

Article

Geomorphic river characterization: a systematic, automated approach ~~for~~ river segmentation ~~illustrated~~ for the Magdalena River (Colombia) and ~~the~~ Baker River (Chile)

Andrea Nardini ^{1,2}, Santiago Yopez ^{3,4,*}, Bruno Mazzorana ⁵, Hector Ulloa ⁵,
Maria Dolores Bejarano ⁶, Alain Laraque ⁷

¹ Fundación CREACUA, Riohacha, La Guajira (Colombia), nardiniok@gmail.com

² PhD program in Advanced Forestry Engineering, E.T.S.I Montes, Forestal y Medio Natural, Universidad Politecnica de Madrid –UPM, Madrid (Spain).

³ Departamento Manejo de Bosques y Medio Ambiente, Facultad de Ciencias Forestales, Universidad de Concepción — UdeC, Concepción 407374 (Chile).

⁴ Laboratorio de Geotecnologías y Modelamiento de Recursos Naturales (LGM), Universidad de Concepción (UdeC), Concepción, (Chile).

⁵ Instituto de Ciencias de la Tierra, Facultad de Ciencias, Universidad Austral de Chile, 5090000 Valdivia (Chile), bruno.mazzorana@uach.cl, hector.ulloa@uach.cl

⁶ Departamento Sistemas y Recursos Naturales, E.T.S.I. Montes, Forestal y Medio Natural, Universidad Politécnica de Madrid -UPM, Madrid (Spain), mariadolores.bejarano@upm.es

⁷ Géosciences Environnement Toulouse—GET (Centre national de la Recherche Scientifique—CNRS, Institut de Recherche pour le Développement—IRD, Université Paul Sabatier—UPS), Observatoire Midi-Pyrénées —OMP, 14 rue Edouard Belin, 31400 Toulouse, (France), alain.laraque@ird.fr

* Correspondence: syopez@udec.cl; Tel.: +56-41-220-4684

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Abstract: The problem addressed in this paper is identifying river reaches from a geomorphic point of view. Essentially this implies getting a holistic synthesis from multi-dimensional information gathered through a reductionist approach. While this task is traditionally a subjective, expert based exercise, here we address the possibility to perform it objectively through a systematic procedure that virtually does not require expert judgement once criteria are set. The key difficulty that motivates this investigation is the fact that some of the attributes adopted to describe geomorphic characters of a river (e.g. sinuosity) depend on the length of reaches, while these latter are not yet identified; this introduces, at least conceptually, an unpleasant, implicit, subjective, iterative procedure that we instead skip. The idea here proposed is simply to first build a set of core attributes independent from reach length (each one defining an appropriate, independent segmentation) and then finding the reaches by the intersection of their segmentations. Examples from two rivers (the Magdalena River, Colombia and the Baker River, Chile) are developed and discussed.

Keywords: river reaches; segmentation; automated approach; fluvial geomorphology; River Styles

1. Introduction

The problem addressed in this paper is identifying from a geomorphic point of view river reaches with which a particular behavior is associated. In principle, one might deal with a river by describing its characters (through attributes) all along its course with no need for segmenting it into “reaches”; actually, a river is a composite, often complex, pattern/collection of process transitions

from source to sink, with variable balance of erosion and depositional processes along the way. Identifying parts of the river similar one to another, and different from others, is however very useful in order to develop a meaningful description of character and behavior of a river and to conceive and design interventions. This is where the “reach” concept comes into play. River “reach”, as noted by Parker et al. [1], is a very much used concept, but with a very loose definition, non-homogenous amongst authors (Kellerhals et al. [2] is the key starting point or more recently Gurnell et al. [3]). A geomorphic reach is in the end a length of river that presents a distinctive and recognizable character and process regime. This implies that each single descriptor (called “attribute” in what follows, like for instance active channel width) can be given a meaningful, unique, representative value for the reach, although the underlying variable can vary significantly, but displays a recognizable spatial pattern, a kind of regularity.

We are here a step ahead of the problem of automatically identifying key elements (i.e. active channel, islands, bars) as faced for example by Bertrand et al. [4] or De Marchi et al. [5] with the GEOBIA approach (which recognizes shapes of pieces of land with consistent properties of image pixels) and many other researchers. We imagine to have already identified and characterized such elements, while we now need to interpret their assemblage in order to identify segments of the river (“reaches”) which present a distinctive character (and behavior which provides insights into the ‘range of variability’ and the ‘capacity for adjustment’).

The essence of the problem is to obtain a holistic synthesis from a bunch of reductionist information (presence and characters of geomorphic units and descriptors of the fluvial elements) while recognizing those segments where this synthesis provides a meaningful view. This holds for complex assemblages of features -like those needed to identify planform types- as well as for a sequence of mono-dimensional data (e.g. along a river) from simple attributes of the type “presence, absence” (denoted in what follows as “sporadic attributes” and measured by binary variables). For example, one isolated island along a significantly long reach (depending on the river size) cannot lead to label that reach as an “island reach” (i.e. populated by islands), because it is just a local anomaly; but a series of sparse islands, “here and there”, even separated by some distance, tells us that indeed that is an “island reach”. Essentially, we need to capture a prevailing character seen at an appropriate scale that depends on the river at hand. In addition, we must capture “things that matter” as, in particular in biodiversity terms, rare/unique features are often the pivot, and must be viewed alongside common features. This means that a good part of the exercise relies in choosing the appropriate descriptors (attributes).

The following discussion is quite general, however, it has been originally developed to deal with the application of the River Styles Framework of Brierley and Fryirs [6] (denoted “RS” in what follows) where a “procedural tree” specifies a set of relevant attributes to be adopted for the characterization and (open-ended) classification of a river, subdividing it in meaningful reaches. In all what follows “confinement”, unless differently specified, is hence meant as defined by Fryirs et al. [7] and O’Brien et al. [8], i.e. as a statistical measure of the contact length between the active channel and either of valley bottom margins.

In all what follows we refer just to “forms” unless time is involved (i.e. looking at changes). This is not at all to say that processes are not relevant, but rather to stress that, in general terms, as a starting point, the characterization of a river indeed just looks at forms (including presence of bars, levees, etc.) and later infers processes. It depends on the choice of attributes, because if attributes like “stability” or “activity” (i.e. the rate of movement recorded in the past) are included, then processes are directly called into play. The important point, however, is that here we are just concerned with defining reaches; an investigation of the historical evolution of each reach is in any case necessary to fully understand behavior and changes occurred, but can come at a later stage.

2. Approaches to identify reaches

It is out of the scope of this paper to discuss in an exhaustive fashion the various possibilities relevant for the problem addressed; what follows has rather to be viewed as a logical framing of the discourse. Different options are available (and mixed solutions are possible too) which can be classified as follows:

- a) Manual segmentation based on expert judgement (most applied)
- b) Artificial Intelligence and Machine Learning algorithms based on image recognition
- c) Statistical algorithms
- d) Logical or heuristic algorithms.

The traditional procedure (approach a) to determine reaches (as resumed for instance in the REFORM project: Bizzi et al. [9]) is based on a preliminary segmentation (based on changes of slope, valley bottom width, basin area because of tributaries input), then further refined by considering confinement, sinuosity, planform and additional aspects which are based on a more or less explicit holistic recognition by expert judgement (a structural, taxonomic approach for such units is for instance proposed by Wheaton et al. [10]).

There are a few difficulties associated with this procedure:

- it is expert-based, subjective, not replicable, and work-intensive (although subjectivity implied by expert judgment also ensures flexibility and the capability to appraise things that really matter)

- it includes an intrinsic kind of paradox: several attributes depend on the segment length chosen (e.g. sinuosity, confinement: we call these *extensive attributes*), a length which, being the reach itself the sought output, at the beginning is still undefined (see Figure 1). Essentially, the characterization is impossible without the reaches, but these can only be defined through a characterization process. The only practical way out from this difficulty is undertake iterations that are, however, traditionally driven by intuition and remain hence obscure. The result is that different experts may come up in general with not coinciding segmentations.

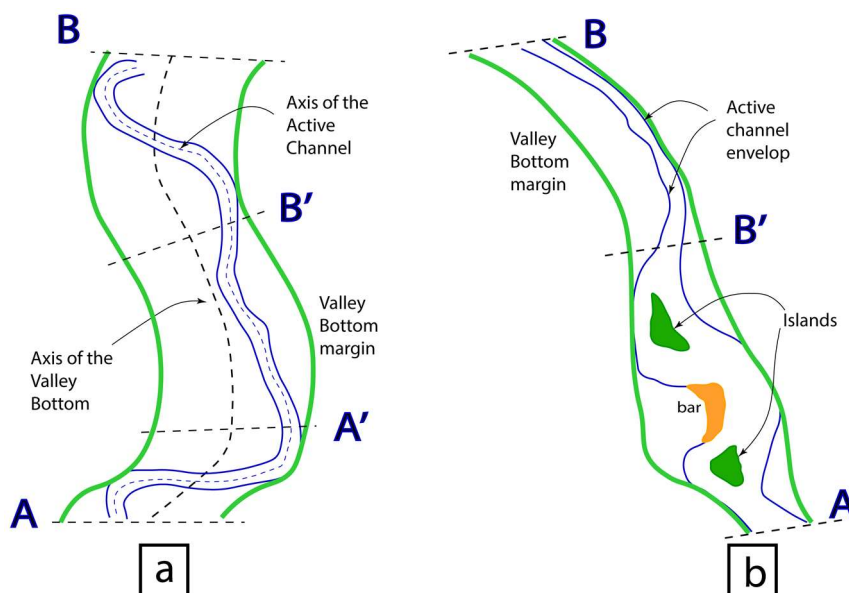


Figure 1. Examples of ambiguity related to extensive attributes: (a) Sinuosity of segment A-B is much higher than that of segment A'-B' (almost straight); that of A-A' is even higher; (b) Example of the problem implied by the usual procedure for defining reaches: based on confinement, the whole segment O is identified as "confined" because along more than 85% of its length one of either banks of the active channel is in contact with the valley bottom (VB) margin; however, based on planform, two well different sub segments are identified (A, B); but now confinement for segment B gets the value "partly confined" (because the total contact length is less than 85%, but more than 10%) (definition of confinement according to Brierley and Fryirs, [6]; Fryirs et al. [11]; O'Brien et al. [8]). A similar behavior occurs with the other attributes, so each time an attribute (in particular amongst

those envisaged in the RS procedural tree and concerning presence of geomorphic units) comes into play, all previously assessed attributes need to be re-assessed possibly obtaining different values.

Notice, by the way, that when the river moves (adjusting without changing character), “confinement” possibly changes; as it is the head of RS classification procedure, this may imply dramatic changes in RS classification and requires a lot of work to be re done!

