limited systems, which may be associated with braiding processes occurring in both sand-bed and gravel-bed channels which were analyzed without any discrimination. To identify braiding potential, distinctions from meandering rivers are commonly made by using discrete thresholds denoted as S_0-Q (slope-discharge) since the pioneer diagram by *Leopold and Wolman* [1957]. A recent work by *Bledsoe and Watson* [2001] posed channel type instability thresholds taking into consideration the bed material size and annual flood magnitude as a surrogate of the formative discharge, with promissory results to define probabilistic diagrams of instability in stream reaches. Insights from that kind of approaches can be adopted to generalize the classification approach here adopted, especially because stream power is the variable underlain them.

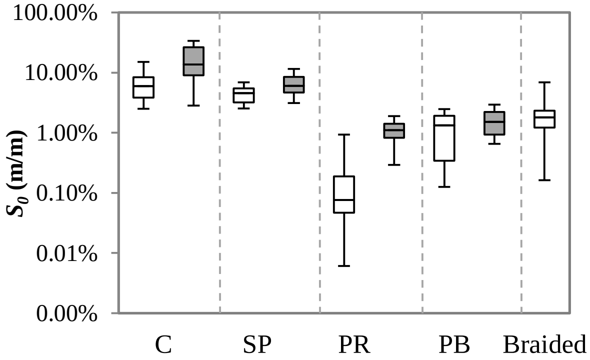

Figure 6-1. Channel slope variability in *cascade* (C), *step-pool* (SP), *pool-riffle* (PR), *plane bed* (PB) and *braided* reaches. Blank boxes correspond to values founded using the available data in this study. Filled boxes correspond to intervals by Flores et al. (2006)

The applicability of the classification scheme at the basin scale revealed high sensitive to the quality, resolution a sampling method of digital elevation models, as well as the influences of such factors on slope assessments, especially in mountainous landscapes. Such sensitive rely on the discrete structure of the classification method, a common characteristic of most of classification methods based on thresholds. Again, it must be explored stochastic approaches to determine probabilistic thresholds instead a discrete scheme.

6.2 IN-STREAM SOLUTE TRANSPORT PROCESSES

Solute transport mechanisms are discharge-dependent as clearly display by the time-discharge diagrams reported in several reach-scale studies wherein the ADZ model is applied. However, it is also clear that the size of the regions where solutes are superficially retained cannot be linked with discharge, and exerts an important influence on how dissolved substances are dispersed downstream along a stream reach.

The volume of those regions, represented in terms of the dispersion fraction -*DF*- in the ADZ model, was correlated with morphological signatures of step-pool systems according with the findings presented in Chapter 3. For such morphological type, the ratio between the mean length of a pool, L_{pool}, and the mean step-to-step length, L_s, was found to be a good predictor of the mean *DF* value for the set of stream reaches available in the Colorado database. Likewise, it was found that by the selection of appropriated morphological descriptors, the characteristic travel times t_m and τ could be taken to a dimensionless form for *step-pool* systems. Bankfull width W_B and the mean step height, H_s, can be used to estimate one of the two temporal parameters following equations (6-1) and (6-2), and then combined with equations (6-3) and (6-4) to represent the overall solute movement within a specific reach. Nonetheless, the proposed method goes far beyond, given the arising limitation when the focus of analysis is the basin scale (drainage network) where is likely to have few or maybe no data to infer neither W_B, H_s nor the ratio L_{pool}/L_s. An uncertainty framework was then proposed based on the generation of random *step-pool-run* sequences using normalized Poisson distribution functions for the random variables L_{pool}/W_B *and* L_s/W_B. Secondary contributions to uncertainty were consider to include the inherent errors of the empirical equations derived to assess travel times as well as those taken from *Comiti et al.* [2007] to estimate H_s in the random sequences.

