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A Qualitative Hydro-Geomorphic Prediction of the Destiny of the Mojana Region (Magdalena-Cauca Basin, Colombia), to Inform Large Scale Decision Making

Andrea Nardini [1,*] and Freddy Leonardo Franco Idarraga [2]

[1] International advisor for water resources management, Riccione (RN) 47838, Italy
[2] Instituto de Estudios Ambientales-IDEA, GTA en Ingeniería Hidráulica y Ambiental, Universidad Nacional de Colombia-Sede Manizales, Manizales 170004, Colombia; flfrancoi@unal.edu.co
* Correspondence: nardiniok@gmail.com; Tel.: +39-3397023057

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Abstract: Colombia is undergoing a period of rapid development. In particular, the Magdalena-Cauca Rivers basin, and the Mojana region within it, is going to experience rapid expansion in infrastructure growth, entailing hydropower development, road and navigability works along hundreds of kilometers of channels, as well as standard flood control measures. This paper argues that unexpected and undesired outcomes are very likely to occur as a consequence of the hydraulic and geomorphological reaction of river systems to such development schemes; namely, we foresee heightened hydro-morphological risks, along with the loss of environmental services and strong increases in maintenance costs. River behavior has been the subject of extensive study by diverse disciplines. As a result, key principles of fluvial dynamics have been elucidated and specific quantitative prediction tools developed. In this paper we do rely on this wealth of knowledge. However, since specific local information and interpretative tools in Colombia are either lacking or unreliable, it is inevitable that, at the moment, any basin scale analysis has to remain qualitative and must incorporate several assumptions, leaving it open to questioning and further refinement. Nonetheless, we argue that advancing such type of speculative conjectures is the "right thing to do". The undeniably desirable but hard to achieve alternative of waiting for sufficient datasets and tools would entail excessive delay in obtaining relevant answers while large-scale development would continue to occur with potentially damaging results. Therefore, our analysis is conceived along the *precautionary principle*. This paper is primarily aimed at technical advisors of policy makers as it offers scientifically-based arguments for informing the political debate, hopefully guiding decision makers towards better choices. Rather than advocating specific solutions, the focus is on pointing out the likely adverse consequences of the currently planned course of action.

Keywords: river basin planning; holistic approach; hydro-geomorphological prediction; qualitative approach; La Mojana (Colombia); developing countries; precautionary principle; complex decision making

1. Introduction

Following a World Bank expert mission in the 1950s, there has been widespread political debate regarding several initiatives for the development of agricultural districts and modern transport infrastructure in the Mojana region, along with proposed policies for a complete control of its natural dynamics characterized by periodic harsh flooding and subsequent drought periods [1]; ecosystem conservation was also considered [2]. This process took on a renewed impulse after the "*Ola Invernal*" (winter wave) of 2008–2009 and 2010–2011, as well as two "La Niña" (i.e., cold ENSO —El Niño Southern Oscillation) periods with extreme rainfall, which caused flooding and severe damages in all of Colombia. The 2010–2011 event had a particularly notable effect in the Mojana region, where the Cauca River breached a large artificial levee, causing widespread damage within one of the most developed areas within that basically poor region.

As a result, the region received significant national and international emergency funding through the Colombia Humanitaria organization, while the government created the Fondo de Adaptación, a country-wide agency designed to promote economic recovery for the population affected by "La Niña" through sustainable and secure infrastructure work. Since then, there has been a vigorous societal and political debate around flood control concepts; although many proponents invoke the need for large defense infrastructures, this notion has been challenged, particularly within academia and the environmental movement.

We focus on the Mojana region (Figure 1), whose context within Colombia and the Magdalena-Cauca Rivers basin is briefly summarized in Table 1.

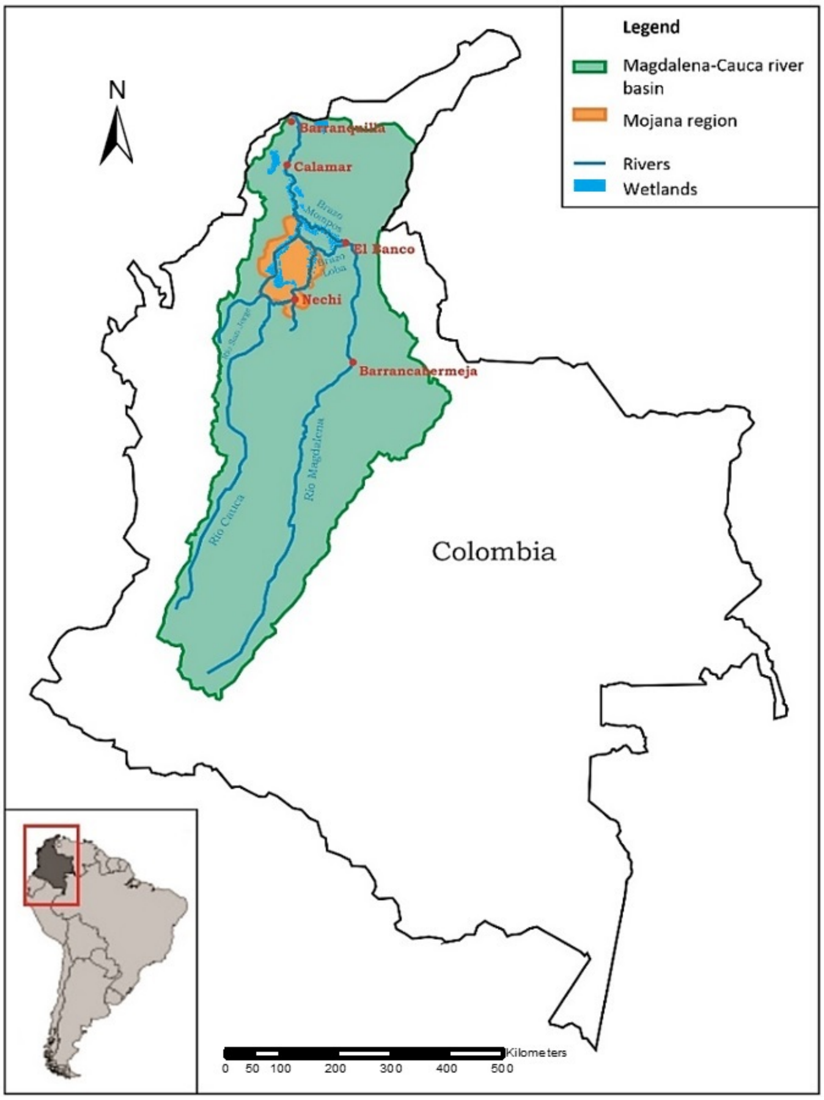

Figure 1. Map of Colombia pointing out the Magdalena-Cauca Rivers basin and the Mojana region with the Cauca, San Jorge, Nechí and Magdalena Rivers, and the two branches of the latter: Brazo de Loba and Brazo de Mompox.

Table 1. Some descriptive data on the Mojana region [1–3].

Surface area of Colombia	1,141,748 km^2
Magdalena-Cauca Rivers basin area	271,249 km^2
Mojana region	28,461 km^2—28 municipalities in 4 political regions Antioquia, Córdoba, Bolívar and Sucre
Area covered by the Fondo de Adaptación within the Mojana region	10,982 km^2 (11 municipalities), Antioquia (Nechí), Córdoba (Ayapél), Bolívar (Magangué, San Jacinto del Cauca and Achí), Sucre (San Marcos, Guaranda, Majagual, Sucre, Caimito and San Benito Abad)
Total population (est. 2014)	401,734 inhabitants
Average Unsatisfied Basic Needs	70.1%
Population affected by La Niña ENSO floods in 2010–2011	170,000 (39%)
Portion of the population in subsistence activities	About 70% (of which: 44% Agriculture, 35% Livestock, 18% Fishing, 3% Not reported)

Considering the sheer size of the Mojana, it is not surprising that the decision-making process has developed in a multi-faceted, multi-channel fashion, involving several social arenas and a number of parallel leading actors with little or no coordination. The breadth of agencies involved in the process include: the National Planning Department (DNP); the Ministry of Environment and Sustainable Development and its Institute of Hydrology, Meteorology and Environmental Studies (IDEAM); the Ministry of Interior and Justice; the Ministry of Economy; the Ministry of Agriculture and Rural Development; the Ministry of Transport; the Fondo de Adaptación; the Unidad Nacional de Gestión de Riesgos y Desastres (National Unit for Risk Management and Disaster Rescue); several universities; international agencies; Non Governmental Organizations (NGOs), etc.

This has resulted in numerous, sometimes conflicting, lines of thought, with their corresponding political actions: Many participants push for the construction of new transportation infrastructure as a key element in the development of the region (part of [3,4] among others); some focus on flood control as a core component, proposing specific projects ([5,6] among others); others emphasize the socio-economic and socio-cultural dimensions of the situation, stressing the need for empowerment of local communities, provision of basic services, and management of conflicts and illegal armed groups [7–9]. Finally, there are those who propose that any solution should focus on ecological capital and restoration (part of [2,3,10], some chapters of [11]; some chapters of [12,13], among others).

All of these approaches are still far from addressing the set of twelve (12) core procedural and substantive sustainability criteria proposed in [14] to be used as a guide for clarifying development purposes, identifying potentially desirable options, comparing alternatives and monitoring implementation for infrastructure.

Notwithstanding these issues, a serious coordination effort is currently underway to come up with a final Action Plan, based on the most scientifically-sound knowledge about the flood dynamics and associated risks in the Mojana region. This process is the result of a large research project conducted by a national modeling team at the IDEAM, with a select group of risk experts under the lead of the Fondo de Adaptación. Despite the very high quality of this study, two key weaknesses can be identified:

1. The approach lacks a holistic view of the whole set of development interventions envisaged within the different planning instruments (i.e., looking at them all together).
2. The likely effects of the different development projects on the future geomorphic evolution of the river system have not been considered nor assessed.