Artificial Intelligence-AI (approach b) develops suitable algorithms (e.g. based on Artificial Neural Networks: Rutkowski, [12]; Olson and Delen, [13]) that go beyond the pure interpretation of spatial configuration (by itself very powerful, as shown for instance by Jacquez, [14]), being able to interpret the whole assemblage of a wide array of elements (spatial configuration, altimetry, "colors"). Incidentally, it can be observed that more than "intelligent", anyway, they should be denoted as "powerful, visual-memory, comparers". In any case, there are hindrances:

- AI depends on training, it is not able to face unexperienced situations in fact, as noted by Bhamare and Suryawanshi, [15], "The general problem of recognizing complex, arbitrary patterns with arbitrary orientation, location and scale, remains unsolved...";

- It is computationally heavy.

- Unavoidably, AI algorithms must be informed by a subjective choice of scale, otherwise they can “get lost” as they could jump into finer and finer scales capturing irrelevant distinctions of forms assemblages.

- The outputs of AI algorithms heavily depend on the images resolution and are hardly exportable to other situations.

- Most important, AI would just provide the label assigned to that type of image, but it cannot explicitly inform on the attributes (although from a kind of signature some related information can be extracted), while this is vital to the aim of producing reaches accompanied by clear, understandable, descriptors.

For approaches c) and d) the problem faced is obtaining a holistic synthesis starting from reductionist, analytical information associated with nearby points (or “segments”) along a river. So, they need a regular discretization of the whole Valley Bottom (VB) and river in “slices” (polygons pseudo-perpendicular to the VB axis), associating with each VB slice the value of all relevant attributes or the information needed to determine them (e.g. the presence/absence of a geomorphic unit, see Figure 2). We refer to this base as the “skeleton” which is -by the way- what can be set up by means of the Fluvial Corridor Toolkit (FCT) (Roux et al. [16]).



For mono-dimensional attributes, statistical approaches (c) that automatically and objectively identify relevant changes have been discussed by Parker et al. [1] who provide an interesting literature synthesis starting from geological analysis (Harmar and Clifford, [17]), recalling Davis' [18] classification in i) "local boundary hunting" and ii) "global zonation". These latter are best suited for the identification of river reach boundaries because they statistically minimize within-reach variation and maximize between-reach differences and are less influenced by local inconsistencies in the data sequence. Hubert, [19] introduced a test which works in a similar manner and is considered the key tool within the Fluvial Corridor Toolkit (Roux et al. [16]) in order to define separate reaches. Although possibly the best performing one, still its outputs are not exempt from questioning (Figure 3). Martinez-Fernandez et al. [20] applied similar tests by comparing three techniques: the Pettitt, the Mann-Kendall and the MRPP (which is commented afterwards) with three different river attributes (the VB width, the active channel width and the slope); their conclusion is that the three tests lead to quite different results, being Pettitt and MRPP the less diverse, while the VB width is the most explaining attribute.

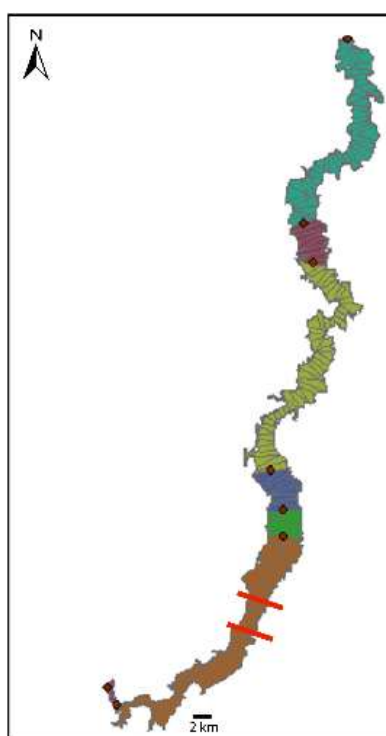


Figure 3. (A) Example of segmentation of a continuous, quantitative attribute (the VB width of a stretch of the Magdalena River) via Hubert statistical test (as implemented in the Fluvial Corridor Toolkit): the output (stretches of different colors) is questionable as, for instance, the stretch marked by the two red segments (amongst many others) would certainly be classified by expert judgment as narrower with respect to the one above it (notice that there is no criterion linked to the length as Hubert test determined both short and long segments): (source: Nardini et al. [21]).

Moreover, it must be recognized that all these techniques have been designed thinking of quantitative, continuous, mono-dimensional variables; when binary (e.g. presence/absence of a geomorphic unit) or categorical variables (e.g. planform typology) variables are involved instead, they conceptually and practically fail. We are not aware of working extensions to multivariate data sequences (as envisaged for instance by Davis, [18]). The non-parametric Multi Response Permutation Procedure (MRPP) test experimented by Martínez-Fernández et al. [20] might seem a suitable candidate in this class, however we better see it as belonging to the category d) (discussed below) as in its operational version it resembles more to a randomized search than to any statistical algorithm. In fact, it randomly considers clusters of sequential slices (i.e. setting "cuts" of the river

axis) measuring each time the dispersion around the mean in each cluster trying to minimize it, while maximizing the difference amongst clusters. Unfortunately, MRPP too cannot work with categorical variables like the planform typology.

For the multi-dimensional case, Bizzi and Lerner, [22] present an interesting development based on the Self Organizing Maps (SOM) technique, which can be classified as a type d) algorithm, as it is not based on statistical criteria. It groups multivariate data in an exogenously imposed number N of clusters; such data, once grouped, can be tracked back by their identifier and located along the river axis so originating reaches.

Notice that to this aim, for our fluvial case, again, an a priori, arbitrary, regularly spaced discretization (“slices”) has to be carried out and all attributes have to be assessed on each such “slice”, as shown in Figure 2.

The purpose of SOM is grouping similar data; in addition, it is inherently multidimensional. Therefore, it would be more reasonable applying it to cluster data by considering all the relevant attributes at a time, i.e. all their dimensions (Bizzi and Lerner, [22] considered, by the way, a limited set of attributes not coinciding with those suited for a River Styles analysis). In such a case, however, it would face a difficulty linked to sporadic or extensive attributes because these, by constitution, cannot meaningfully be determined over arbitrary segments (and different discretizations would produce completely differently behaving data sets: imagine a “presence of islands” binary variable that occurs with a 1 value in a segment and 0 in the following, while both belong physically to a given longer reach with sporadic islands). Moreover, SOM cannot deal with categorical variables (e.g. planform typologies) because it exploits as a measure of “similitude” a Euclidean distance which can only be computed for quantitative variables (or at least variables defined on interval scales, where difference have a meaning as explained in Volta and Servida, [23]).

Bertrand et al. [4] present a logical-heuristic approach that, as will be apparent in the next section, is very similar to the one proposed here. Their aim is to identify reaches with different and meaningful river typologies (as a result of sediment replenishment interventions). They do not address explicitly the core circular problem underlined here (reaches → characterization → reaches) and they somehow bypass it by identifying “homogeneous units” based on active channel width and valley bottom width only. Then, they define a large number (30) of attributes with associated quantitative or qualitative (categorical) indicators, for each “slice” of the discretized river. Some of such attributes are indeed extensive and as such defined and calculated over such homogenous units (i.e. segments). After a first screening of such attributes via Principal Component Analysis to identify the most meaningful ones (independent), they carry out a classic cluster analysis which identifies indeed a few river typologies with their associated reaches. This strictly speaking leads to a certain degree of inconsistency because the extensive indicators should now be computed over the found reaches, not over the original homogeneous units giving hence rise to iterations.

3. A “humble” new method for defining “reaches” and their characters

In this section we explore ~~therefore~~ an alternative “logic-heuristic” approach which at first does not try to identifying clusters of similar data, but rather exactly the opposite, i.e. the diverse ones in an exhaustive fashion (with the only restriction to neglect the too short reaches). The identification of “similar” reaches is then the focus of a second stage, dedicated to classification where also the attributes not considered in the first stage of identifying reaches are included, with no forcing linked to discretization (and hence, no distortions). In what follows we address only the first part of the problem; an example related to the second part is presented in Nardini et al. [24]).

3.1. Concept

Our proposal is simply to first build a core set of attributes (all *intensive*, i.e. not requiring reaches to be given), which define, each one, a specific, independent segmentation of the river. Then, we find the reaches essentially by the intersection of their segmentations. Extensive attributes like confinement and all the attributes describing the presence of geomorphological units within the active channel or the floodplain are then computed as statistics over the reaches so identified: they do not contribute hence in defining the reaches, but they still play an important role in distinguishing different typologies of reaches, together with the main attributes. In such a way, the ambiguity of current manual practice is avoided.

In practice, the definition of reaches is organized in three steps:

- a) Choose and assess core geomorphic attributes.
- b) Identify geomorphic reaches as a “least common denominator” (spatial GIS intersection) of such segmentations.
- c) Refine the result found by considering anomalies (like artificial disconnections by civil works) and possibly (automatically) eliminating very short reaches with respect to the scale of analysis.

This extremely simple procedure does not require any particular algorithm (apart possibly the last step), does not need any training, nor is restricted to experienced datasets. In addition, it makes explicit which characters do specify each reach. It can be noted that curiously this solves the multi-dimensional holistic view problem essentially by a mechanical sequence of mono dimensional operations.

3.2. Choosing and assessing selected attributes

Concerning point a), criteria to choose the “core attributes” are as follows:

- Avoid extensive attributes, because they cannot be properly determined without a prior segmentation.
- Consider just few attributes, because there is a certain degree of intrinsic redundancy, so many just complicate things (this statement has not been proven statistically in a rigorous fashion, but is supported by experience and, amongst others, the two case studies presented in this paper).
- Avoid those describing the “presence-absence” property of geomorphic units (binary attributes), because these are irregular, spatially spread spots of “yes or not” hard to interpret. Notice that this does not imply at all disregarding such attributes (they may be very insightful in process terms, as is the case for instance of levees or ridges and swales), but just that they are not used to split the stretch into reaches.
- Prefer those clearly recognizable on a map (imagery).

Relevant attributes hence are for instance Valley Bottom width and Entrenchment (ratio of Active Channel width over Valley Bottom width), because they are intensive attributes and they are visible in a map view (or image). Others however can be added, like active channels width, number of active channels, bed sediment texture, bed morphology. Even some process attribute, i.e. intrinsically linked to time, like channel activity (recognizable by the presence of bars) can be adopted. However, the simplest choice (few attributes, easy-to-determine) is probably sufficient and as such preferable.

In any case, it is assumed that for each of such core attributes it is possible to define a proper segmentation of the active channel where each of the spatial elements assumes a clearly determined

value of the indicator measuring the attribute. In other words, we assume they are spatially discrete. This is clearly an abstraction (e.g. bed material can vary virtually continuously longitudinally –and laterally/vertically), and all attributes require in general carrying out some kind of spatial averaging, smoothing out too frequent variations along the river. Actually, often local scale patterns are very insightful in process interpretations (e.g. reworking), but we are still far from linking this information to the ‘range of behavior’. Still we assume that this procedure is reasonably acceptable in practice for the segmentation purpose and can be supported by suitable reductionist-holistic algorithms (e.g. the Hubert test, as proposed by the FCT, for quantitative, continuous attributes, like VB width; or the Categorical Holistic algorithm proposed in Nardini et al. [21]).