$$\frac{t_m\sqrt{gH_s}}{L_r}=1.4247\left(\frac{Q}{W_B\sqrt{gH_s^3}}\right)^{-0.507} \quad (6\text{-}1) \qquad \frac{\tau\sqrt{gH_s}}{L_r}=0.8973\left(\frac{Q}{W_B\sqrt{gH_s^3}}\right)^{-0.474} \quad (6\text{-}2)$$

$$DF=0.5744\left(\frac{L_{pool}}{L_s}\right)^{0.5527} \quad (6\text{-}3) \qquad DF=1-\frac{\tau}{t_m} \quad (6\text{-}4)$$

A closer inspection of equation (6-3) shows that *DF* reaches a maximum value *DF* = 0.5744 when the ratio L_{pool}/L_s equals 1. Regardless of using data including boulder steps and LWD steps to derive the empirical relation, the referred limit must be seen cautiously because it could be biased for the reduced sample size. In such regard, further work should be addressed to carry out new surveys along *step-pool* reaches having different step-forming processes, and performing tracer experiments at least for three hydrological conditions. Additionally, it could be useful to characterized the set of parameters (DF, t_m, τ) for individual units *step-pool-run*, such that an entire stream-reach can be treated as an in-series arrangement of units, as those randomly generated.

At the other hand, the nondimensional hydraulic geometry for travel times given by equations (6-1) y (6-2), showed a better fit using H_s into the normalization technique, instead D_{84} as the roughness scale. Studies in which data is surveyed in reaches featuring bedforms dominated by clasts of boulders, take D_{84} as an appropriate roughness descriptor. However, the streams in the Colorado Mountains here analyzed, are set by both boulders and large woody debris, which explain the selection of H_s as substitute of D_{84}. Supporting evidence was found when it was verified the geomorphological stability of the analyzed reaches. For this, it was calculated the ratio between the standard deviation of the bed residuals -$\sigma\delta$- and both D_{84} and H_s, for all the available reaches and flow conditions q^*. Similar than travel times, a clear distinction appears for LWD steps and boulder steps, which did not occur when D_{84} is replaced for H_s. Figure 6-2 illustrates these findings.

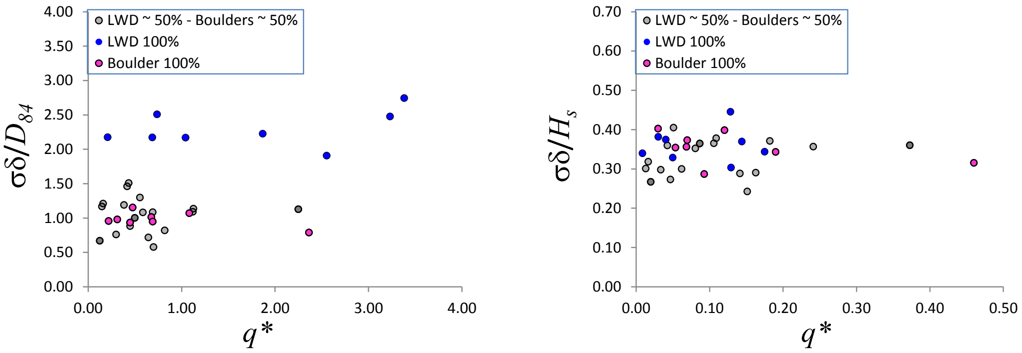

Figure 6-2. Step forming processes segregation when D84 is used to normalized time and discharge

A question arises regarding the invariance of the solute transport processes for streams featuring cascade, plane bed, pool-riffle and braided morphologies, which were not analyzed in detail in this work as step-pool systems. To motivate further research, the morphologic-based ADZ parameterization for step-pool reaches was applied in simulation mode for the available cascade and low-gradient reaches from the Colorado and Bogotá databases, respectively (see Chapter 1).

