ENABLING COORDINATION OF INDEPENDENT STAKEHOLDERS TO MINIMIZE IMPACTS OF DAM CONSTRUCTION AND OPERATION AT MACROBASIN SCALE: AN INFORMATION TECHNOLOGY APPROACH

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To support Integrated Water Resources Management (IWRM), adequate methodologies and tools are needed. Decision Support Systems (DSS) are one of the tools that play an important role as a support to policy development and implementation for IWRM. However, the success of a DSS is "to be truly used", including continuous improvements. To this aim, clearly identifying from the very beginning who will be the DSS users and what they expect to receive from the DSS, is a must for success. In this identification of stakeholders, their roles and requirements, typically an important issue related with their understanding and perception of the basin emerges which is at a time a difficulty and an opportunity: it is a difficulty because, visions can diverge and misunderstandings and even tensions or conflicts may arise; it is an opportunity, because –if suitably shared and managed- from multiple views a more robust mutual understanding of problems and opportunities can be reached. Commonly, as in the case of the Magdalena river basin, a single decision maker (DM) cannot be identified; rather decisions are made in a somehow disconnected fashion, often just at a local scale, without considering the opportunities that a system-scale approach can provide. Being aware of this, the Support System for Decision Making at Macro-Basin Scale (SIMA) has been designed and implemented to stimulate and help these different policy/decision makers to adopt a system view, by ensuring that the "different pieces of the puzzle are taken into account at the same time", so promoting a view of the problems of the basin that is integrated, transparent, coherent and uniform amongst the multiple stakeholders involved. SIMA incorporates a set of analytical tools to predict the accumulative impacts of basin development, while integrating geography, hydrology with ecology. In this paper, an overview of the main features of SIMA are presented and an implementation of the system for the Magdalena macro-basin in Colombia is also illustrated as a case of use of the proposed methodological framework focused in minimizing impacts of hydropower development.

1 INTRODUCTION

Due to the complexity inherently associated with Integrated Water Resources Management (IWRM) in large scale river basins, a system capable of dealing with information relevant to different types of interests is a necessary tool to coordinate interventions and development. All stakeholders are connected through water, and impacts are accumulated and reflected in the fluvial network; if interventions are not coordinated, inefficiency, dissatisfaction, unsustainability and even conflicts may derive; a system that can inform transparently and clearly, promoting the dialogue amongst the different stakeholders , can help avoiding this problem. Over the past 40 years the concept of Decision Support Systems (DSS) has been developed in the field of decision theory and has shown great potential for environmental management [1]. However, considering the high risk that a DSS may fail in practice, a special effort on the identification of potential users, and the particular conditions in the specific basin where the DSS is going to be implemented, is a priority activity in the conceptualization of the system [2].

The Support System for Decision Making at Macro-Basin Scale (SIMA) has been conceptualized as a tool for the integrated analysis, at the macro-basin scale, of the state of the environment and cumulative impacts, with particular emphasis on fresh water ecosystems, and large-scale development actions in the sectors of hydropower, irrigated agriculture, flood control and environmental restoration and, on the other hand, by non-controllable factors such as climate and climate change.

Some of the main features of SIMA are:

- It is a free and open tool, web based, which has models and analysis tools to estimate cumulative and long-term impacts within a large scale river basin.
- It allows different actors to dialogue and share perspectives with the same information, under the same assumptions (verifiable), and in turn, be informed and involved in strategic decisions of the basin, with the spirit of supporting participation in the decision making process, strengthening governance.
- Its open source architecture (at the level of source code and APIs) makes adaptation and upgrading by different subjects possible and paves the way to a long life
- It currently includes a number of modelling tools (described below) which are able to capture a substantial, although partial, portion of the complex cause-effect network relevant to assess cumulative impacts. Different or additional analysis tools can however be adopted. In such a way, SIMA can be continuously upgraded to cope with the particular needs of the stakeholders, recognizing that each macro-basin requires particular features.
- It has interoperability capabilities to easy connect with national or regional information systems.

Section 2 of this paper presents the general concepts behind the system as the methodological framework for its development. In section 3 the implementation of SIMA in the Magdalena basin is shown as an example of an operative system in practice that initially has been focused in minimizing impacts of dam construction. Finally, in section 4 conclusions of the exercise are presented.

2 METHODOLOGICAL FRAMEWORK

2.1 General concepts

SIMA has been conceptualized along two main structure lines: the first one is that of a core system where main functionalities are developed, these are capacities of the system in an abstract domain (not related with a particular geography), e.g. user interface, indicators manager, interoperability, analytical tools, etc.. This core system is the main component of the informatic tool that incorporates research and development for SIMA as an abstract tool. The code of SIMA-Core is open with full access for contributions.