Attributes like bed slope or specific streampower, apart from not being recognizable from a map, are here considered of extensive type and hence not suited. In fact, slope (the same holds for streampower) could be defined virtually in each point, but from a geomorphic point of view the relevant slope is not that one, but rather the average of a still unknown reach. On top of that, if slope is computed based on the thalweg elevation severe inconsistencies may be generated as the section geometry may vary greatly along any stretch (the bankfull channel slope would be preferable, i.e. the VB slope divided by sinuosity, which again...depends on the still unknown reach length).

If a scheme like the River Styles Procedural tree is adopted, the core attributes have to be selected just within those included in the procedural tree, because it is with them only that a classification is obtained. Other attributes (like slope, contributing basin area) either influence the original attributes, in which case they are redundant, or they don’t, in which case they are transparent to the final classification (and hence useless). This does not mean that information like the location of tributary inputs or slope changes be ignored; that will be considered at the level of reach scale analysis (e.g. the “proformas” envisaged by the River Styles Framework) because with them a change of flowrate, sediment load and streampower is typically associated.

The specific choice of core attributes in relation to the River Styles framework hence certainly falls on *planform typology*, and *bed material texture* (sediments), as all the others are extensive. The RS Procedural tree does not involve VB width directly (it does indirectly through confinement), and as such it would not be essential, provided that planform be accurately defined. Anyway, being VB width certainly a key control factor, it may be used in replacement of others missing for some reason, as in the Baker case study presented below.

At this point, it may be objected that we did not solve anything as planform itself rises the same difficulties we started from: it is multidimensional as it depends on a number of elements, like: number of active channels with their size and relative location; sinuosity; spatial pattern of geomorphic units like bars, and so on, requiring a holistic synthesis; and it is not a pure “intensive” attribute, because all this depends again on the segment length considered (sinuosity in particular). Of course, expert-based planform-recognition is the traditional way (which has also been applied here), but here we are wondering whether automation is possible and suited, therefore the weaknesses of AI algorithms previously briefly pointed out re-emerge here. However, there is a substantial difference: now, concerning planform, we are just interested in assessing a categorical attribute within a finite set of possibilities, with no particular need to distinguish the underlying attributes; therefore, an automatized identification based on image recognition (through AI algorithms) is sufficient, and other automated approaches are also possible like for instance adopting a logical-heuristic algorithm (this idea has been developed by Nardini et al., [25]); but this cannot be applied to the original problem we started from because the characterization –particularly in the RS Framework- is open-ended so there is no a pre-defined finite set of typologies. A scale of analysis has to be provided, but a typical criterion of a significant length L_s of about one order of magnitude larger than the width W (i.e. $L_s = 10\div 20 W$) can work, where W is the width of the envelop of completely connected active channels. This does not mean that segments of a given attribute SHP polyline all have an L_s length; but rather that differences amongst contiguous segments are searched for with a

detail of that order (not finer, nor coarser). Segments can result hence longer but not (significantly) shorter.

Perhaps another doubt arises, doesn't it make sense to just assess all relevant attributes over pre-defined segments defined by this significant length criterion? In our opinion the answer is "no", as argued in subsection 3.4 "Avoiding inconsistencies".

3.3. Identifying reaches

Concerning point b), we can systematize and simplify the required procedure as follows:

- Obtain the candidate reaches by intersection of the segmentation of each "core attribute".
- Possibly consider new cuts where natural singularities (e.g. waterfalls, rocky outcrops, isolated constrictions or tributary inputs) or anthropogenic interventions (transversal infrastructures like dams or weirs) are present.
- Refine the output by eliminating too short reaches (always possible because of approximate definition of single attributes), either manually or by an automatized algorithm like that presented in Nardini et al. [21]).

The suspicion may arise that two consecutive potential reaches, where the core attributes are constant (say, same sediments and same planform typology), instead differ by confinement or sinuosity: the procedure proposed would not distinguish them. But the most likely reality is that...it is indeed a unique reach with just a local anomaly and as such it is correct that the extensive attributes (confinement, sinuosity, etc.) be computed over its full length.

Anyway, if objectivity and automation are not a concern, it is always possible to intervene manually and cut the candidate reach into further parts. Notice, then, that this procedure is likely to produce different reaches when fed with the information related to different time instants because some of the attributes may have suffered some changes. Getting hence reaches that vary in time introduces a serious difficulty in the analysis of time changes. However, it is easy to realize that this same difficulty arises with the traditional, expert based approach too.

In conclusion, the output, consistent with the River Styles Framework, would eventually be of the type: "confinement C [unconfined, partly confined, confined], planform P [single channel sinuous, or island braided, etc.], with bed material M [sand, or cobble and gravel, etc.], and [continuous or discontinuous, or absent, prevailing, etc.] levees, [continuous or discontinuous, or absent, prevailing,...] islands, etc."

Interestingly, this whole exercise, by its own structure and contents, can substantially be automated through PC aided Tools and procedures.

3.4. Avoiding inconsistencies

It is important to notice that this procedure avoids possible inconsistencies that may occur if one includes within the core set also segmentations built on intrinsically extensive attributes. Think for instance of sinuosity: one of the new shorter segments (reaches) obtained by intersection of its segmentation with that from other attributes may possibly present a different ratio of the river axis over the VB axis lengths. Or think of the attribute "island reach" already introduced above based on a significant (frequent) presence of islands: a "yes" value for the original stretch may occur while now, in a shorter reach obtained by intersection, no islands may occur within it. Although this latter is not, from a logical point of view, a mistake, it clearly is an undesirable output. The proposed procedure avoids it.

On the other hand, also a radically, seemingly simpler approach would be just to define reaches by a regular discretization of segments of, say, a significant length ($L=10 \cdot W$), although clearly simpler, would lead to inconsistencies. This is because some reaches physically characterized by a certain value of the continuous attributes -like planform or bed material- would be cut into parts, and all extensive attributes (in particular confinement and sinuosity) would be computed over segments that mix such continuous attributes leading to inconsistent outputs (Figure 4).

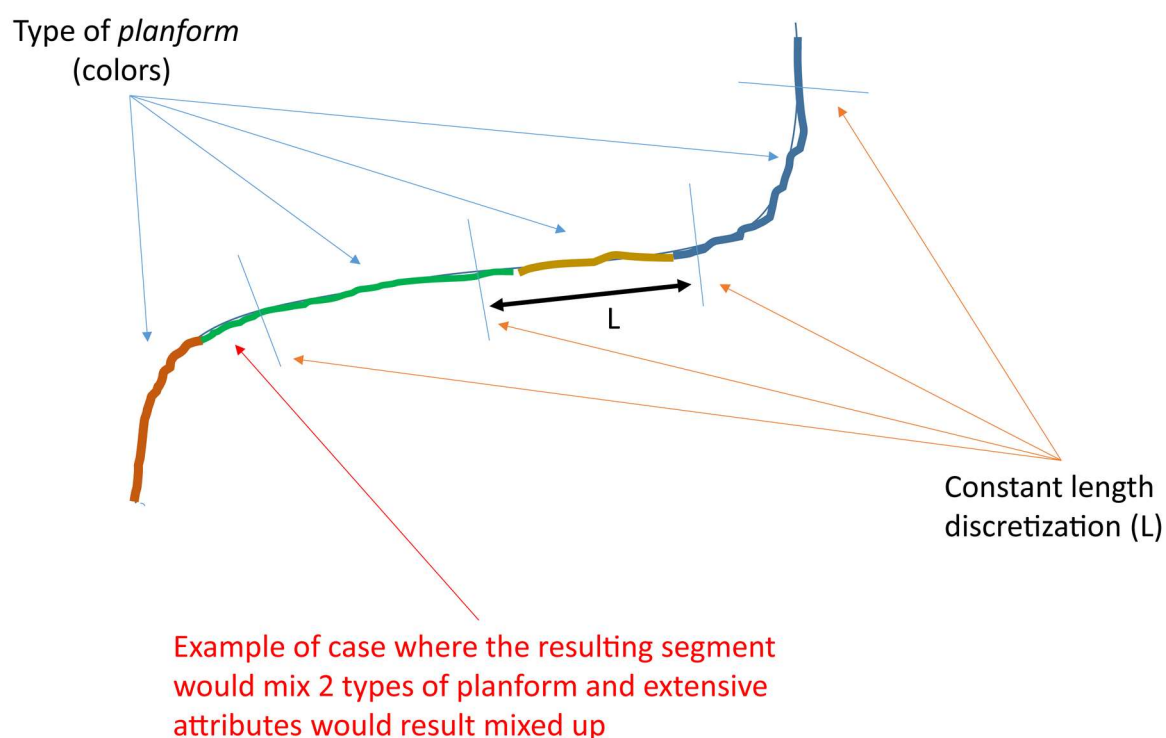


Figure 4. Hypothetical exemplification of why blind discretization is not an appropriate solution.

4. Case studies and discussion

In the two Appendices we present a case study on the Magdalena River (Colombia) and another on the Baker River (Chile) to investigate the appropriateness of the method proposed. In principle, it would be advisable to compare in a straightforward manner the final segmentation (reaches) obtained through our method with that obtained by the traditional, expert-based procedure (Approach a). As, however, the Magdalena River is a very long one and at the moment no specific traditional segmentation is available, we here proceeded by focusing on some emblematic stretches where additional attributes, that would be considered in a traditional procedure, may present significant novelties and as such would introduce a reach break. We refer particularly to slope, Valley Bottom width, and contributing basin area, i.e. tributary inputs. If no reasonable additional change would result with respect to those already identified with our method, the test is considered successful. This test is however weak because in order to judge whether a new reach break would be introduced, apart considering the occurrence of instream geomorphic units (bars, islands), we just look basically at planform type, which is one of the core attributes already adopted in our proposed methodology to identify reaches. The test would hence try to identify changes missed in the previous characterization and possible lacks of overall consistency amongst distinct attributes. This is more meaningful thinking in particular of the River Styles Framework where reaches are identified, characterized and classified essentially by looking only at attributes recognizable from a map. Another criterion adopted, possibly stronger, is to analyze the partly confined stretches and discern whether – based on expert judgement- they would have deserved a further subdivision based exactly

on the degree of confinement (one of the traditional criteria adopted); if not, the test concludes satisfactorily.

Of course, here, like in the traditional approach, the possibility holds to introduce new cuts according to natural or anthropogenic anomalies; but, as this would work the same way in both approaches, we did not consider it explicitly (and any way it can be easily automatized by counting on SHP with the appropriate information).

The two cases deal with large flowrate rivers, a long one (the Magdalena) and a relatively short one (the Baker).