Figure 6-3 displays simulations performed for cascade reaches in the Colorado database, and surprisingly they are acceptable since most of the observed signals are contained between the 5% and 95% confidence intervals. By contrast, simulations carried out in Lejía creek do not perform as well. Likewise, the application of the model for the low-gradient reaches s1s3 and s2s3 (*DataBogota*) was not able to represent correctly the observed breakthrough curves at the downstream edges (Figure 6-5), hence that for lowland rivers the coupled *ADZ-MDLC* model is suggested in the MDTS model to represent solute transport in transport-limited systems. Is it the modelling framework representative for cascade systems? Which are the appropriate morphological descriptors for low-land rivers and for the rest of morphology types did not include in this work? Those are some additional questions unsolved in this work. However, bankfull width is definitely one of such morphological descriptors, especially because it allows connecting the basin-scale hydraulic geometry with the in-stream hydraulic geometry as showed to represent step-pool bedforms and transport processes.

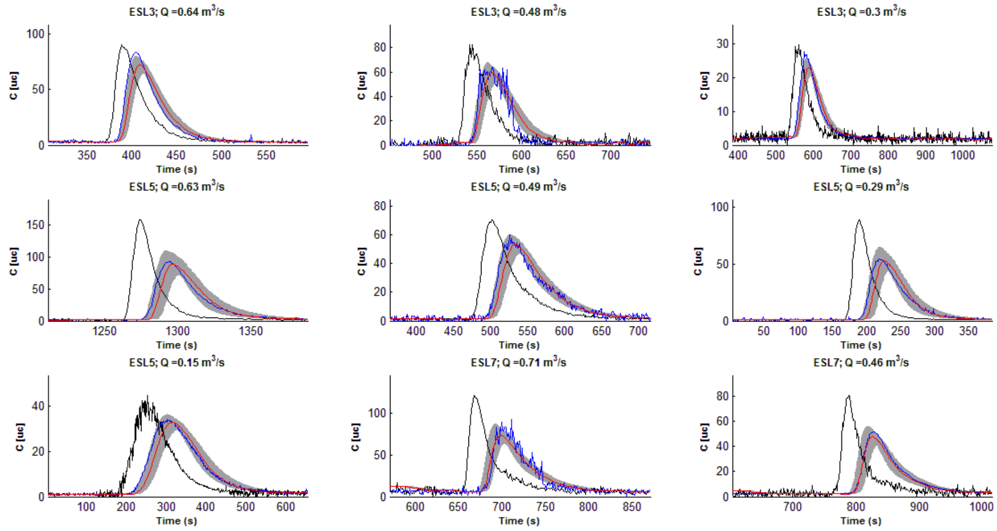

Figure 6-3. Solute transport simulation along cascade systems in East Saint Louis creek watershed using the modelling framework proposed for step-pool reaches (*ColoradoData* stream reaches)

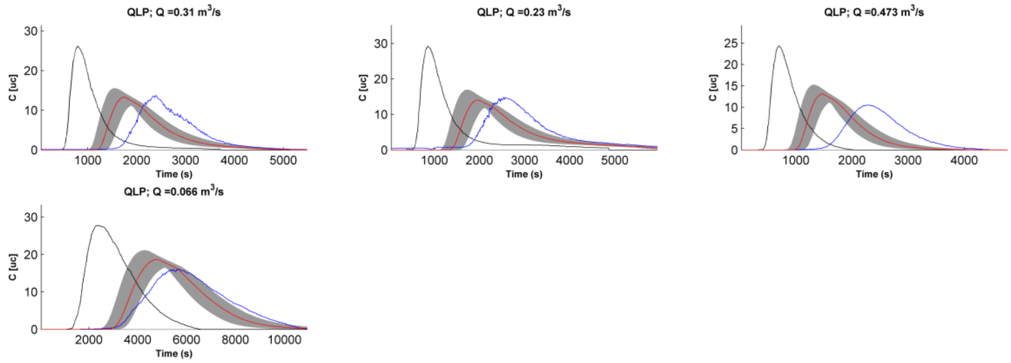

Figure 6-4. Solute transport simulation along cascade systems in Bogotá river watershed using the modelling framework proposed for step-pool reaches (*BogotaData* stream reaches)