In this paper, we argue that seriously considering these two issues could profoundly change the development vision—and course of actions—for the whole Mojana region (and the Magdalena-Cauca

Rivers basin as well). This is a different facet of the discourse about the importance of considering fluvial geomorphology to support land-use decision-making developed in [15], along with similar challenges as in several other large rivers worldwide [16]. An exercise with comparable ambitions, but with a quantitative approach, has been conducted for the Middle-Lower Parana River [17]; it is interesting to note that, in spite of the greater rigor offered by that modeling framework, the analysis still contains—and somehow hides—several subjective hypotheses and assumptions.

We want to make clear from the onset that we are not disregarding specific models; rather, we claim that the descriptive, qualitative analysis of the type we present here is a fundamental, although preliminary, step that can then be supplemented by additional modeling exercises, provided that the underlying hypotheses and limitations are made explicit and critiqued carefully. Current geomorphic knowledge and interpretative tools [1,18] are still too weak to support a quantitative assessment for the Mojana case; nevertheless the arguments presented here is hardly refutable, being based on geomorphic knowledge and world-wide experiences.

In a more rigorous scientific approach, one would prefer to obtain all the data and tools needed before announcing the type of strong conclusion we present in this paper; but waiting until those elements are available and obtained would not provide support to the decisions that are being taken now. Hence we preferred to sacrifice some level of rigor, and strive to provide qualitative, but relevant information at this time, while the decision-making processes are still under way. This is an aspect that is certainly of interest to many other cases throughout the world: the attempt to significantly contribute to the decision process by advocating scientific arguments while relying on scarce and mainly qualitative information, particularly concerning the long-term geomorphic behavior of the system considered.

Our case can be framed within the *precautionary principle* [19] as it deals with a decision of national scope which may induce adverse and irreversible impacts and where consequences are highly uncertain. According to the analysis framework set up in [20], we should try to separate the uncertainty related to the possible effects (scientific side) from the degree of risk acceptance (socio-political side). Coherently, we could assess the level of scientific uncertainty we manage as "reasonable belief" or "clear indication" and label the aptitude we recommend as that of the "Cautious environmentalist" (in Weiss' scale [20] (p. 144), the lowest category of 5 is the "Environmental absolutist" who says take no action until it is proven that that it will cause no harm; the highest (5th) is the "Scientific absolutist" who says make no precautionary intervention until the danger is scientifically proven; the "Cautious environmentalist" is the 2nd).

While this knowledge level would be insufficient to permit an exploitation or development project to be undertaken when proposed by a private party, it could be enough, according to [20], in case whereby society (through its environmental scientists) were to demonstrate that counteraction needs to be undertaken due to the high likelihood that an adverse effect is certain to occur. Or, said in the words of ([21], p. 318), " ... uncertainty erodes the traditional positivistic model of knowledge, in which science speaks truth to power"; these authors also discuss the *uncertainty paradox* which is based on the fact that " ... the role of experts was framed in terms of providing certainty about uncertain risks" and point out, citing [22] in ([21], p. 331), that " ... uncertain risks 'defy "normal" scientific analysis, for they are indeterminate' and " ... inseparable from the political and social context of which they are an outcome and a contributor ... ". Hence, a more figurative approach would be the classification proposed by [23] where the classic impulse to defeat uncertainty in scientific knowledge would be labeled as "monster exorcism" and would typically lead just to nothing, or at least to time incompatible with the need to make a decision.

Coherent with this position, this paper does not claim to be a rigorously scientific contribution; it aims to offer a scientifically consistent understanding and arguments to the community and, particularly, to the technical (not scientific) advisors of policy makers. Rather than advocating particular solutions, it addresses the likely adverse consequences of the course of actions currently planned.

The methodology we adopted is reflected by the structure of this paper: first, a description of the Mojana region and a rapid *River Style* assessment of its main hydro-morphological actor, the Cauca River, are presented in order to characterize the system. A holistic picture of the main structural interventions planned at both scales (i.e., that of the Magdalena-Cauca Rivers basin and that of the Mojana region) is then provided: the former is needed to specify the boundary conditions of the Mojana (which may affect the processes inside it); while the latter refers specifically to that territory.

A discussion of the likely future evolution of the river basin system is then developed, based on the understanding provided by the rapid *River Style* assessment and a qualitative cause–effect conceptual model developed for the study. Finally, management conclusions and recommendations are provided. Note that we are often obliged to jump from one scale (Mojana region) to another (whole Magdalena-Cauca Rivers basin) depending on the step of this process: without maintaining a look at the wider scale, we would lose very important relationships that can be determinant for the long term destiny of the Mojana region.

2. The Mojana Region

2.1. Physiography and Peculiarities

The Mojana region is not a basin, rather it is a part of a larger region called Depresión Momposina (i.e., depression of Mompox), itself part of the Magdalena-Cauca Rivers basin (see Figure 1). It is a fluvio-deltaic plain formed by the rivers San Jorge, Cauca and the Magdalena branch called Brazo de Loba. Over the course of time, the notably flat topography and the presence of large rivers generated a complex ecosystem with ever-changing wetlands, inter-connecting channels (*caños*) and other components (see Table 2) according to the flood pulses and complex bidirectional temporary flows. These were well exploited by ancient Zenúes civilizations through extensive land preparation, including a number of man-made small canals (see Figure 2a).

(**a**) (**b**)

Figure 2. (**a**) Ancient indigenous Zenúes irrigation canals (segments perpendicular to the water body border) showing a long-dated art of living with this pulsing water environment [24]. (**b**) Present day wetlands (*humedale*s or *ciénagas*) within the Mojana region (photograph taken by author 1).

National and regional roads do exist around the region, but they are scarce and in bad condition, therefore access to the internal areas is difficult; communication is mainly by boat in the Cauca, San Jorge and Magdalena Rivers and the swamps. Some paths (e.g., San Marcos-Majagual-Achí) were built that had profound disturbance of the ecological equilibrium of the area, cutting through swamps and in some cases restricting hydraulic interconnection—resulting in more frequent floods in some areas [1].

Table 2. Types of areas and uses (ha and %) in the Mojana region [3,25].

Ecosystems Characterization in the Mojana Region According to the Temporary Flood		% of Total Area
Aquatic ecosystems	Lotic waterbodies (rivers, creeks and streams)	4
	Average lentic waterbodies (swamps, wetlands—*humedales* or *ciénagas*)	8.8
Transitional ecosystems (aquatic and terrestrial interface)	Temporary emerged bars (riparian and emergent aquatic vegetation, grasslands and wetlands)	17.1
	Zápales (flooded forests)	5.4
Terrestrial	Natural areas (forest dense, open and fragmented secondary vegetation and pasture in natural spaces)	9.0
	Agricultural areas (permanent and temporary crops and heterogeneous areas)	6.8
	Livestock areas (clean pastures, choked and scrubby)	39.6
	Mining, burned areas, among others	2.6
	Not reported	6.7

2.2. Rapid River Style Assesment

Three main rivers act within the Mojana region: the great Magdalena River, which borders its northeastern side; the San Jorge River, marking the main drainage axis of the large system of pulsing wetlands (*humedales* or *ciénagas*); and the Cauca River in the south-eastern part (see Figure 3). In this paragraph we perform a rapid assessment of the Cauca River only. This analysis is followed later on by a more comprehensive examination of the whole Magdalena-Cauca basin and its other rivers, with the purpose of seeing how "the rest of the world" surrounding the Mojana region may affect it in terms of boundary conditions.

Starting with the Cauca River is justified in our view, because it is in some sense the key actor for a number of reasons:

1. It is this river that historically produced the harshest damage due to its geomorphic behavior.
2. It greatly influences the hydrological dynamics of the *humedales* (wetlands) as a result of its periodic overflowing events.
3. It is in its basin that most of the future dams are envisaged.

Moreover, looking at the Cauca in some detail as a first step will help us to develop an understanding and basic (qualitative) predictive capability.

The key idea of the *River Style* framework [26] is to look at the river on different scales at the same time: from the landscape and river basin scales, down to corridor and reach scales, until that of single geomorphological units within either the fluvial corridor or the river channel itself. From this analysis, an effort is undertaken to understand the functioning of the river in different hydrological conditions, particularly during bankfull stage and large floods events. It is hence not just a classification exercise (like the approach in [27]), but a real framework for a thorough understanding that opens the door to the analyst to predict future behavior in a rather qualitative, but very illuminating fashion.