As a general conclusion from this exercise (see Appendix 1 and 2), we can state that the test has been successful in both cases, i.e. the criteria generally adopted in the traditional approach to identify reaches would not lead to a segmentation different from the one obtained with our methodology. The VB width appears to be a key factor (as, by the way, assumed also by Bertrand et al. [4] and found by Martinez-Fernandez et al. [20]) and the slope changes too (at least for the Baker), however, they do not add new information to that conveyed by the chosen attributes. All this supports the suggested criteria for the choice of core attributes as there is an evident correlation amongst attributes, particularly as far as changes in VB width, slope and planform are concerned. Although these observations only hold for the two case studies considered, we guess this may be a quite general result.

In Annex A of the Deliverable D2.1, Part 2 of the REFORM project (Bizzi et al. [9]), an experience is presented which resembles very much the approach we presented here. However, some important improvements are introduced here, we believe: our methodology clarifies how sporadic and extensive attributes (like the presence/absence of geomorphic units and confinement, respectively) can be incorporated; we provide criteria to select core variables in general and specifically for a River Styles oriented analysis; our approach explicitly exploits the areal segmentation of the Valley Bottom (obtainable in particular with the Fluvial Corridor Toolkit) to assess presence-absence binary indicators, very suited to deal with geomorphic units; it explores a completely different technique from the statistical, mono-dimensional Pettitt (or Hubert) test, through a new logical-heuristic holistic algorithm (which applies a significant length restriction concept); last but not least, it simply avoids redundancies. Finally, the whole procedure to determine reaches is defined.

Concerning Bertrand et al. [4], it has to be noted that they chose their attributes with criteria rooted in the theoretical understanding of riverine ecosystems joined with engineered thought, leaving to a logical-heuristic algorithm (clustering) the responsibility to reveal which attributes carry indeed more information (although introducing an inconsistency related to the length adopted for extensive attributes). Adhering, however, as done here, to the River Styles scheme has the advantage to lead to an identification of reaches, and their characterization-, which supports a more straightforward behavioral interpretation based on an established logical scheme (that of Brierley and Fryirs, [6]).

The SOM algorithm adopted by Bizzi and Lerner, [22]) and the MRPP algorithm adopted by Martinez-Fernandez et al. [20]) seem quite promising as they use multidimensional algorithms that, in principle, might lead to the sought holistic synthesis of the set of selected attributes. However, they cannot deal with categorical attributes.

5. Conclusions

We believe this paper states the segmentation problem in a clear and original fashion as one of obtaining a holistic synthesis from reductionist information while focusing on the distinction between intensive and extensive attributes, distinction which lies at the core of the discourse.

It presents a methodological - operational improvement to obtain meaningful reaches in a very simple, systematic and objective fashion. It also solves the paradox “reaches → characterization → reaches” and clarifies how other important sporadic or extensive attributes like confinement or presence/absence of geomorphic units can be incorporated.

In addition, the output of the here proposed methodology hence a double value with respect to the River Style characterization problem: reaches are defined, and intrinsic (by construction) consistency with the RS framework is ensured. We believe this can make the RS approach much more applicable by practitioners than it currently is.

In summary, this paper constitutes a step forward for the automation of the whole process of river analysis, assuming that soon the algorithms for the interpretation of satellite images will allow to automatically identify the active channel and its geomorphic units in the channel and within the floodplain (e.g. Bertrand et al. [4]; and Fryirs et al. [7] for a recent review; and for instance the CHAMP project, <https://www.champmonitoring.org/>). In particular, the whole River Styles characterization can basically be automated: assess attributes (mono or multi attribute reductionist-holistic exercise), identify reaches (this paper), classify them (see Nardini et al. [21]).

In agreement with the Fryirs et al. [7] “plug in” paper, it is vital to respect diversity and total automation is quite alarming in some ways. But what is proposed here is just the systematized information basis for characterization, while the interpretation of behavior is left in the hands of expert judgment, at least for the moment being, as is the detailed definition and selection of suited attributes (procedural tree).

Of course, our conclusions need further experimentation and a systematic research aiming at proving statistically the correlation amongst attributes would certainly be of great support.

Author Contributions: Conceptualization: A.N., S.Y., B.M. and H.U.; Methodology: A.N., S.Y., B.M. and H.U.; Software: S.Y. and H.U.; Validation: A.N., S.Y., B.M., H.U., A.L. and M.D.B.; Formal analysis: A.N., S.Y., B.M. and H.U.; Investigation: A.N., S.Y., B.M. and H.U.; Data curation: A.N., S.Y., B.M. and H.U.; Writing—original draft preparation: A.N. and H.U.; Writing—review and editing: A.N., S.Y., B.M., H.U., A.L. and M.D.B.; Project administration: A.N. and B.M.; Funding acquisition: A.N. and B.M.

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Conflicts of Interest: “The authors declare no conflict of interest”.

Appendix A. Magdalena River

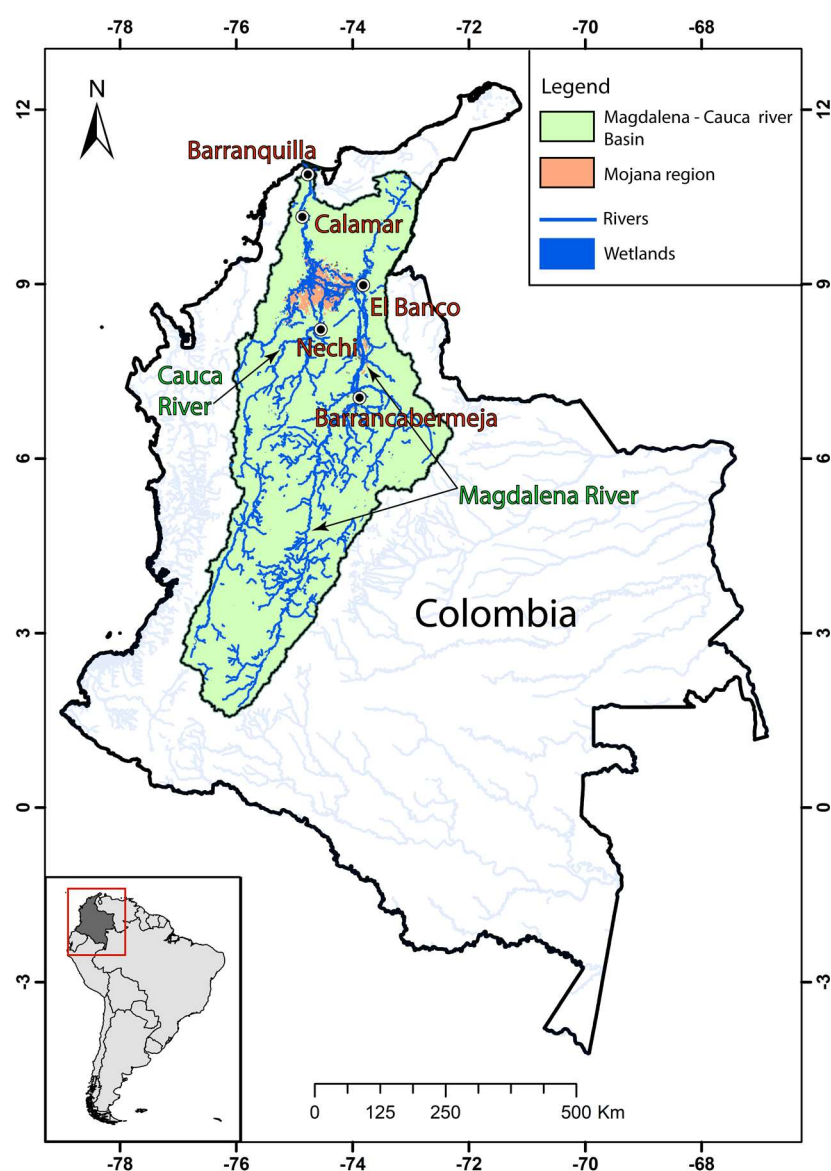


Figure A1. Location of the Magdalena River basin (Colombia).

The Magdalena is a large river with an average flow rate of 7200 m³/s (Restrepo, [26]) and a length of the axis of its Valley Bottom of approximately 1400 km (the river is longer). This implies that any elaboration is quite time demanding and the typologies displayed very numerous and diverse (Nardini et al. [24]). The core attributes selected in the cited study are: Planform type, Bed material texture, Stream surface (as a substitute of bed morphology, invisible in turbid rivers like the Magdalena). It must be reminded that they have been assessed at a preliminary approximation level, as information is scarce and disperse (see the original GeoMagda project report for details: Nardini et al. [27]).

The essential results obtained by applying the method proposed are shown in Figure 4. In total, 43 reaches have been identified.

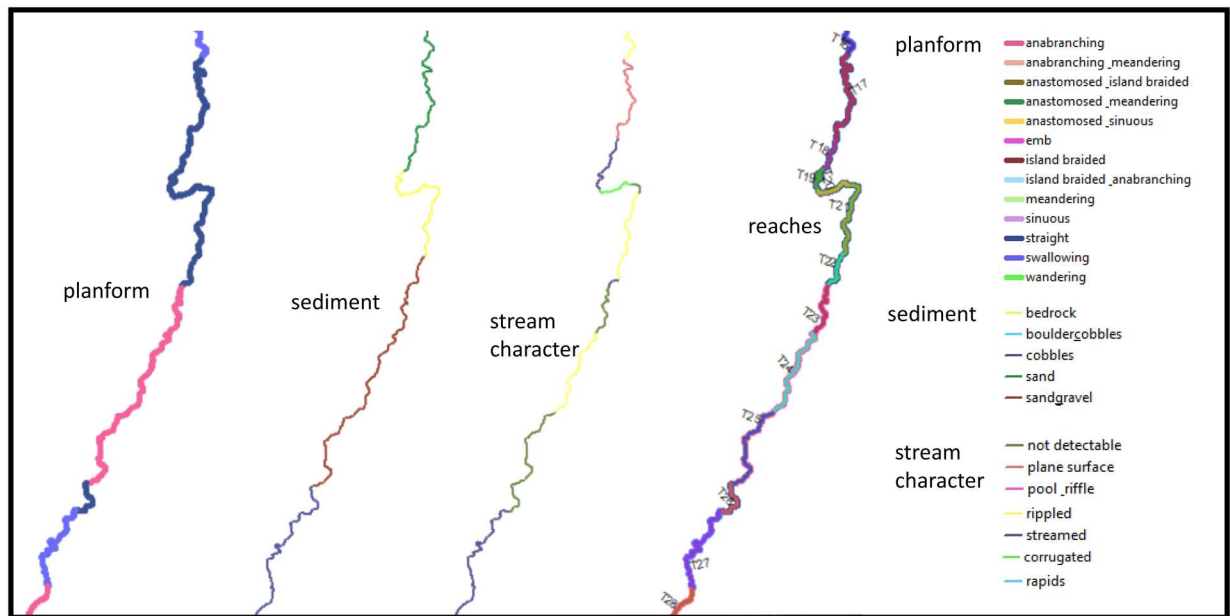


Figure A2. Magdalena case study: Definition of reaches for a stretch of the Magdalena River (Colombia) obtained within the GeoMagda TNC-CREACUA project via the procedure presented here. From the left: segmentation of the: planform type; bed material texture; stream surface (“current”). Right: final Reaches. (Approximate scale: 1: 3,000,000). It can be noticed that, after applying the categorical Reductionist-Holistic algorithm (Nardini et al. [21]), a short reach of current segmentation exactly on the elbow has been removed because shorter than the chosen significant length of 5 km.