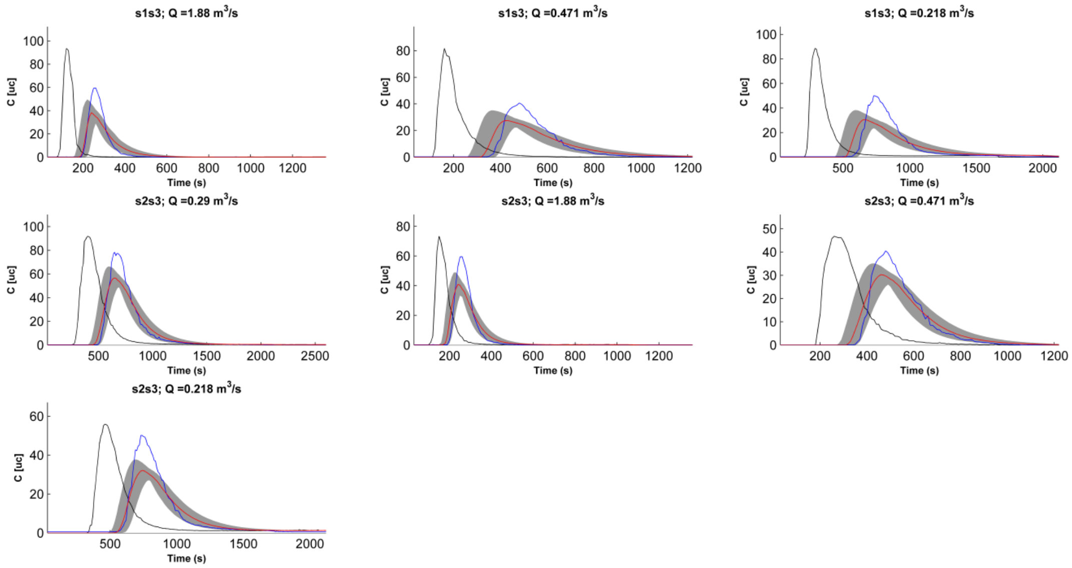

Figure 6-5. Solute transport simulation along low-gradient systems using the modelling framework proposed for step-pool reaches

6.3 HYDRAULIC GEOMETRY AND SCALING

Three hydraulic geometry levels were articulated in this work going from the basin scale to the channel unit scale. At the reach scale, reach-hydraulic geometry relations were found for characteristic travel times of solutes along step-pool reaches in terms of the ADZ model parameters. Alternative relations has been posed previously to estimated mean flow velocities in terms of the unit discharge $q*$ here used, which lead to better estimations than methods based on roughness calculation and cross sections surveys. As mentioned in section 6.2, using the mean bankfull width W_B and the mean drop height H_s in step-pool channels, it was possible to propose such kind of hydraulic geometry relations which seem to be independent of the step forming process. Additionally, the mean bankfull width became a key parameter to stochastically represent the arrangement of *step-pool-ru*n units downstream a channel, an issue that can be seen as a kind of unit-hydraulic geometry since it has behind changes of scale and frequency.

Linkages between the reach-scale and the basin-scale were expressed through the bankfull-width hydraulic geometry relations presented in Chapter 4, for which watershed area was used as surrogate of discharge. Four different relations were derived for streams corresponding to the morphological classes supply-limited, transport-limited, free-transport-limited and braided. All but the braided classes were defined according with *Flores et al.* [2006] as previously mentioned in section 6.1. It was found that the morphological settings of the analyzed data set, had more influence on the dispersion of the pairs (A,W_B), than the exerted by climatological differences among the regions containing the data, or by the fact to use the watershed area instead a formative discharge as independent variable.

Distinction between the transport-limited and free-transport-limited categories was possible using the median bend length (L_b) to mean bankfull width (W_B) ratio, and a threshold around 13.23 below which 78% of the reaches classified as transport-limited corresponded to those displaying evidence of having an active channel migration zone. In a recent work by *Beechie et al.* [2006] a threshold channel size for migrating streams was found between 15 to 20 m, represented as a gray band in Figure 6-6. It is interesting noticing that despite some of reaches are below that threshold, there is a general correspondence. Deviations could be related to the low density or total absence of riparian vegetation along the margins of some migrating streams used in this work, which is the same reason they were selected in order to make readily the digitalization procedures.