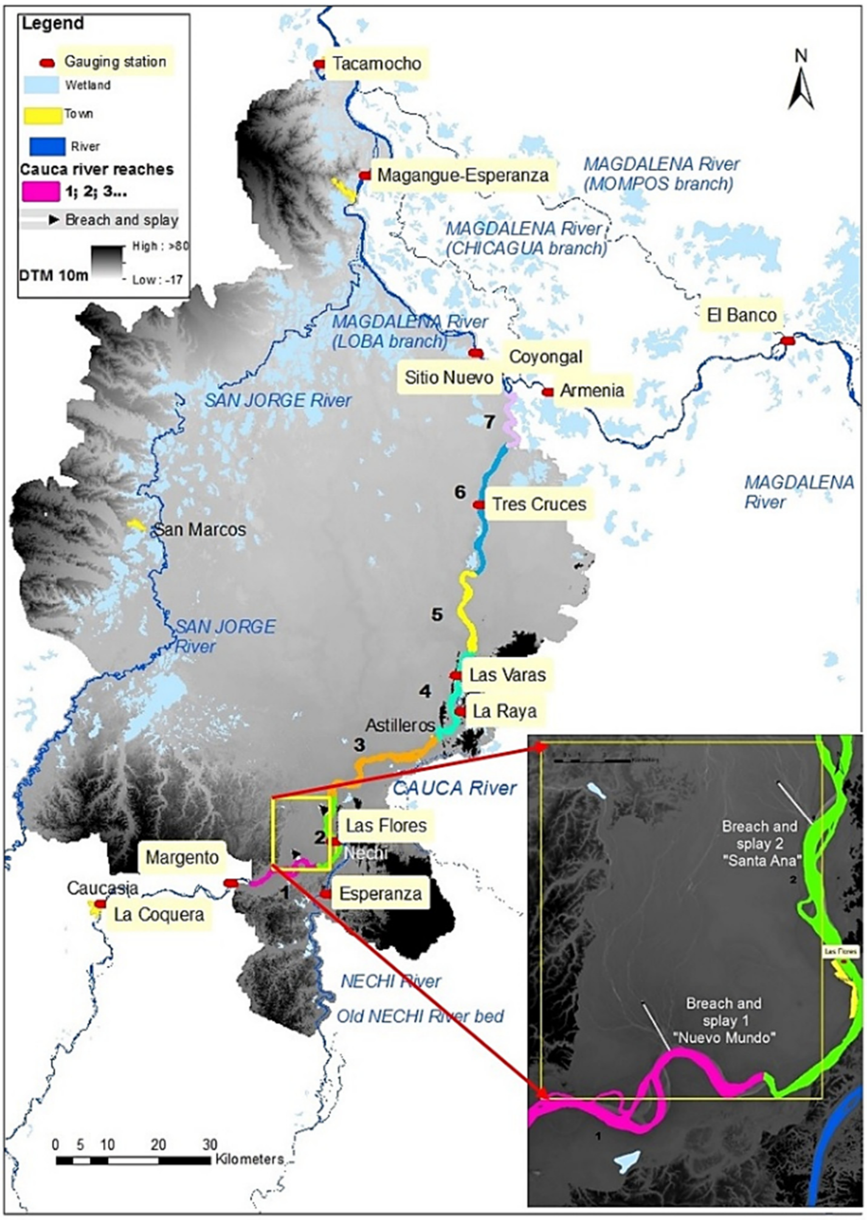

Figure 3. The seven (7) reaches considered for Cauca River within the Mojana region (the location of this region within the Magdalena-Cauca basin and Colombia is shown in Figure 1). In the floodplain between the rivers, light blue marks the wetlands. The grey base is a 10 m pixel Digital Terrain Model (DTM 10 m). On the left, is the highly sinuous San Jorge River, partly confusing with the wetlands it feeds. The major splays (track visible in black arrows in the inset) from left bank natural levees crevasses of Cauca River—named Nuevo Mundo and Santa Ana—are located within reach 1 and 2, pouring their water and sediments northwards.

Table 3 presents a set of attributes adopted to characterize the reaches under consideration according to the *River Styles* approach of [26]. Their assessment is still mainly qualitative and preliminary, but sufficient to capture some of the key features of the *Cauca* River and its territory. The following Figure 4 presents in schematic form some planform features of the river to underline its setting in terms of "freedom of movement", i.e., confinement and alignment. Figure 5 shows a representative detail of river morphology to offer a multi-scale view. Figure 6 then shows some long topographic cross sections to point out the relationship between the river and its floodplain.

Table 3. Attributes describing the seven (7) reaches for Cauca River within the Mojana region.

ID Denomination	Valley Reach Length Lv (km)	U_Landscape	Natural Confinement	Artificial Confinement	Valley Width V (km)	Start Elevation ys (masl)	End Elevation ye (masl)	Valley Slope i (‰)	Bankfull Flow Q (m^3/s)	River Reach Length L (km)	Sinuosity s	Width of Meanders Belt B (km)	Alignment	N Canals
1 Margento-Colorado-Puerto Nare	13.5	hilly and undulated	unconfined	levee at left side	6.0	38.2	35.0	0.24	2600	16.7	1.24	2.9	central	1–2
2 Nechí-Mejico	16.3	hilly and undulated	partially confined on the right	levee at left side	5.1	35.0	31.8	0.20	3700	17.8	1.09	1.4	right	1–2
3 San Jacinto-Galindo	23.4	piedmont of hills	unconfined	levee at left side	41.0	31.8	28.4	0.15	3700	29.2	1.25	3.6	right	1–4
4 Caimatal-Boyacá	18.4	piedmont of hills	confined	several groynes	1.5	28.4	26.0	0.13	3700	22.4	1.22	1.5	alternated	2–1
5 Guaranda-Buenavista	15.0	alluvial plain	unconfined	some groynes	55.0	26.0	25.8	0.01	3600	19.4	1.29	2.5	central	1–3
6 Pto. Isabel-Guacamayo-Playa Alta	26.1	alluvial plain	unconfined	-	29.0	25.8	20.3	0.21	3600	27.8	1.06	1.9	central	1–3
7 Santa Mónica-Desembocadura	10.3	alluvial plain	unconfined	-	6.0	20.3	17.5	0.27	4500	16.5	1.61	3.0	central	1

ID Denomination	River Slope i_R (‰)	Surface Area of Bankfull Reach A (km^2)	Bankfull Width w (km)	Bankfull Depth h (m)	Entrenchment	Pseudo-Entrenchment	Specific Stream-Power (W/m^2)	w/h Ratio	Corridor Units	Channel Units	Lateral Movement
1 Margento-Colorado-Puerto Nare	0.19	6.3690	0.382	5.0	0.06	0.48	12.8	76	natural levees; crevasse and splays; meanders cut-offs; paleo-channels; ridge and swales		high
2 Nechí-Mejico	0.18	7.8027	0.437	5.0	0.09	0.27	14.9	87	natural levees; crevasse and splays; paleo-channels (*madreviejas*); input of Nechí tributary		significant, but with fixed points
3 San Jacinto-Galindo	0.12	14.1319	0.484	5.0	0.01	0.09	8.7	97	natural levees; crevasse and splays; paleo-channels; ridge and swales; anastomosed arm	several islands	significant, but with fixed points
4 Caimatal-Boyacá	0.11	10.6810	0.477	5.0	0.32	1.00	8.2	95	ridge and swales; input of Caribona tributary	islands	high at the entrance, then moderate
5 Guaranda-Buenavista	0.01	8.4516	0.436	5.0	0.01	0.05	0.8	87	natural levees; paleo-channels by meanders cut-off ; crevasse and splays; derived channels	islands	significant nearby Achí
6 Pto. Isabel-Guacamayo-Playa Alta	0.20	10.9776	0.395	5.0	0.01	0.07	17.7	79	natural levees; paleo-channels; derived channels; anastomosed natural channel	islands	moderate
7 Santa Mónica-Desembocadura	0.17	5.3841	0.326	5.0	0.05	0.50	23.0	65	crevasse and splays; wetland connection	islands	low, but with marked modifications of the island

- The "start (y_S) and end y_E) elevations" refer to the valley altitude (extracted in an approximated fashion from the DTM 10 m) in a representative point outside the natural levees (when present), at the beginning and end of a reach
- Valley slope (i) is determined as the difference between start and end elevations, divided by its length (and expressed as ×1000), i.e., $i = [(y_S - y_E)/L_v] \times 1000$

- Bankfull flows (assumed to coincide with the 2 years recurrence time flow, calculated from IDEAM daily time series data between 1974 and 2008; the last reach value is instead taken from [1], Figures 4–7, p. 491). These are preliminary data; we assume they are sufficiently representative for this preliminary assessment
- Sinuosity: ratio between reach axis length and valley length ($s = L/L_v$)
- Meanders belt width (B): approximated, average width of the corridor occupied by the river (envelop of its meanders)
- River slope (i_R): determined as valley slope reduced by the sinuosity (($i_R = i/s$); this is valid provided that river depth does not change significantly, an information currently missing (expressed in $\times 1000$)
- Horizontal surface area (A) of the bankfull channel in a reach, calculated from GIS polygons
- Bankfull channel width (w), obtained as ratio between surface area and reach length ($w = A/L$)
- Bankfull depth (h): purely indicative data, inferred from [1] (Tables 6–17, p. 415) to give at least an idea of the w/h ratio
- Entrenchment: ratio (w/V) between bankfull channel width and valley width
- Pseudo-entrenchment: ratio (B/V) between meanders belt width B and valley width V; it gives a clear idea on how much the river is free to express its planform dynamics
- Specific stream power: $\gamma\ Q_B\ i_R\ /w$ [Watt/m^2], where γ: water specific weight (approximately: 1000 kg/m^3 = 9.81 $\times$ 1000 N/m^3)

NOTE: geomorphic units within the channel cannot be identified with ample detail at the scale of analysis adopted.

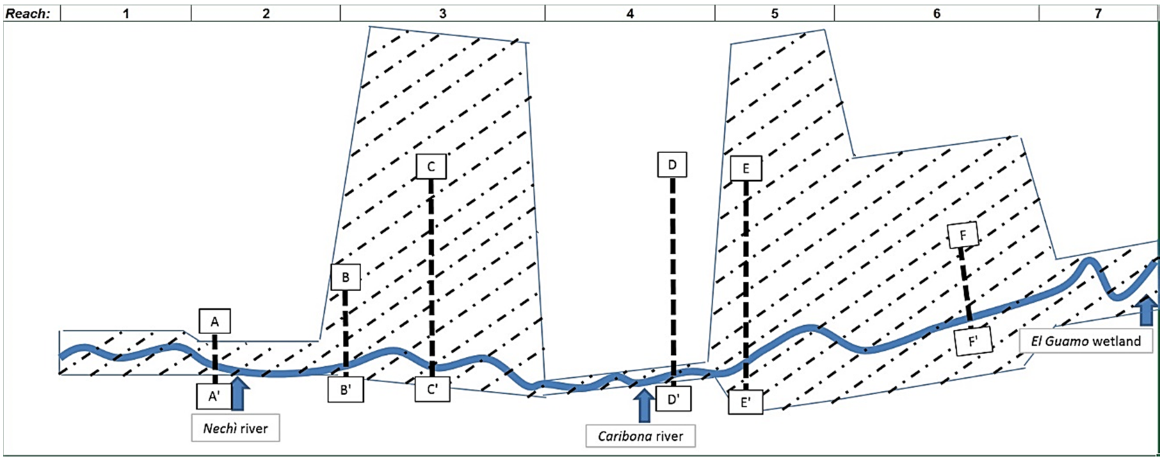

Figure 4. Schematic representation of Cauca River within the Mojana region based on Table 3 (the reach identifier is reported in the horizontal colored bar at the top), which points out the degree of confinement, the alignment of the channel within its valley (dashed zone) and secondarily, its sinuosity. Dashed vertical reddish segments indicate the location of the long topographic cross sections shown in the following Figure 6. Notice the presence of a clear confined reach (4) where Caribona River joins the Cauca. Along reaches 3, 5 and 6 (where sections C-C′, E-E′ and F-F′ are located), Cauca River can move in a very wide floodplain; although the major crevasses are located along reach 1 and 2 (see Figure 2), their splays pour into reach 3 valley domain.