The first criterion based on slope changes could not be applied because apart the upper, mountain stretch, quite marginal, the resolution of the adopted DEM (SRTM 30 m) was too rough. Valley Bottom width shows several minor changes and a few ones quite relevant as shown schematically in Figure A3.

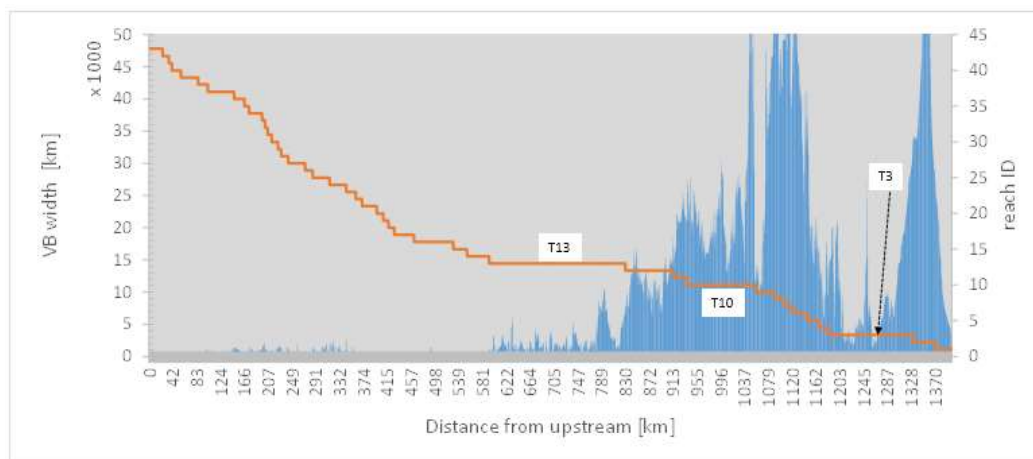


Figure A3. Schematic representation of VB width (blue line) along the Magdalena (upstream is on the left) and of the different reaches determined with the proposed methodology (orange line, with axis on the right); they range from the first at left (T43) to last one on the right (T1) (but they do not relate proportionally to elevation). Reaches T3, T10 and T13 commented in the following are located here. VB width values greater than 50 km have been cut (max is around 80 km) as they do not change the general appreciation, while hiding useful details.

From such figure, the first reach where VB begins to be significantly present is T13; from the same figure, visually it would seem to deserve a further subdivision at its right end because of VB variations. The details shown in Figure A4 demonstrate that the general planform character keeps being island braided with subtle variations (larger and more frequent islands and more tiny lateral channels in inset B than in A); a more marked difference is that in A the river is confined, while in B it is only partly confined and the scale would perhaps support this distinction as the significant length $L_s = 10 \div 20 W$ (being W the width of the active channel envelop) is here about $20 \div 40$ km. Finally, inset C shows that in the short, narrow stretch in the middle, the planform is rather single channel, straight; its length however is quite short and as such should be considered a local constriction. As a conclusion, this case shows that the VB width is a key attribute to discern different reaches, but also that the significant scale issue plays an important role. In this case, staying on the lower bound of it, would have led to identify additional reaches based on the planform criterion itself, but not when the upper bound were adopted.

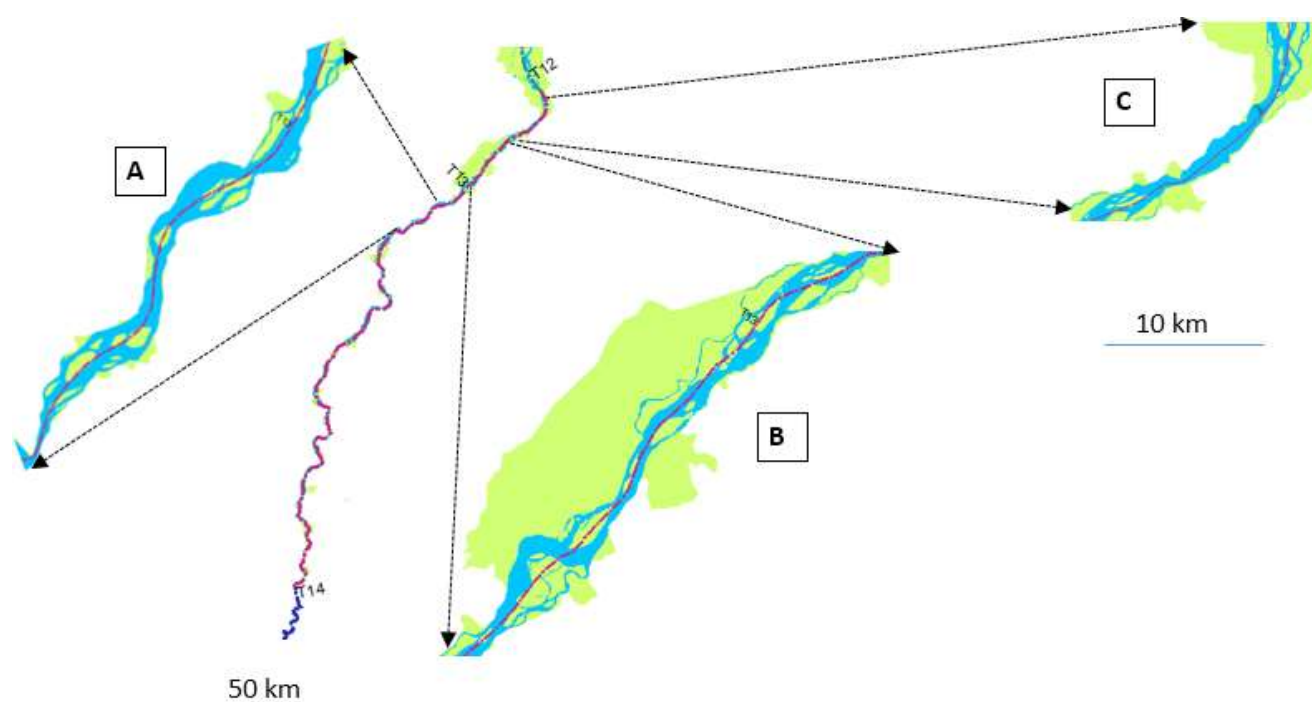


Figure A4. Reach T13 as an example of reach where the VB width criterion might bring in further cuts (main stem scale 1:5,000,000; zoom's scale 1:500,000).

Another emblematic case, according again to Figure A3, is that of reach T3 that seems insensitive to a couple of VBs narrowing and a central peak. As visible in Figure A5, the narrowing (or the enlargement) actually does not change at all the planform character of T3 (compare insets A and B); and the anomalous, local VB widening has to be attributed to an imprecision in the original DEM (SRTM 30 m) adopted for its determination (by the Fluvial Corridor Toolbox).

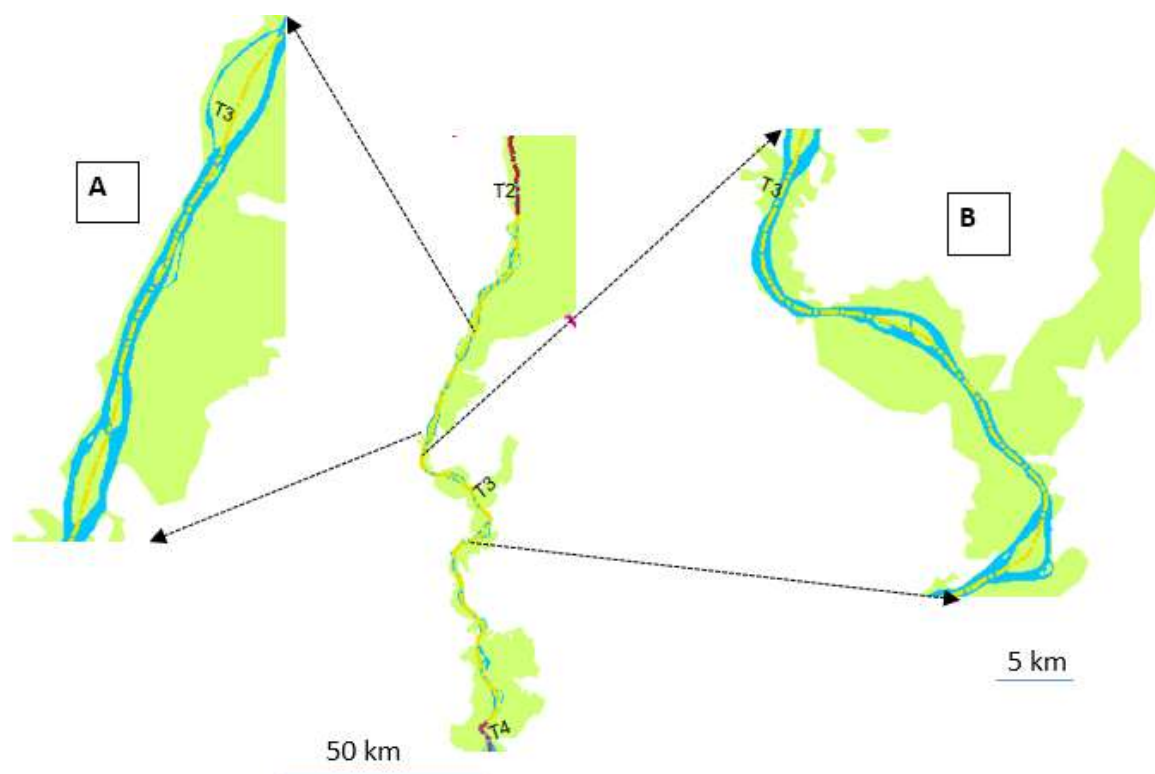


Figure A5. Reach T3, an irrelevant anomaly linked to low DEM resolution in the VB determination.