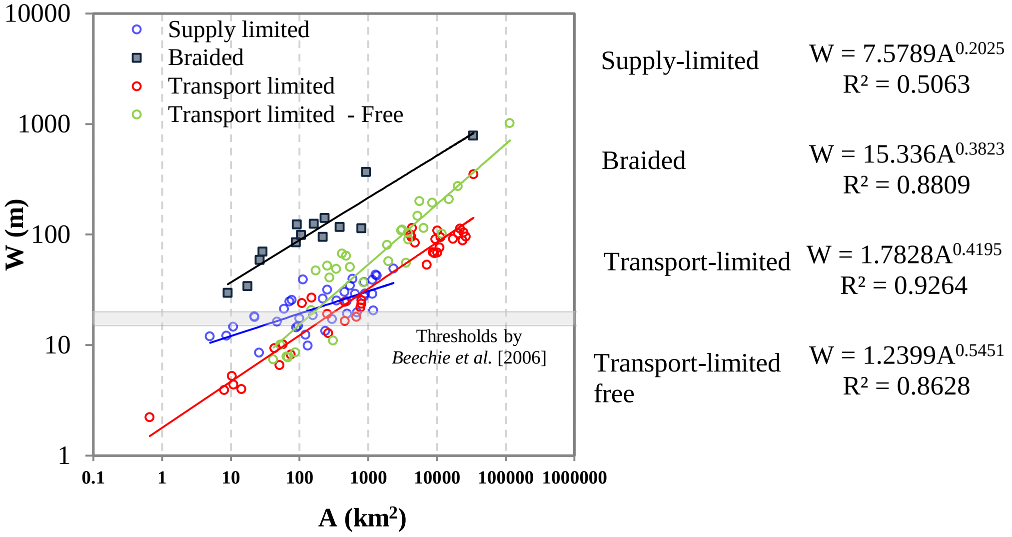

Figure 6-6. Hydraulic geometry for bankfull width

Channel patterns assessment, together with classification schemes based on stream power, must be explored further taking into account the growing availability of more detailed geospatial data both vector and raster. Coupling data formats would be interesting to overcome shortcomings regarding digital elevation models resolution at the upper areas of a watershed, where channels are lower sized, thus favoring digital bend cut-offs which avoid reliable planform assessment only using raster DEM.

6.4 DISTRIBUTED MODELLING

A segmentation method of drainage networks was proposed based on the identification of hydrological (stream confluences) and topographical (knickpoints) nodes, which are used to separate stream reaches. These define topological units which are characterized morphologically and hydraulically based on the findings and outcomes of this work, as well as those posed by previous studies regarding stream classification, hydraulic geometry and solute transport processes.

The *Distributed Solute Transport Model* (Chapter 5) is then proposed as a useful tool for modelling solute transport throughout a basin drainage network. The first intention of such development is to provide a simulation alternative for ungauged basins, wherein is common to have access to digital elevation models, vector drainage networks, and the location of punctual pollution sources. The model capabilities include:

- Digital elevation models processing to enhanced the extraction and treatment of stream longitudinal profiles, and the subsequent reach-slope estimations. The underlain procedures include filtering and smoothing techniques, following by the identification of *knickzones* based on the work by *Hayakawa y Oguchi* [2006].
- Regional maps products including: node locations (hydrological and topographical), stream morphology types, stream reach codes, stream gradients and mean bankfull width.
- Steady and non-steady simulations in terms of the temporal variability of solute disposals to the drainage network. This becomes an important issue for designing water quality monitoring plans and for the model extension to consider water quality issues.
- The model is raster-based, thus making it readily to implement into geographic information systems.

It also worth mentioning that the model provides a characterization of the non-linear behavior of every reach in terms of the variation with discharge of the ADZ parameters t_m and τ, *i.e*, that despite of the actual version of the model was set to consider steady hydrological conditions, it could be easily extended to be integrated with a complete hydrological model.