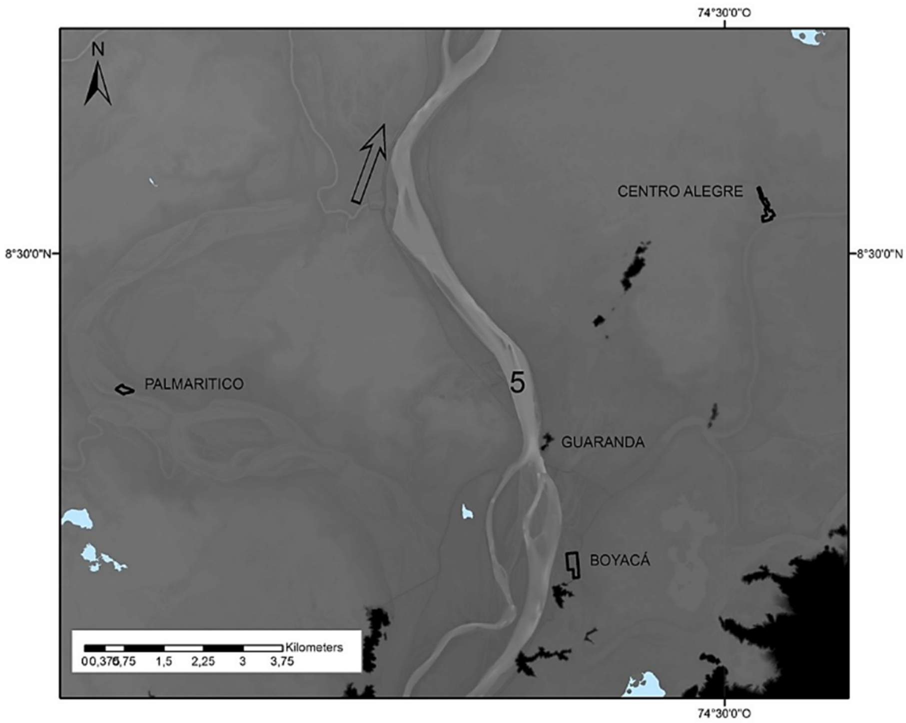

Figure 5. Morphology of sub-reach 5 of Cauca River (within Figures 3 and 4; length: about 10 km, based DTM 10 m). Here it is possible to appreciate the presence of: multiple channels, islands and free bars giving a seemingly wandering appearance; clear signs of lateral mobility including evidence of a paleo-channel quite far apart from the left bank which marks a wide meander (probably cut off by current bankfull channel); longitudinal natural levees (central reach); tiny lateral anastomosed arms which result quite stable in time as confirmed by multitemporal analysis (top, left); recent or ancient crevasse and splays (bottom, right, just upstream of Boyacá).

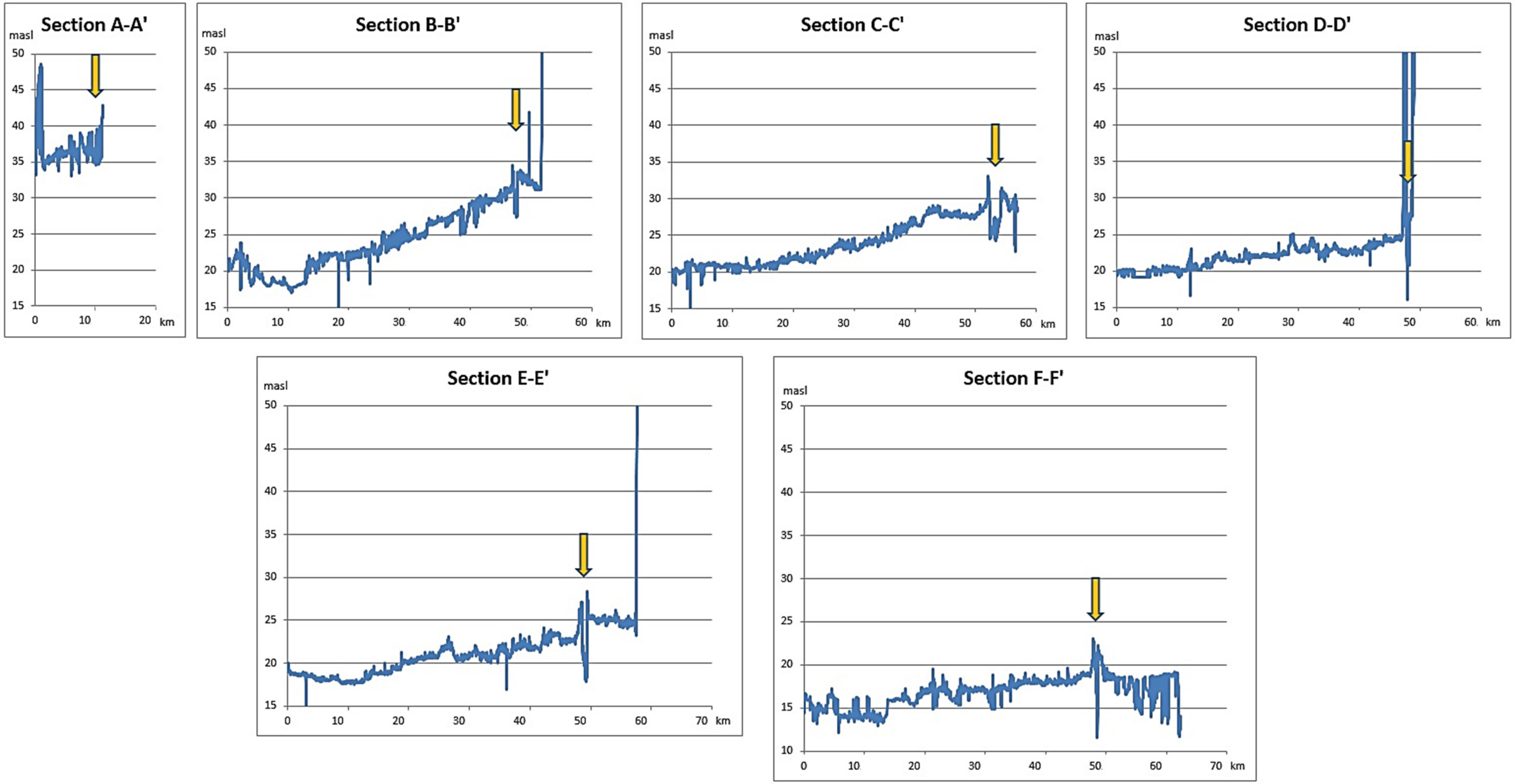

Figure 6. Topographic cross sections of the valley of Cauca River (x: km; y: masl)—located as shown schematically in Figure 4—showing the peculiar setting of the river in a kind of crest, with a clear West-Northwards slope of the same magnitude as its longitudinal slope (figures obtained by GIS sections of the LIDAR DTM 10 m raster).

On the basis of this information, the quite peculiar character of Cauca River within the Mojana region can be inferred: it is a river with a very low slope (0.15 per thousand or less) and low or very low specific stream power. Its sinuosity is low to moderate (the exception being the last reach where it is higher); mainly with a single main channel, but sometimes with up to three (rarely four) channels, seemingly denoting a wandering character, compatible with its high w/h ration (even if the bankfull depth "h" data are very imprecise); accordingly, higher flow rates increase velocity and shear stress more than water depth.

The Cauca River displays very significant (several km) lateral displacements in several reaches and even avulsions (witnessed by the presence of marked longitudinal paleo-channels), facilitated by the generally very low confinement (see Table 3). Its low energy is compatible with the presence of anastomosed channels, while the seemingly wandering behavior of some reaches is indeed witnessing an avulsive character associated with the dynamics of the natural levees that accompany most of its length. Natural levees are created by deposition of coarser sediments (usually transported as bedload) during frequent, lateral overflows, while suspended load is transported further away creating backswamp deposits. Indeed, during significantly high flow events (with flow rates up to even three times as large as the bankfull flow), the occurrence of crevasses in the natural levees of Cauca River is not unusual.

This generally occurs in known preferential sites (called *rompederos*), but sometimes opening new ways. The crevasse flow then feeds an irregular and ever changing, very wide, splay zone, with significant water and sediment volumes, part of which is conveyed by a complex system of more stable natural channels (called *caños*); this whole draining system carries water and sediments to the main drainage axis where the great swamps and wetlands (*humedales* and *ciénagas)* lie. The associated deposition of sediments contributes to contrast the natural subsidence process [28,29].