As far as tributary inputs are concerned, Figure A6 shows the situation related to the main ones, which is here commented:

- a) Rio Suaza (reach T38, T39): no news are introduced with respect to the results obtained; there already is an almost coinciding reach break due to the “Current” attribute which switches from “corrugated” to “pool & riffle”;
- b) Rio Paez (reach T37): a news seems to be introduced as the AC width (light blue) slightly increases; but this effect is in reality due to the nearby downstream Betania Reservoir that induces a backwater effect (neglected in the original analysis);
- c) Rio Cabrera (reach T26, T25): no news are introduced; a planform change had already been detected downstream (upwards in the figure) switching to reach T25 because of a change in both planform (from single, straight to anabranching) and sediments (from cobbles to sand & gravel) which may be due ultimately to the sediment load of the tributary, but is also evidently linked to a local increase of VB width;
- d) Rio Prado (reach T24): no news is introduced; what may seem a local, downstream widening, occurs in several locations along this very same anabranching, sand & gravel, rippled surface reach;
- e) Rio Saldaña (reach T23, T22): a planform change was already identified (from anabranching to straight sinuosity-constrained), mainly due to the VB width; a confluence bar and further downstream bank attached bars appear, but even 6 km upstream there already was one. No news is therefore introduced;
- f) Rio Sumapaz and Bogotá: a current change had already been detected which, however, is almost certainly due to a change of the satellite image observed. The presence of an island right before the Bogota River input may be linked to a certain degree to the sediment input and backwater effect induced by the two tributaries, together with a slight local slope change (not detectable with the

information available). In any case, essentially the tributary inputs do not introduce novelties mostly because this is a sinuosity-confined, bedrock stretch;

g) Rio Negro (reach T13): this important tributary does not introduce significant novelties in the planform, nor in the VB width, or in the presence of instream units (bars, islands) which characterize this whole island braided, sand, rippled reach;

h) Rio Carare and Rio Opón (reach T13): neither these two rivers introduce significant novelties in this reach;

i) Rio Sogamoso and Rio Cimitarra (reach T13, T12): there is an already detected change of planform with an evident anabranching character from just before the important Sogamoso River; so no news are actually introduced;

j) Rio Lebrija (reach T12, T11, T10): no news are introduced by this relatively small tributary, while a planform change had already been detected from a still anabranching character in T11, to a prevailing anastomosed character in Reach T10;

k) Rio Cesar, Cauca and S. Jorge (reach T10, 9, 8, 7, 6, 5, 4): the influence of the important Cesar River is strongly modulated by the large wetland ("ciénaga La Zapatosa") at its outlet into the Magdalena River; its main effect is in terms of water exchanges in both senses strongly driving the dynamics of fish population analogously to many other wetlands in the area (Granado-Lorencio et al. [28]; López-Casas S. et al. [29]). In the whole area the Magdalena keeps its anastomosing character until the exit from the Mojana region (reach T4), with several character variations of the main stem ("brazo La Loba"). The only apparent effect of these tributaries seems to be a meandering pattern of the Magdalena just before its confluence with the Cauca (the most important in the basin). Of course, in terms of water flows and hydrological regime, these tributaries, particularly the Cauca, are key; but no particular novelty in the segmentation can be detected.

In conclusion, the segmentation obtained appears not to be modified by the tributaries input (see Figure A6).

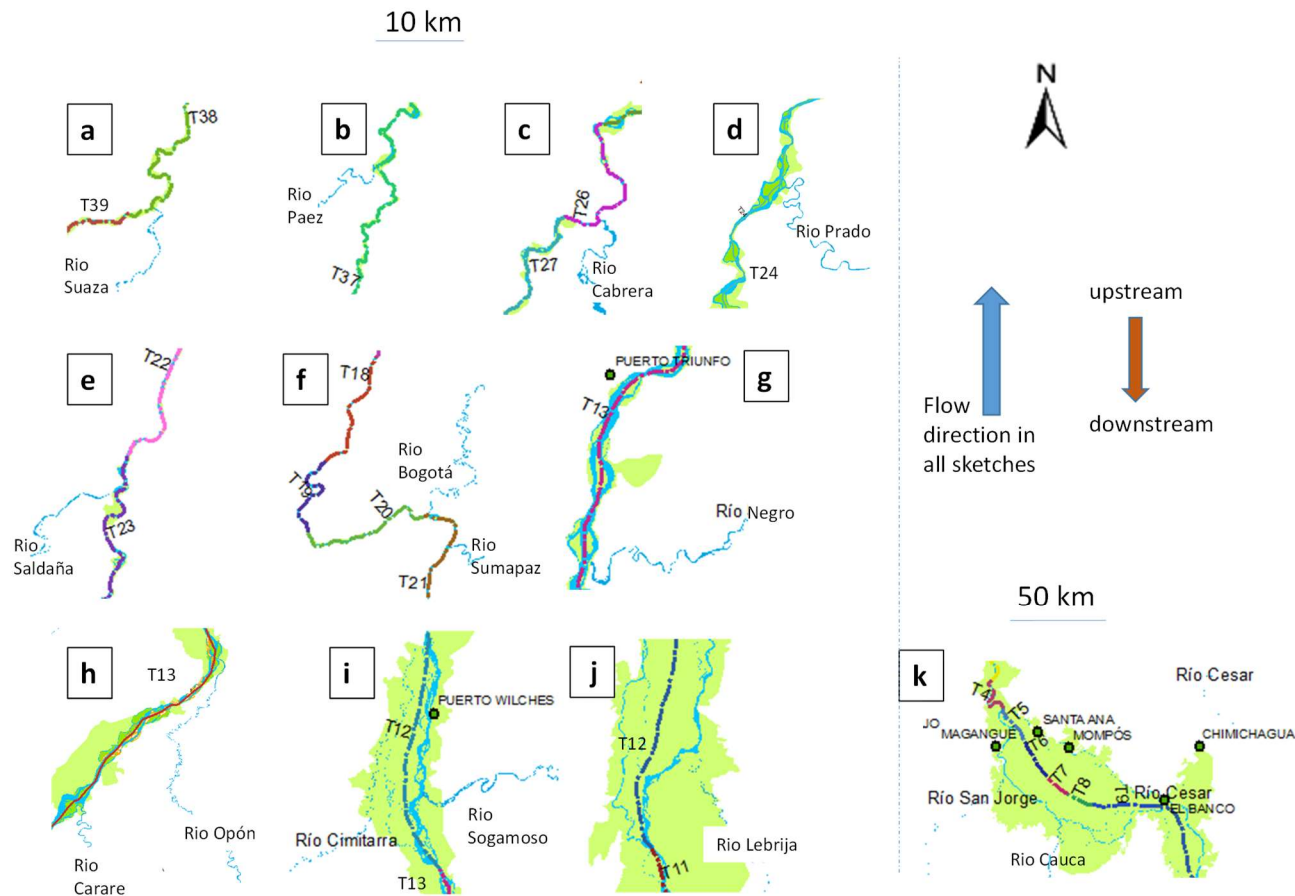


Figure A6. Magdalena case study: stretches (from upstream, top left, to downstream, bottom right) where a significant change of contributing basin area occurs, i.e. a tributary comes in (figure k scale 1:3.200.000 approx.; all other zooms scale 1:500.000 approx.). The figure reports also the active channels (blue), Valley Bottom (light green), islands (dark green) and main bars (dotted yellowish) according to official IGAC information are shown. Colors and numbering (Txy) along the river identify reaches.

We now consider the partly confined stretches and discern whether they should have been split further. According to the characterization described in (Nardini et al. [27] and Nardini et al. [24]), these are as follows (Table A1):

Table A1. Magdalena case study: partly confined reaches of the Magdalena river according to the River Styles analysis carried out over the segmentation obtained with the proposed methodology in (Nardini et al. [27] and Nardini et al. [24]).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
T1	T3	T4	T6	T13	T23	T24	T25	T27	T28	T29	T30	T32	T33	T34	T35	T37	T38	T39	T40	T43

Starting from the upstream reach T43, Figure A7 shows the pattern of the active channel within the valley bottom and the type of confinement. Evidently, no further meaningful subdivision would bring in additional light regarding its character. This situation is emblematic of several others reaches (T40, 39, 38, 37, 35).

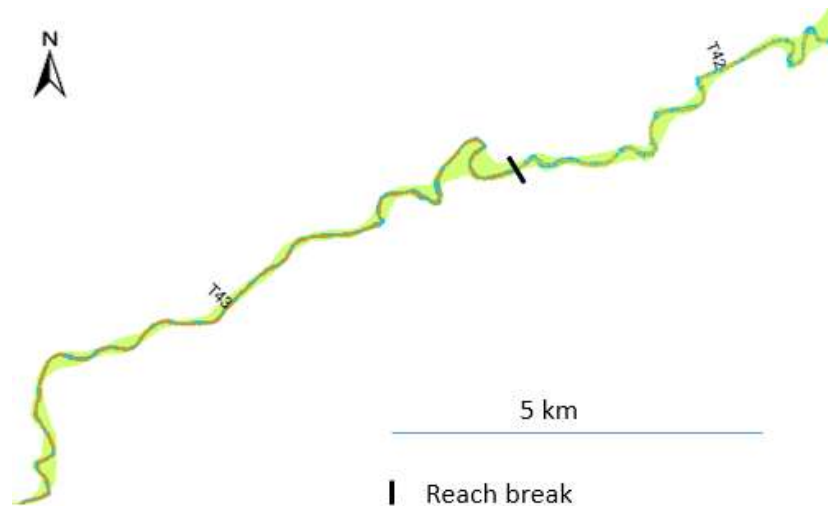


Figure A7. Magdalena case study: Character of an emblematic partly confined reach (T42-T43): no further break would shed additional light in the river character (the break between reach T43 and T42 is due to the “current” attribute).

Reach T34 seems analogous, but deserves a further insight. As apparent from Figure A8, taken as a whole, the reach results as a partly confined one; but if a sub-reach, like A, is considered on its own, that might be classified as “confined” as most of it seems bounded by the left VB margin (look at the complete figure on the right). A similar situation holds for other sub-reaches. However, this is not the case. Indeed, first when carefully analyzed, even reach A shows not to be fully in contact with its VB margin, as shown in the figure inset; second, and most important, the assessment depends on the spatial scale chosen and following the general criterion proposed above of a significant reach length $L_s = 10 \div 20 W$, with $L_s = 5\text{--}10\text{ km}$ in this particular case: accordingly, the initial assessment is confirmed. So, no novelties are to be introduced with respect to the original segmentation. This same observation holds for all the other partly confined reaches (T13 has already been commented in the VB section).

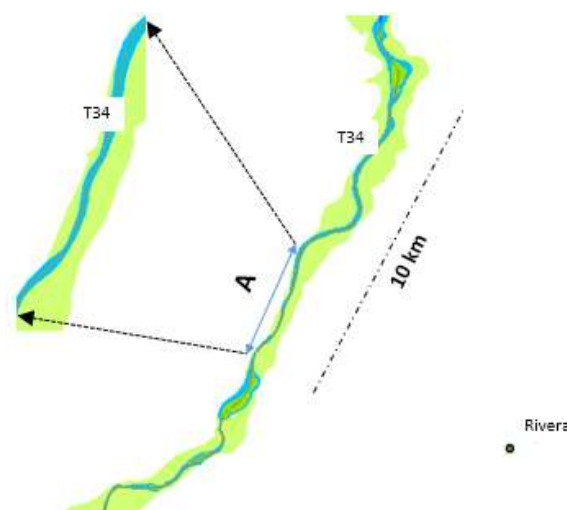


Figure A8. Magdalena case study: Partly confined Reach T35: example of ambiguity: sub-reach A might seem as confined, but it is not and should not.