The second structure lines is that of “instances”; i.e. a particular configuration of the system for a particular geography, including all the necessary thematic contents to be operational. Ideally, when an instance is created, an administrator of the system has to be appointed. This administrator has to decide the necessary features for its personalized system based on the capabilities already available in SIMA-Core and the identification of the particular stakeholders and problems in its macro-basin. Due to the particularities of each basin, it is probable that some special features have to be developed for the specific instance with contributions of universities, regional or national authorities, and local communities among others. These contributions can be either thematic or functional contributions. In the case of functional contributions that come from an instance, it is possible for SIMA-Core to also assimilate these new features as an abstract functionality.

Figure 1 summarizes the concept previously explained of SIMA as an open two ways system for contributions in thematic information and core functionalities.

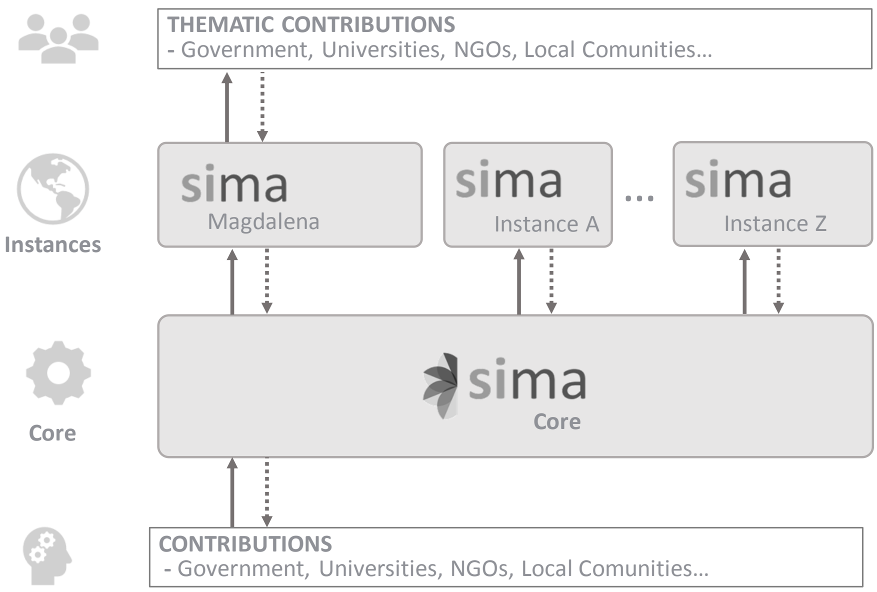

Figure 1. Structure of SIMA-Core and SIMA instances

When an instance is created, the tool as a useful DSS is available for stakeholders and decision-makers in the specific macro-basin. However, the integrated vision of SIMA is more than the WEB based platform. For a successful SIMA instance, at least 5 main dimensions that have to be developed are identified: (1) Informatic tool, (2) Thematic content, (3) Inputs for decision making, (4) Administration (ICT) and (5) Users able to use and understand the system. Figure 2 presents this vision related with a successful exercise for a SIMA instance.