The long topographic cross sections (see Figure 6) show the peculiar setting of the river on a kind of crest, with a clear West-Northwards slope of the same magnitude as its longitudinal slope (exception made for the confined reach 4). This setting indicates a river in the process of building-up its alluvial valley mainly by vertical deposition, but also by a re-working due to shifting meanders (ridge and swale topography) and partly because of splays and deposition associated with crevasses. It is exactly on the slightly more elevated spots of land left by natural levees or meanders' convex bank ridges that people settled and created the towns.

Perhaps other factors, including tectonic or differential subsidence, contribute to the creation of this topographic setting. In practice, the river channel keeps its current alignment mainly because of the presence of its own natural levees which perform a kind of guiding function; it cannot be excluded, however, that in a particular flood event, the river might suddenly change its trajectory, "plunging" into its wide floodplain towards the draining axis of the San Jorge River and its wetlands (*humedales* and *ciénagas)* and giving life to a completely new main river bed (coherently with the generally very low value of the entrenchment and pseudo-entrenchment indices of Table 3).

3. The Planned Future

In Section 2, we provided some insight into how the Cauca River behaves as the main actor within the Mojana region; however, it is impossible to predict what will happen there, without specifying what will happen at its border, owing to the evolution of the rest of the whole Magdalena-Cauca Rivers basin. The Magdalena River actually marks the northeast border of the Mojana; but, more importantly, even if that were a short reach, some changes in the Magdalena River may deeply transform the whole territory. For instance, incision: By regressive erosion it can lead to incision of the whole hydrological network and that can have a very significant effect.

This vast basin is going to be affected by a number of significant processes:

1. Climate change is expected to rise the level of the Caribbean sea—at the Magdalena's mouth—by some 3.5 mm/year [30] (which may significantly affect the flooding probability in the lower Magdalena-Cauca Rivers basin and particularly of Barranquilla) and the progressive (or sudden?)

modification of rainfall patterns including the El Niño and La Niña (ENSO) phenomena with longer and harsher droughts and more intense/frequent flood events [30];

2. Land use change in the river basin: this is a process which possibly already touched its apex, but it is still going on (particularly deforestation and urbanization more or less un-controlled) and whose consequences—particularly the increment of sediment load to rivers—are on-going [31–33]; this is accompanied by industrial and illegal mining development and its proved toxic consequences [34–41];
3. Population growth and its associated demand for goods and production of wastes.

In addition, a set of very heavy interventions is on the political agenda (see Figures 7 and 8), including:

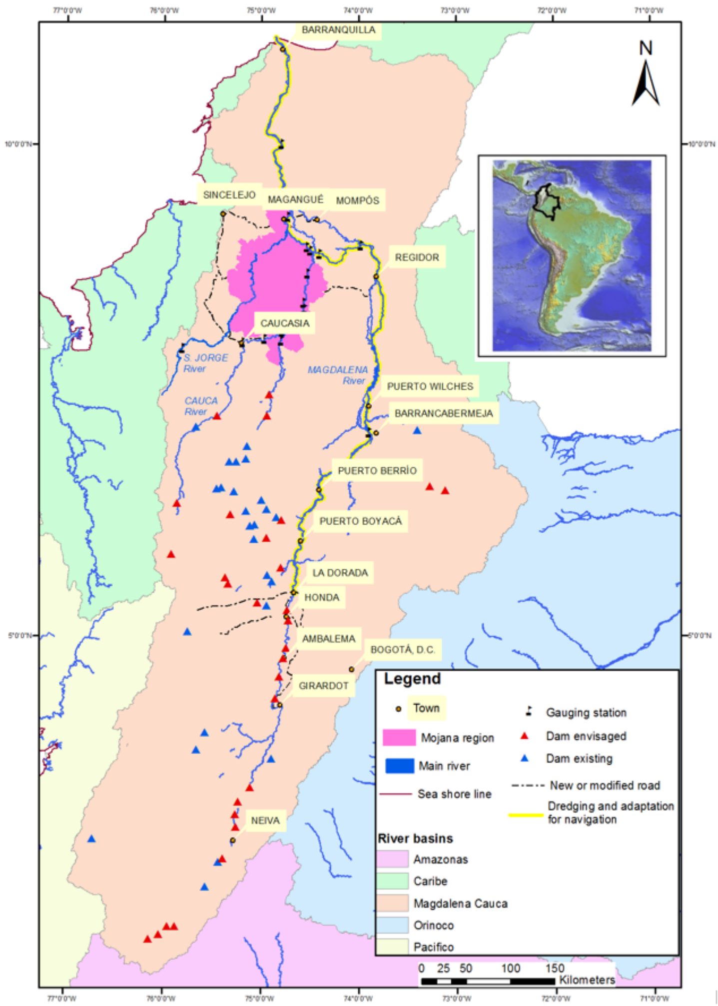

Figure 7. Infra-structural interventions planned or foreseen in the Magdalena-Cauca Rivers basin (the map does not show the expected changes in land use and population, which nevertheless will have a strong influence). Dams location is according to the HydroChina Plan.

1. Several roads and many new dams (existing documents point to up to 50 new ones);
2. Hydraulic works to control floods (levees) and fluvial dynamics (groynes, rip-rap protections, gabions, etc.) in several river sectors (which, as experience demonstrates—as partly shown in the Supplementary Material—very often activate a never-ending process that affects the whole river network, while implying much higher expenditures than initially planned);

3. Morphological re-sectioning of several *caños* in the region designed to ease the evacuation of flood waters and the reduction of flooding in the exploited region;
4. Mega interventions to ensure the commercial navigability along 900 km of the Magdalena River and in some *caños* of the Mojana; this includes very extensive and continuous dredging as well as bank defenses (rip-rap, gabions, walls, etc.).

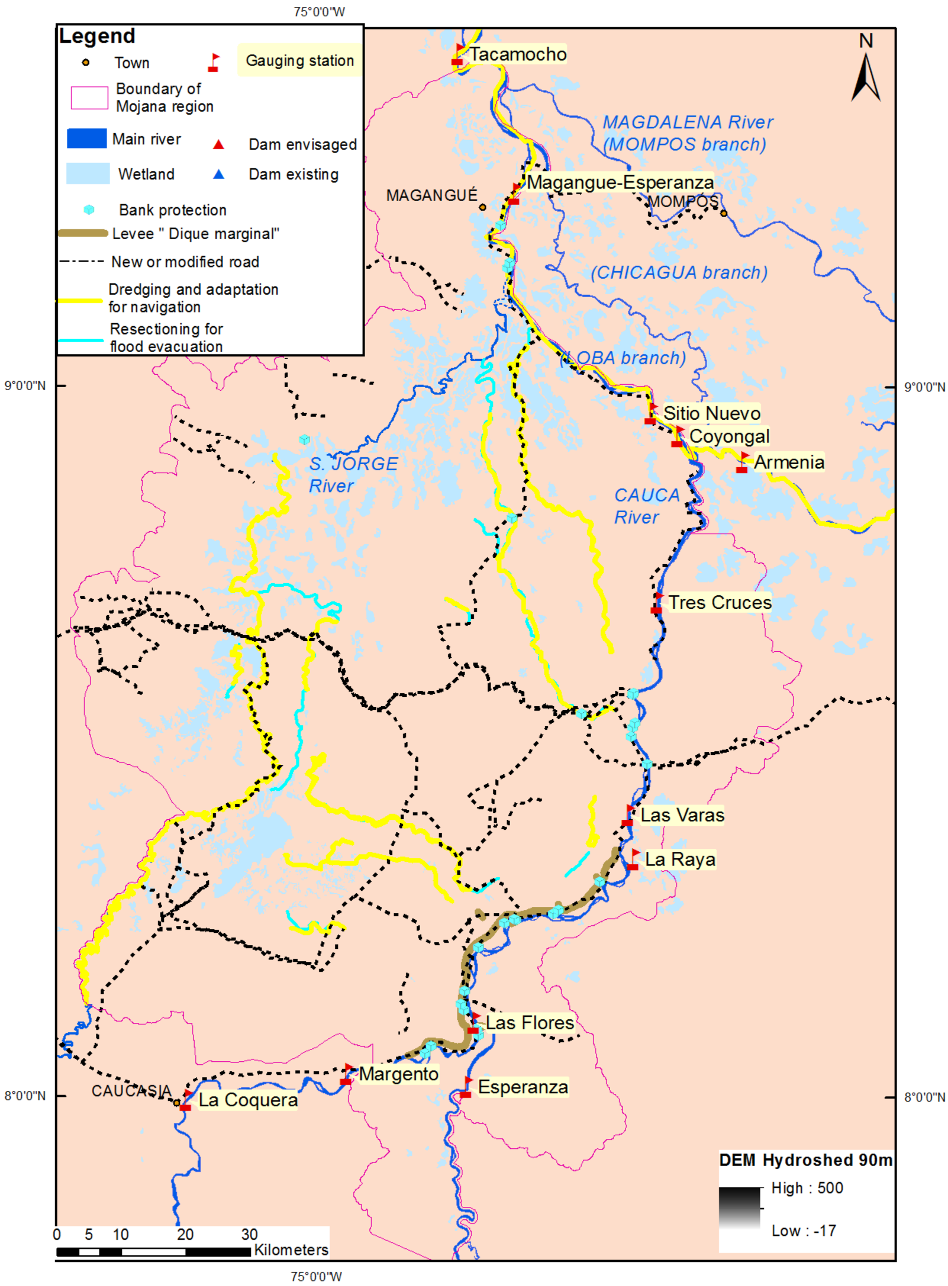

Figure 8. Envisaged interventions within the Mojana region (approximated). Dredging (yellow thick line) is foreseen only in some reaches of the main river and of some "*caños*", while others are going to be closed to avoid flooding of nearby properties). Roads to be built or modified according to the plans of Instituto Nacional de Vías (INVIAS) (National Roads Institute). Main interventions for flood control and other "development" indicated in official documents are presented here in an approximate fashion (it has not been possible to ascertain which works do already exist, which ones are planned and which have been planned and then discarded at some moment in the past). (The location of this region within the Magdalena-Cauca Rivers basin and Colombia is shown in Figures 1 and 7).