As a conclusion from these tests, even if they cannot be considered absolute proofs, the segmentation obtained by the proposed methodology for the Magdalena River seems sufficiently accurate and robust as needed. As a lesson learnt, the VB width appears to be a key factor and, as such, should be in general adopted amongst the core attributes, while the current attributes seems quite weak (it was considered more as a trial hypothesis).

Appendix B. Baker River

The Baker (Figure B1) drains a bi-national watershed located in the Chilean and Argentinean Patagonia between 46° and 48° S. The basin has an extension of ca. 28,000 km², i.e. approximately one tenth of the Magdalena. It is flanked to the West by the North Patagonian Icefield (NPI). The upper part of the Baker basin (ca.15,000 km², 52% of the entire basin area) drains to the Lake Buenos Aires - General Carrera (the second largest lake of South America) and the Lake Bertrand (210 m.a.s.l). The length of Baker River properly said, i.e. from its outlet from the General Carrera Lake is about 180 km. It has the highest mean discharge of all Chilean rivers: $Q_{av} \approx 1100 \text{ m}^3/\text{s}$ (Dussaillant et al. [30]).

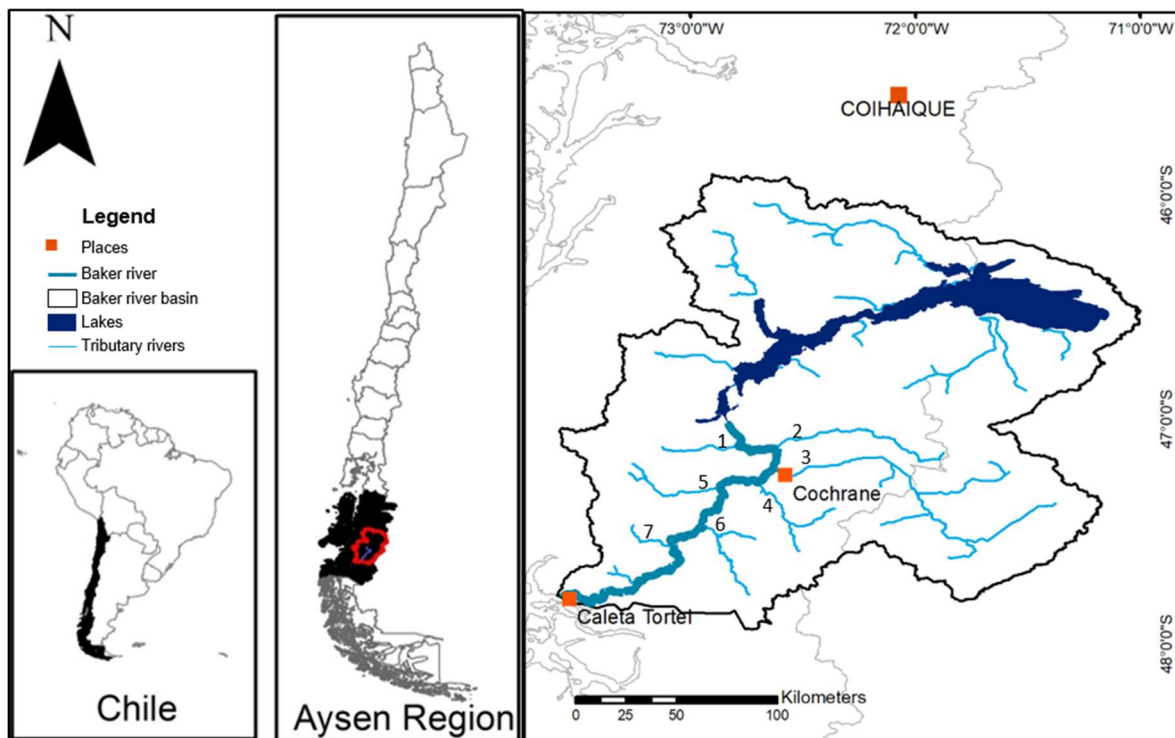


Figure B1. The basin of the Baker River between Argentina and Chile. Numbers on the right figure identify tributaries.

In this case we only adopted the VB width and the planform type as core attributes as we could not count on bed material texture data. More precisely, a Wolman sediment sampling had been carried out but only referring to bars; moreover, despite the notable effort spent, it covered only a limited number of bars that cannot provide a sufficiently continuous measure. Finally, data do not show a consistent spatial pattern most probably owing to the considerable, irregular sediment input provided by short, but aggressive tributaries all occasionally affected by GLOF phenomena (Glacial Outburst Flow, Dussaillant et al. [30]) which heavily alter a somehow regular sediment pattern. The very utility of such data lies exactly in studying the GLOF dynamics.

Concerning planform typology, we named a stretch as “sinuosity-confined” when the river axis mainly follows a narrow valley whose axis -the valley bottom axis- is already sinuous or even meandering. More precisely, when the absolute sinuosity of the VB axis, measured with respect to straight segments, is greater than that of the AC axis with respect to the VB axis segment length.

Results are presented in Figure B2. A total of 25 reaches has been obtained.

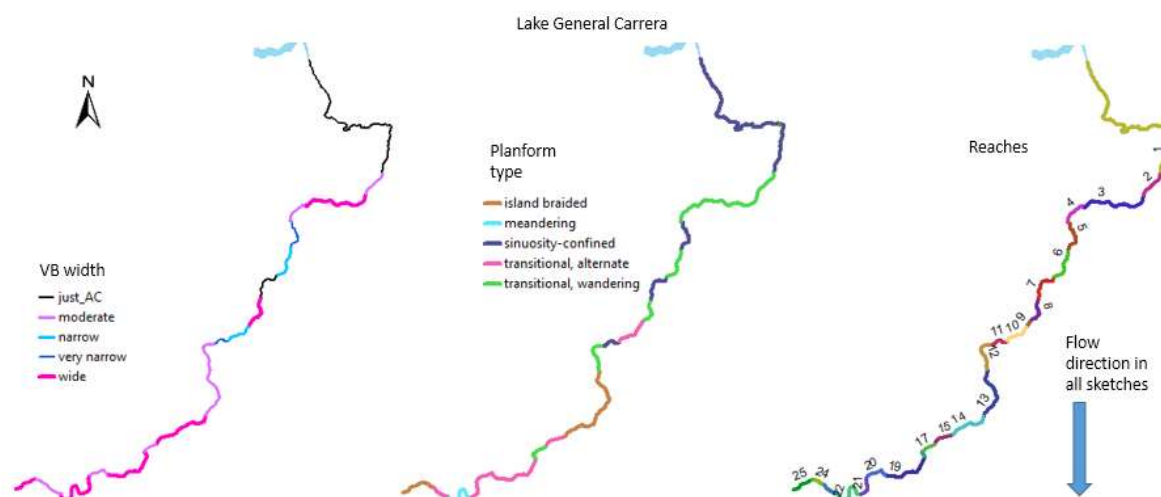


Figure B2. Baker case study: Definition of reaches for a stretch of the Baker River (Chile) obtained via the procedure presented here. From the left, segmentation of the: Valley Bottom width; planform type, and the reaches obtained. (Approximate scale: 1:1,000,000).

It must be noted that in Ulloa et al. [31]) a segmentation has been produced with 34 reaches that might seem appropriate for comparison. However, the procedure adopted there was not actually the “traditional” one, rather a mixed procedure: reaches have been defined by expert judgment, based mainly on a qualitative appreciation of confinement; then slope, braiding index and sinuosity indices have been computed and considered. But quantitative indices, as noted before, while being objective measures, are intrinsically linked to the initial, arbitrary choice (i.e. they have an extensive nature) and, furthermore, are strongly affected by measurement details (e.g. precision of altimetry information, sites where elevation is assessed; how many transects are considered to compute the braiding index). Therefore, the numerical output of indices, because of this fact, inevitably introduces additional reasons for differentiation of reaches which carry little geomorphic information particularly when a River Styles Framework is considered.

For this reason, we do not use that segmentation for comparison purposes; rather, we proceed in a fashion analogous to the previous case study, by investigating whether some further reaches would be identified with respect to those generated by our proposed methodology when additional attributes were considered (Figure B3).

We start with slope changes (considering the elevation of the valley bottom along the axis of the active channel envelop).

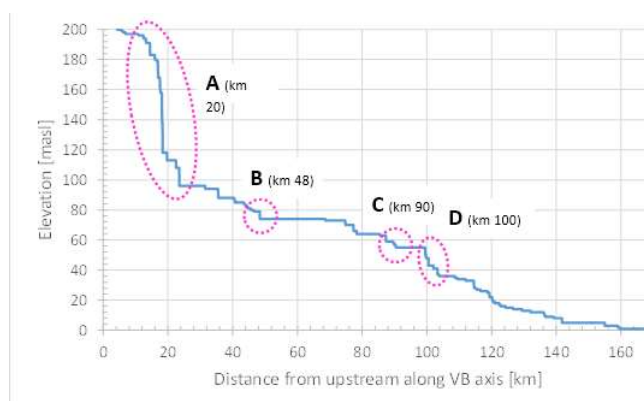


Figure B3. Baker case study: approximate elevation of the Valley Bottom along the river axis (from USGS Earth Explorer, Digital Elevation: GMTED2010, Entity ID: GMTED2010S50W090, November 11, 2010)

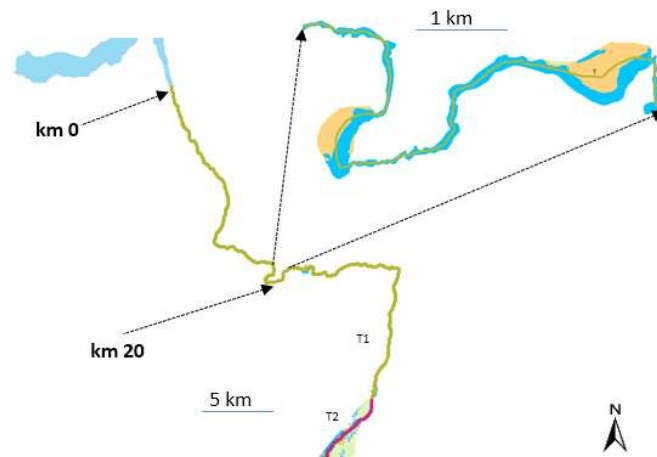


Figure B4. Baker case study: detail of the river at the major slope change (location A in Figure B3).

As apparent from Figure B3, the sharpest elevation drops (and presumably slope change) occurs at location A, just before and then after km 20. The inset in Figure B4 shows that indeed the river presents there an anomaly with two isolated very large bars, right downstream the two falls around km 20. Although certainly deserving attention, this is however not suited to originate new reaches, being in fact just a local anomaly. The jump at km 36 does not reflect in any of the local visible planform and geomorphic units. Location B at km 48 in Fig. 15 coincides incidentally with the point where a change of planform was already established between reach T3 and T4 as shown in the following Figure B6 (bottom, left) and hence does not introduce any novelty. This situation is representative of several other jumps of similar magnitude (e.g. that at km 87 between reach T7 and T8; and that at km 100 approx. between reach T11 and T12, at location C and D, respectively, in Figure B3) where the change is even more evident (see for instance Figure B5).