4. The Foreseen Future: A Different Picture

In this paragraph, we put forward a large scale, long term prediction of the likely geomorphic effects associated with the whole array of interventions and boundary conditions portrayed above. As the current political debate is concentrated on the Mojana region, that is our focus of discussion; however, we have to consider the whole basin because interventions there may affect the boundary conditions of the Mojana, and because the basin itself (particularly the lower basin) is likely to suffer consequences, including those due to the Mojana region dynamics.

The "model" adopted to carry out such a prediction is merely conceptual and is based on known physics of fluvial dynamics (see for instance [42]) as well as a number of world-wide experiences of similar cases (the "conceptual cause–effect model", see supplementary material to this paper; see Figure 9). The model addresses three main components: hydro-morphological risk, environmental consequences and economics; we describe synthetically here just the most relevant aspects.

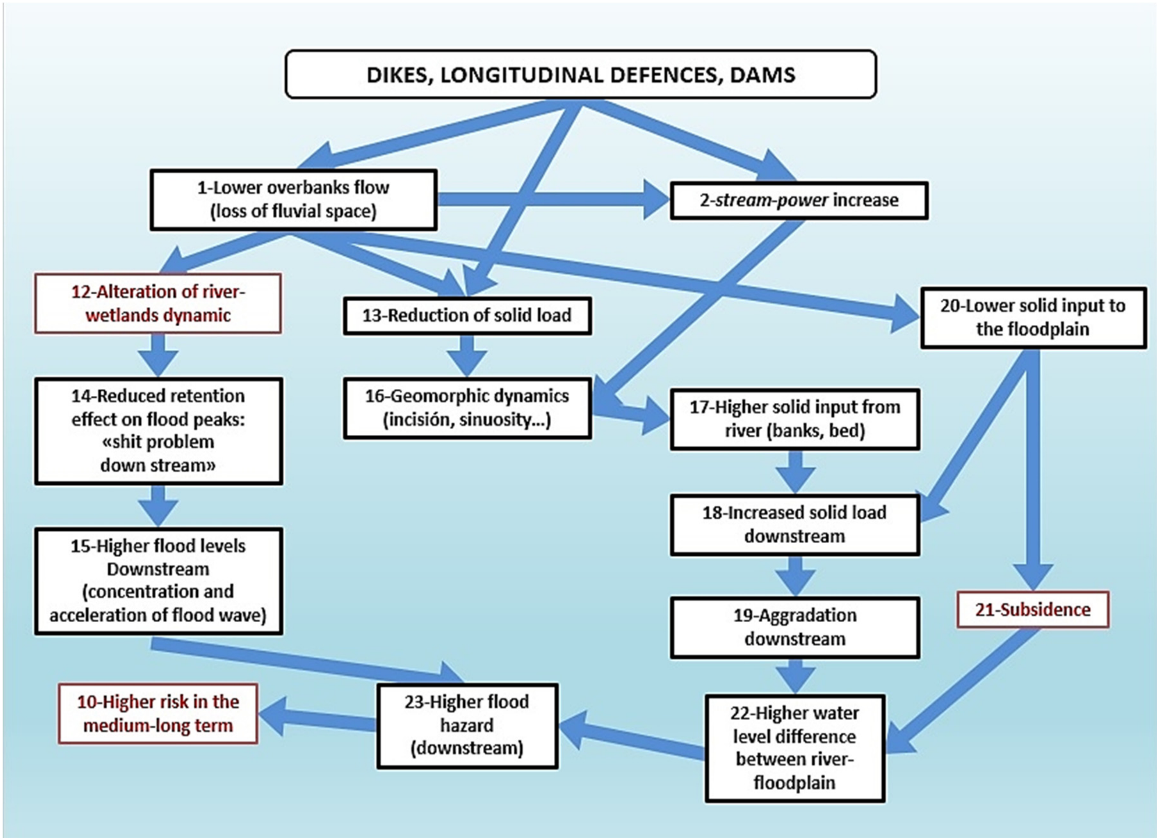

Figure 9. Example of the conceptual cause–effect model utilized linking, in this case, some type of hydraulic works to flood risk (other relationships are available in the full version: see Supplementary Material). Notice that the figure is somehow aggregated: although it presents the set of dikes, weirs, and dams as a unified element, their effects are of course not the same and sometimes the arrow only carries a partial relationship. For instance, only dams and partly weirs have a sediment retention effect which hence reduces solid load; on the contrary, it is mainly levees which reduce overbank flows; and so on. Red boxes denote "pivot effects" that are key to other components of the cause–effect network, not represented in this scheme, but in others.

As stated at the beginning of the paper, a scientifically prudent approach would prefer not to put black on white the following statements as they involve several assumptions; but the desire and need to support as far as possible the decision making process before it is too late motivated us to undertake this daring and uncertain exercise (along the line of what has been carried out by [43]). We are aware that some phenomena counteract others; at the moment it is virtually impossible to state which one would prevail. The most probable future is that they will all take place, but in different reaches and at different times.

To give an idea of why we are obliged to accept a qualitative, semi-subjective approach such as the one here adopted, consider that overcoming these kind of limitations would require a very detailed, broad scale, time consuming and costly exercise to fill several information gaps at the scale of the Magdalena-Cauca Rivers basin (271,249 km^2). Namely, a thorough process would probably include the following:

(i) The available official time-series of flow rates and suspended solid concentrations at different gauging stations should be verified to eliminate the likely effects of subsidence and morphological changes (particularly aggradation/incision) occurred during time so far; they should be depurated by eliminating wrong or doubtful data, and—where needed—completed by reconstructing missing data; finally—and so adjusted—they should be shared and recognized as an accepted database within the Colombian scientific community.
(ii) Data on granulometry should be taken regularly at several monitoring points (un-existent today).
(iii) Also topographic sections in the rivers and topography of the floodplain should be surveyed systematically to create a complete database, detect changes and verify how subsidence (and tectonics or orogeny) works.
(iv) A systematic, complete and updated mapping of relevant infrastructure and its status (bridges, dams, intakes, bank protection works, levees, etc.) should be made available.
(v) Identification and measurement of morphological characteristics at different scales (e.g., the river valley, the floodplain, the bankfull, the islands, the bars, etc.) should be made at different time instants with an homogeneous approach—a process that requires a wide set of good quality, whole coverage, aerial or satellite photographs (a very interesting example is given in [44]).
(vi) A geomorphic classification possibly based on the River Style approach (similar, but more refined than the Rapid River Assessment of Section 2.2, Table 3) would usefully identify homogeneous geomorphic reaches.
(vii) Sediment transport capacity should be assessed (and suitable formulas calibrated) and bankfull and effective flow rates should be assessed and compared.
(viii) Mapping of sediment sources should cover the whole region and models estimating supply—based on empirical formulas like for instance the RUSLE [45]—should be calibrated by performing historical sediment budgets of relevant reaches and reservoirs, which would take into account morphological changes and all inputs/losses.
(ix) A "story of the river" for relevant, representative river reaches would be elaborated which would describe synthetically and systematically the changes experienced so far, capturing amongst others those changes that are due to damming (the idea is introduced in [46], a very nice example is provided by [47]).
(x) The historical mobility space of the rivers should be determined as a reference [48].
(xi) Geomorphic dynamic equilibrium should be assessed by integrating several elements like those already included within the River Style classification, the comparison of transport capacity amongst reaches (to identify sedimentation/incision propensity), the historical sediment budgets, the "story of the river" itself, the evidence of armoring/paving, the condition of bars and riparian vegetation, and of course modeling.
(xii) An "interpretative theory", trying to find credible explanations that show relationships between causes and effects should then be conceived and described.
(xiii) Suitable mathematical models should be developed (and calibrated), and then coupled, to describe all relevant processes, amongst which in particular: hydrological rainfall–runoff behavior (to capture the effects of climate change and land use changes); reservoir operation and sediment trapping; rivers hydraulic simulation coupled to sediment transport/balance and

morpho-dynamics, to eventually determine the characteristics of overbank flooding as well as channel changes (more aggregated models, despite the clever ideas they incorporate (e.g., [33]), cannot provide the sought answers as they always miss part of the problem/phenomena, as for instance morphological changes of river beds).

4.1. Effects at the Border of the Mojana Region: Hydro-Morphological Risk

The whole picture of the causal factors/processes that are likely to affect the borders of the Mojana region in the next future can be summarized as follows:

- "From the sky" (climate change): Higher and/or more frequent flood peaks and longer and harsher droughts (deeper hydrological variability).
- "From the sea side" (climate change): Rising of sea level, which controls the level of the Magdalena River at its outlet at Barranquilla.
- "From the mountains": Reduction of sediment load to the rivers because of dams (see following Box 4.2), of the control works and of the dredging (we ignore, however, when these factors will overcome the experienced increment of solid load due to land use change occurred during the last decades).
- "From the rivers": Geomorphic adaptation reaction (change of the transport capacity of liquid and solid flows) because of anthropogenic interventions as well as the change in the hydrological regime due to climate change. This implies a change of longitudinal profile and slope (incision and aggradation); bankfull width; sinuosity; number and planform of channels; riparian vegetation, fish, fauna, etc.; and increment of instability (divagation with bank erosion, avulsion, incision/aggradation, etc.), eventually affecting river dynamics also within the Mojana region.

In particular, the middle reach of the Magdalena river (possibly between La Dorada and Barrancabermeja—see Figure 7—or even more) might experience an incision process (once the increment of solid load due to land use change upstream will have come to an end: when?) owing to the construction of dams upstream which will capture a significant portion of the sediment load (see Box 4.2 impact of dams), as well as owing to the extensive dredging and the control works against river dynamics envisaged for the sake of fluvial navigability (bank protections, re-sectioning) (see Figure 8).

4.2. Evolution of Cauca River

Without new dams upstream, but with the "*dique marginal* Nechí-Astilleros" in the Cauca River (the artificial levee on the left bank, between Colorado and La Raya settlements, see Figure 8), the riverbed is likely to suffer a significant aggradation. In general, the effect of embankments depends on the balance of two opposite phenomena: (i) if the cross section is significantly narrowed, velocity—under the same flow rate—increases and so does scour and the river incises trying to lower its slope and hence its transport capacity towards a new balance (one of such cases is described for instance in [49] for a gravel bed river); and (ii) when naturally a significant fraction of (suspended) sediment load is frequently lost by overbank flows to the floodplain (as in the Cauca River), embankments prevent this loss, so increasing sediment load; hence, sediment start accumulating within the river bed itself and aggradation occurs as the river requires a higher slope in order to increase its transport capacity and get rid of this sediment excess towards a new balance (this is a case, for instance, of the lower Po River in Italy). The Cauca River, according to the rapid *River Style* assessment (see Section 2.2), is likely to exhibit this latter process.

The available information does not allow us to determine whether, with the construction of the new dams foreseen upstream (see Figure 7), the process of sediment capture by reservoirs would compensate or even overwhelm the aggradation process; but some evidence speaks in favor of this hypothesis (see Figure 10).

Figure 10. Evidence of riverbed incision at Plato—Zambrano bridge, lower Magdalena downstream of Tacamocho (see Figure 8 upper border) [50].

Preliminary Estimation of the Impact of Dams on Solid Transport

We introduce here a very simplified approach by assuming that the progressive filling of the dead storage of reservoirs can be an acceptable estimator of the solid load captured and subtracted from the solid load transported by the river.

Supposing then that the dead storage (V_d) of each reservoir be approximately one-tenth of its capacity (we have no more detailed information) and supposing that all reservoirs will take T years to fill it with sediments without significant artificial emptying, it is possible to estimate the fraction β of the solid flow ($Q_{S\ Magda}$) of Magdalena River captured, as follows:

- Q_d: volume of wet solids captured yearly by reservoirs: $Q_d = V_d/T$ (10^6 m^3/year)
- Q_S^*: corresponding solid flow (captured) as dry weight:

$$Q_S^* = Q_d \times (1 - \eta) \times \gamma_S / 365\ [\text{k ton/day}]$$

$$\beta = Q_S^* / Q_{S\ Magda} \times 100$$

where η: porosity of wet sediments; $\gamma_S = g \times \rho_S$, with g acceleration of gravity (m/s^2) and ρ_S density of dry sediments (kg/m^3).

According to what is shown in the following Table 4, the upper limit of β would result significantly high (around 50%) in the scenario considering the dead storage of all new foreseen reservoirs (including those being currently constructed: Ituango and Quimbo) plus half of that of existing reservoirs (approximately 1200×10^6 m^3) and that filling would take only 30 years with a porosity of 58% (corresponding to a bulk density of 1080 kg/m^3): the effect of reservoirs on the subtraction of sediments load would be extremely high (most probably exaggerated). However, the lower limit (around 8%) would still be quite significant—considering only the new reservoirs, a longer horizon of 50 years and a porosity of 85% (corresponding to a bulk density of 380 kg/m^3). Results more alarming than these have been found in the Mekong River [51].

An efficiency of sediment capturing around 20%–40% for existing reservoirs in the Magdalena-Cauca Rivers basin was estimated by [52]; this datum, however, is not immediately comparable with ours—because there is a whole river network in between—but speaks anyway of significant impacts.

In summary, the problem of sediments capture seems to be quite important.

Table 4. Estimation of the fraction of solid flow captured by the whole foreseen set of reservoirs.

Item	Data			Hypothesis		Computations			
definition	dead storage	specific weight of solids	solid flow of Magdalena	horizon	porosity	captured volume	dry solid flow captured	dry solid flow captured	fraction captured
symbol	V_d	g	$Q_{S\ Magda}$	T	h	Q_d	Q_S*	Q_S*	b
units	10^6 m^3	kg/m^3	kt/day	year	–	10^6 m^3/yr	10^6 kg/yr	kt/day	%
lower	1500	2600	400	50	0.85	30	11,700	32	8
upper	2100	2600	400	30	0.58	70	76,440	209	52

Note: location and reservoirs volumes from data facilitated by The Nature Conservancy.

$Q_{S\ Magdalena}$ obtained from [1], Figures 8–17: Armenia approximately 180; Figures 8–19 Sitio Nuevo approximately 300; Figures 8–20 Magangué approximately 280; Figures 8–21 Tacamocho approximately 400.

In this latter case, the river is likely to change style (possibly downstream of Caucasia—see Figure 8, lowest part) because of the solid load deficit: we would hence witness a progressive incision and/or an increment of its sinuosity, in order to reduce its slope and hence its transport capacity and, at the same time, trying to get some material from its own banks and bed (see Figure 11). In any case, this process will also lead to a more frequent/likely de-stabilization of works (bridges, bank protections, levees, etc.) and eventually again to an (important) increment of OMR costs (Operation, Maintenance and Replacement). All these phenomena will be aggravated by climate change (more frequent and intense floods).

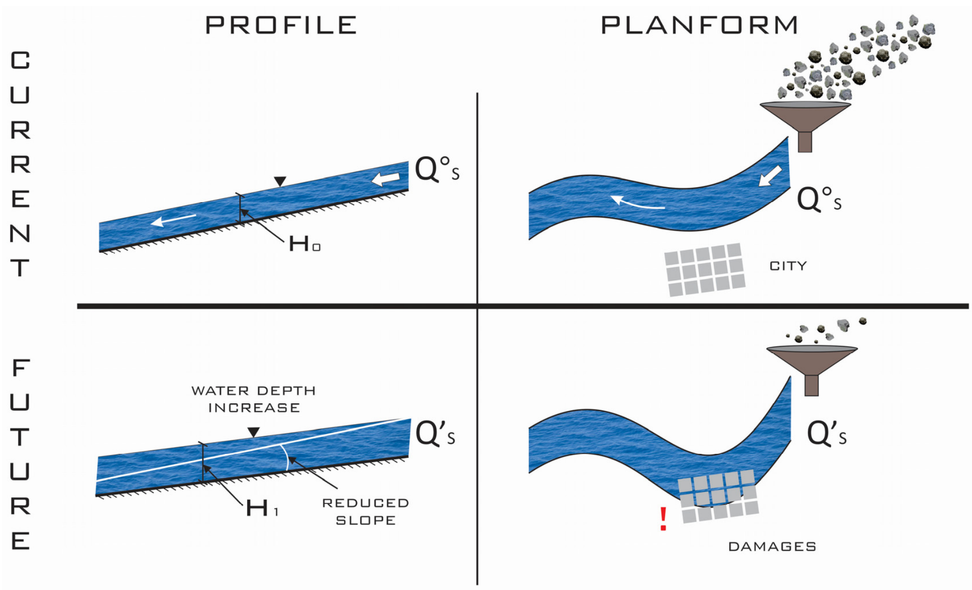

Figure 11. The capture of sediments by existing and future reservoirs (mainly on Cauca River, upstream of Caucasia and on Nechí River basin) will lead to a reduction of sediment load downstream; this will trigger an adaptation of the river to reduce its transport capacity, basically by lowering its slope and getting to a new river style: it probably will widen its meanders belt downstream of Caucasia, and increase its water depth owing to the lower slope.

4.3. Flooding Hazard Increases in the Lower Basin

The phenomenon of incision of the middle Magdalena River reach (which would take place probably in few decades, after dams construction and in parallel to dredging) might lead to increased peak flows downstream as the water retention of current floodplain would be partially inhibited, so concentrating enormous water volumes downstream and elevating water levels there, around Magangué, and—owing to backwatering—even in the zone around the San Jorge River and possibly affecting Plato, Calamar and even the very important city of Barranquilla and along the Canal del Dique towards Cartagena (see Figure 12). This phenomenon would be exacerbated by the presence of the "*dique marginal*" (Cauca River left bank levee) as this work is exactly meant to reduce flooding towards the North Western *humedales* zone (furthermore, it would definitely worsen the flood risk in stretches of the *Cauca* River itself downstream of the dike itself).

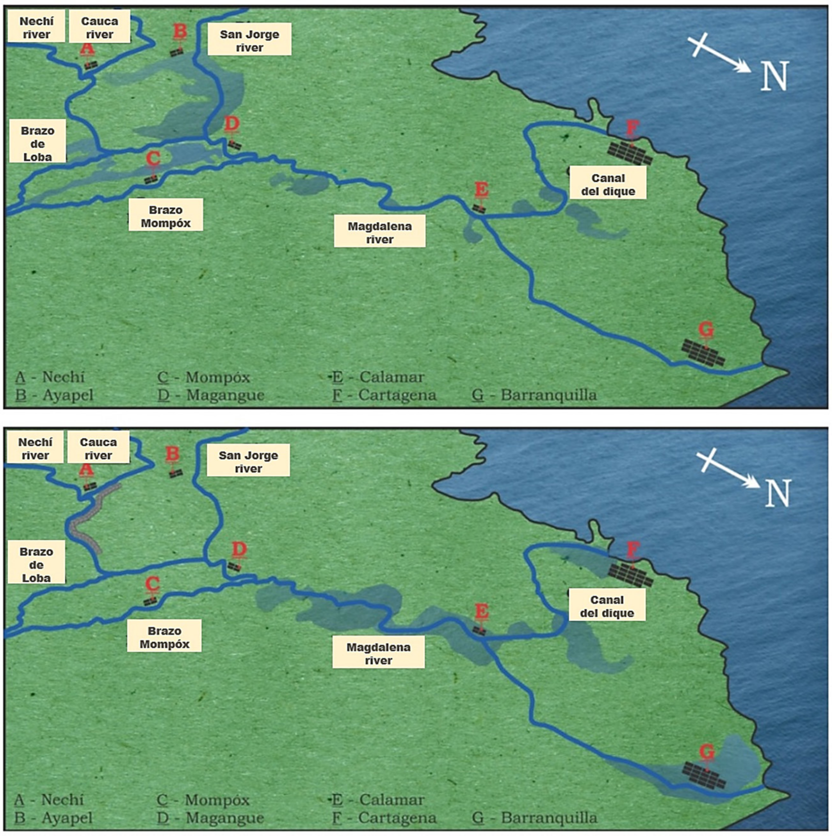

Figure 12. Possible flooding increase in vulnerable zones (**below**), with respect to current situation (**above**), owing to upstream protection works and to the likely incision of the middle Magdalena River (not represented).