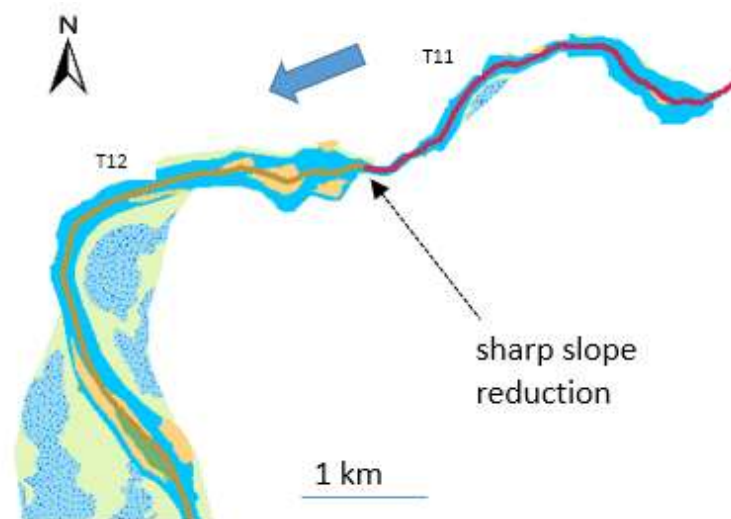


Figure B5. Baker case study: example of typical coincidence of a reach boundary with a slope change...and a VB narrowing (or widening in other situations): end of segment D at km 100 approx. (Figure B3). The blue arrow indicates the direction of flow.

Valley Bottom width is one of the core attributes, but was assessed on a qualitative, visual basis. Here we compare it with a more quantitative assessment carried out through the Fluvial Corridor Toolkit. Figure B3 shows several minor changes and a few ones quite relevant.

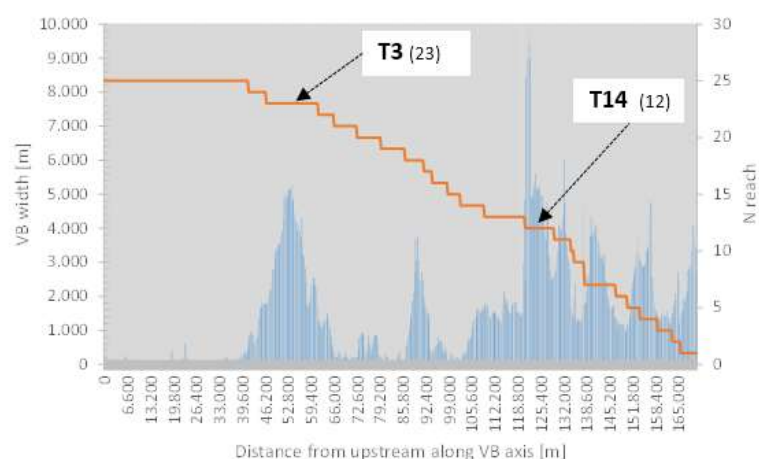


Figure B6. Baker case study: schematic representation of VB width (blue line) along the Baker River (upstream is on the left) and of the different reaches determined with the proposed methodology (orange line, with axis on the right); they range from the first at left (T1, denoted as 25 on the right scale) to last one on the right (T25) (but they do not relate proportionally to elevation). VB width values greater than 8 km have been cut (max is around 10 km) as they do not change the general appreciation, while hiding useful details (the numbering of reaches on the right axis is the complement of the one adopted in the following figures, for ease of representation here).

From such figure, the first reach which may rise some suspicion is T3 (n.23) where the Valley Bottom ranges from less than 2 up to about 5 km. The details shown in Figure B4 (left) demonstrate that the general planform character keeps however being the same within that reach. A possibly distinct character (alternate bars) might be detected in the short reach of the inset, but its length does not pass the significant length criterion (here about 5–10 km) and would any way not be linked to the VB width. Another situation perhaps worth of consideration is that of reach T14 (n.12) where the Valley Bottom ranges from 2.7 up to 9.8 km (see Figure B3). The details shown in Figure B4 (right) demonstrate again that the VB variations do not support relevant changes in the planform or other characters at the significant scale; moreover, it has to be noted that the VB width values are somehow artificially exaggerated by the FCT algorithm adopted that produces in particular situations like this very irregular polygons, while partitioning the VB, changing dramatically their orientation and, as such, their width; in addition, the kind of queue on the top right seems very much a legacy of an ambiguous cut if the Baker VB from that of a local tributary.

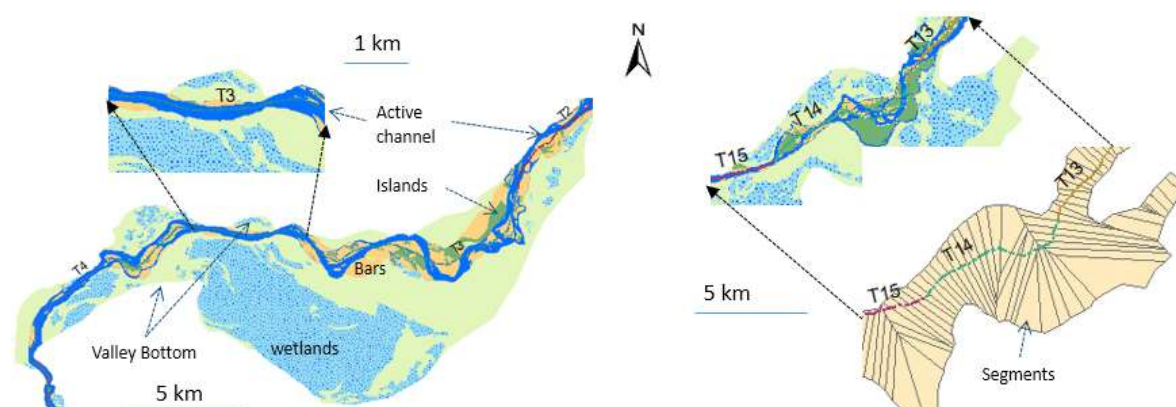


Figure B7. Baker case study: details related to reach T3 (figure on the left; denoted as 23 in Figure B3) and T14 (right): no novelty is introduced by the VB width changes criterion. Flow direction goes with increasing reach numbers.

Very similar considerations hold for the other situation's exception made for the last T25 which, as shown in Figure B8, would have perhaps deserved a further subdivision as the last part is clearly

a transitional area seemingly significantly influenced by tides. This would however not be linked to the VB width criterion.

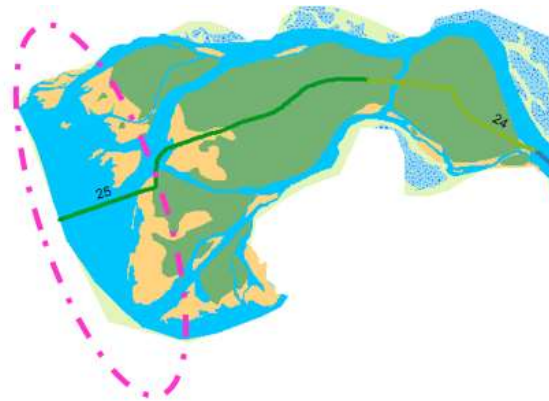


Figure B8. Baker case study: the last reach deserving further splitting.

Concerning tributaries, from Figure B9, it can be appreciated that tributaries 1 and 2 (from upstream) do not introduce any novelty (perhaps just a slight narrowing of the active channel the former -associated with a bed fall- and the opposite the latter, both escaping a reasonable range of differentiation). Tributaries 3 and 4 are seemingly associated with the significant VB widening and change of planform style, already captured by the segmentation (this widening is however more probably generated by the accumulated material carried by tributary 5 that –as visible from Google Earth imagery- has a tremendous sediment load from the western ice field). Tributary 5 demarcates a significant narrowing, already captured, however, by a planform change. Tributary 6 seems to contribute to the generation of large bars right upstream its confluence, a fact already captured by a planform change that after it becomes “transitional, alternate bars”. Tributary 7 seems instead to be associated to an increment in sediment load that gives rise to a change of bars and islands pattern; a fact already captured however by a change in planform typology right downstream of its confluence from a transitional, wandering into an island braided typology. Also, the last tributary seems to introduce a change that, however, has been already captured by the planform attribute (transitional, wandering until upstream of its confluence and transitional, alternate bars downstream).

Analogously to the Magdalena case, even here tributaries do not introduce significant novelties to the segmentation based on map view (they of course may change the water flows, sediment load and streampower).

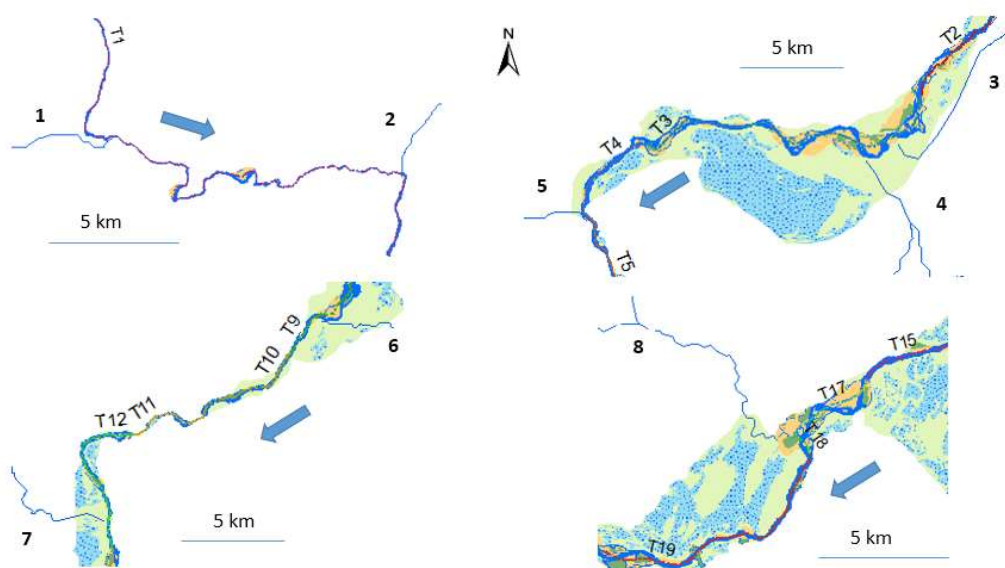


Figure B9. Baker case study: investigating the effect of tributaries.

As far as partly confined reaches are concerned, the first one from upstream is reach T3 which has already been commented above: no novelties are introduced by the confinement criterion as visible in Figure B4 (left). Another partly confined reach worth considering is T12 (Figure B5, bottom left), but it is evident that splitting it into confined and not confined sub reaches would violate the significant length criterion while not shedding particular light on the planform type. Totally analogous considerations hold for the following partly confined reaches (T13, T15, T19, T21, T22, T23).

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