An increased flooding frequency/intensity of the lower Magdalena-Cauca Rivers basin will occur also—and without any possibility of countermeasures—because of the expected sea level rise which will affect hundreds of km upstream owing to the very low river slope (virtually zero or few units per thousand). In addition, the harsher flood events due to climate change will contribute to worsen the flooding hazard. The problem will also worsen because of the exacerbated subsidence process that the Mojana region will very probably experience as a result of the reduction of solid load to the floodplain caused by the "*dique marginal*", the interventions (dredging and re-sectioning) for increasing the conveyance of some key *caños* to reduce their overflows (while others are going to be closed to avoid flooding of nearby properties dedicated to cattle farming), and the embankments that will accompany the extensive system of new roads foreseen (e.g., the San Marcos-Majagual-Achí road) (see Figure 8) (an additional point refers to the effect of tectonics and orogeny, which we did not explore), while the floodplain will plunge, the riverbed elevation in lower reaches protected by levees is, on the contrary, likely to rise (as lateral sediment dispersion is impeded) and with it also the flood peak levels.

In summary, higher flood levels, higher elevation difference between the water level within the river and the surrounding terrain because of subsidence (where human activities lie) and river bed aggradation and flood concentration due to levees, together with an increase of the exposed value—as settlements and activities will assuredly grow towards hazard-prone areas (as the international experience demonstrates)—and together with harsher climatic events, will inevitably increase flood risk and eventually provoke more damages.

4.4. Both Drought Hazard and Vulnerability Increase

More prolonged dry periods due to climate change, together with the incision of the Magdalena River, and its reduced frequency of overflows on its floodplain, will lower the water table. The resulting lower water availability will provoke harsher water crisis in agricultural activities, increase human water supply costs and affect ecosystems.

4.5. Transformation of Wetlands

The destiny of the vast, characteristic wetlands of the Mojana region is uncertain. The "*dique marginal*" along the left bank of the Cauca River, together with the other interventions, will reduce water supply to the *humedales* zone and, what is worse, bring about a reduction of the water "pulses" which characterize so profoundly their functioning; governing fish reproduction, migration and hence fishery, amongst other aspects. However, in case the net subsidence and the flood peaks concentration downstream prove very significant, the *humedales* will experience, on the contrary, a progressive transformation into permanent water bodies. The sad part of it is that in both cases an impact on ecosystems will take place, particularly on the more delicate "transition components" (*playones:* temporary emerged bars; *zápales*: wet woods; etc.) together with their associated processes and environmental services [1]. This does not prevent the wetlands from drying up in an even more radical fashion than today, when the El Niño (i.e., hot ENSO) phenomenon occurs, particularly if the current tendency to close some natural "*caños*" which feed them (in order to widen dry lands for cattle raising (as already noted, the situation is articulated, because some "*caños*" are going to be modified to increase conveyance and/or navigability, while others are being closed)) and to destroy the riparian vegetation (which contributes to capture atmospheric water and reduce evaporation through shadow effect) will keep going on.

4.6. Economics: Increased Operation, Maintenance and Replacement Costs (OMR)

Any work, once it has been built, implies ongoing expenditure virtually forever—or at least until a new configuration is implemented—in order to operate, maintain and, periodically, rebuild it (depending on its technical life span). Our argument is that such costs are usually estimated on the basis of engineering criteria, which do not include the effects of such a wide infrastructural change throughout the whole river basin and its associated geomorphological consequences.

It is very difficult to estimate the increase in OMR costs due to fluvial dynamics and the impact of interventions; attempts based on historical data usually fail because:

(i) It is extremely hard to get the whole list of interventions (and associated dates and costs).
(ii) It is very hard to discern based on denominations/descriptions whether it was actually an OMR cost of an existing work or rather a different, new work.
(iii) The behavior of the system was certainly (very) different from the one that will take place in the future once the new interventions will be implemented.

As an indicative figure, we attempted an estimation based on the official data (available online in a Excel® file that can be consulted as Supplementary Material), which presents the investment figures for risk management in the Mojana region between 2003–2013 spent by governmental entities. By performing the most credible and prudent selection of the items presented, we obtained (in Colombian pesos with no actualization of money value) a total expense in the period of about 338 mil M$, a total OMR cost of 121 mil M$ and a net total investment C of 217 mil M$; with these data, the ratio OMR/C is about 56%, a figure which, in just 10 years, is undoubtedly an extremely high one: in a planning time horizon of 50 years, a similar OMR cost would triple the net investment cost. In addition, because of the hydro-geomorphological processes described above, this figure is very likely to become much higher than this in the future.

5. Conclusions

This paper is not intended to propose a particular solution; it rather makes a point on the likely adverse consequences of the course of actions currently planned. We took a delicate position according to a "preventive approach" [19–23] in order to provide information useful to the decision making process even if scientifically questionable, as several assumptions need to be supported by evidence yet lacking. We think this is a sensible choice, as a more scientifically prudent approach requiring more data (which would be available possibly in 10 or 20 years from now if a coordinated research effort were put into place immediately) and more scientific evidence would miss the purpose of a timely contribution to a balanced country development.

We conclude that the assessment of flood hazard recently conducted by the modeling group at IDEAM through mathematical modeling—although very refined and consistent with its hypotheses—will inevitably lead to an under-estimation of risk, a fact which, in turn, will bias the cost–benefit evaluation and, in turn, decisions.

Indeed, actual hazard will definitely be higher owing to the dynamic, geomorphic behavior of the system, very much linked to sediment transport, an aspect (as already noted by [53]) not considered in the hydrological-hydraulic modeling which performs all of its simulations on a fixed morphological context coinciding with a picture of the current system. We argued in this paper that, to the contrary, morphological evolution will conduct to a very distinct behavior with undesired increases of flood levels in vulnerable zones, increasing gradients between fluvial water level and terrain (subject to subsidence) and higher morphological risk due to more frequent and stronger destabilization action of fluvial dynamics on existing and foreseen works and infrastructures. The benefit–cost balance may seem now more positive than it actually should be because of risk under-estimation. However, another reason is that actual costs will be significantly higher simply because OMR costs of works are very likely to grossly exceed what can be estimated by ignoring the above aspect. This very fact can, by itself, drastically change the economic judgment of the whole plan.

As well, risks due to droughts would increase, while a broad array of environmental services associated with the characteristic pseudo-periodic "water pulses" would be progressively, but inevitably, lost or diminished with enormous adverse consequences.

These observations—together with socio-economic and cultural considerations not discussed here—should foster a deep re-thinking of the development model envisaged for the Mojana leading to the recognition of its very peculiar nature and to a strategy aiming at maintaining the "water pulses" peculiarity, while helping the anthropogenic system to adapt to it and take more advantage from it than was previously done. In other words, the recommendation we give is to not interfere, within the limits of possibility, with natural processes and, as such, build as few infrastructures as possible or, at least, ensure their compatibility with such processes.

In line with several other studies, like for instance [49], we can state that the geomorphic view of the consequences of development actions opens an illuminating perspective that adds important arguments for the decision process and can help avoiding choices that might dump heavy impacts on future generations.

To overcome the limitations of the qualitative approach adopted here, several information gaps should be filled at the scale of the Magdalena-Cauca Rivers basin, a task very hard to accomplish and which would require definitely several years or decades. Undertaking this exercise is certainly advisable, but not for the decisions to be made now.

Supplementary Materials: The following are available online at www.mdpi.com/2079-9276/5/3/22/s1. The conceptual cause–effect model "*Modelo conceptual: Reflexión sobre los Posibles Efectos de las Alternativas de Manejo Fluvial sobre el* "*Desarrollo de La Mojana*".

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Author Contributions: Freddy contributed to develop a sensible discourse with his knowledge of the area, carried out most of bibliographic review and analysis, wrote the descriptive sections on the Mojana; he also prepared most of the figures and carried out the editing of the text. Andrea conceived the general argumentation, developed the Rapid River Assessment and the preliminary estimation of solid transport alteration and wrote the remaining sections of the paper**.**

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

Abbreviations

IDEA	*Instituto de Estudios Ambientales, Universidad Nacional de Colombia—Sede Manizales* (Environmental Studies Institute in the Colombia National University, Manizales branch)
GTA	*Grupo de Trabajo Académico* (Academic Work Group)
CIRF	*Centro Italiano per la Riqualificazione Fluviale* (Italian Centre for River Restoration)
ENSO	*El Niño/La Niña* Southern Oscillation
DNP	*Departamento de Planeación Nacional (*National Planning Department)
IDEAM	*Instituto de Hidrología, Meteorología y Estudios Ambientales* (Institute of Hydrology, Meteorology and Environmental Studies)
NGO	Non Governmental Organizations
GIS	Geographic Information System
INVIAS	*Instituto Nacional de Vías* (National Roads Institute)
RUSLE	Revised Universal Soil Loss Equation
OMR	Operation Maintenance and Replacement costs of the infrastructural works

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