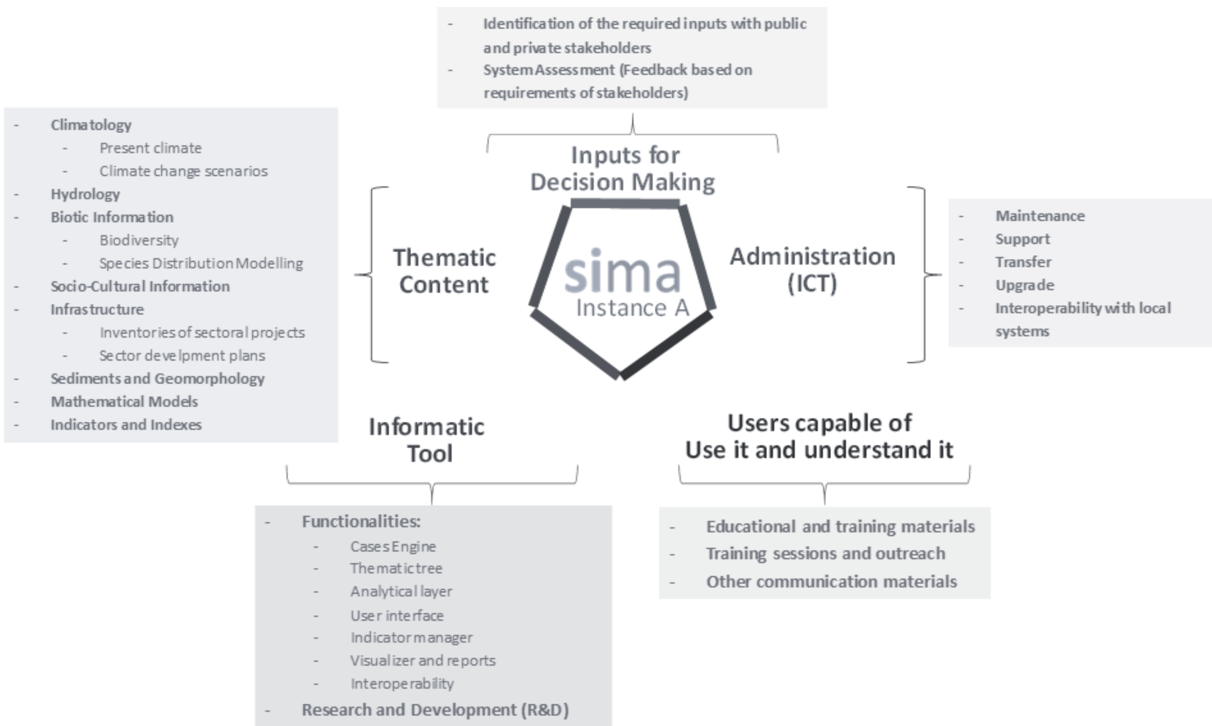

Figure 2. Dimensions of a successful SIMA instance implementation

Notice how SIMA conceptual architecture recognizes the importance of the identification of the required inputs with public and private stakeholders and the feedback through system assessment. Also the educational and training component is very important for the success of a SIMA instance, combined with Information and Communications Technology (ICT), functionalities, research and development and specific thematic content related with the study area.

In this way, SIMA has been conceptualized as a DSS where different users can present and give shape to their alternatives of development including technical data to configure case study to be analyzed at a macro-basin scale. The analysis can be perform using “tier 1” or “tier 2” tools. Tier 1 tools are associated with the screening evaluation of projects siting & sizing and their impacts at system scale to provide early warnings on loss of ecosystem processes or habitats and hence guiding the definition of consistent sectoral and integrated plans; tier 2 tools allow the assessment of such plans at system level with further details under a multi objective perspective. Following this framework, Figure 3 schematically presents the use of SIMA for the hydropower sector.

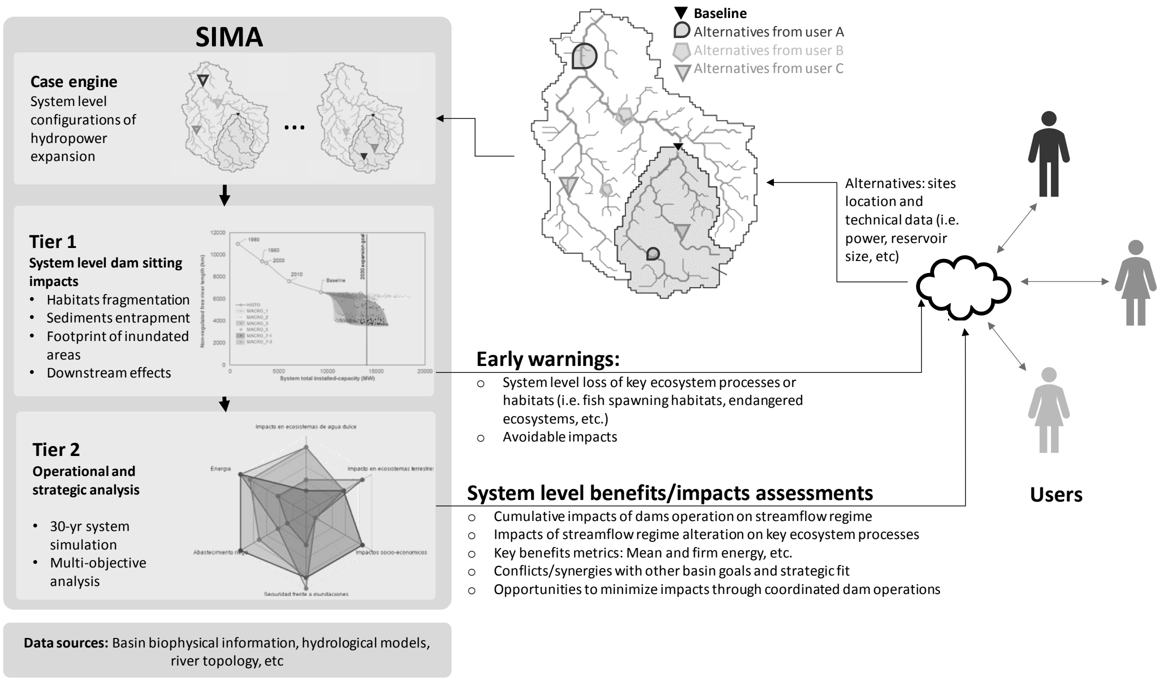

Figure 3. Use of SIMA for the case of the hydropower sector

2.2 *Historical* mode and *Future* mode

SIMA has been designed to operate in two functional modes: *Historical* mode and *Future* mode. The Historical mode is mainly a functionality of an Information Support System (ISS) useful to report the current status of the objects of interest (base line) and their evolution in time (monitoring). One of the purpose of the historical mode is to show all types of information available associated with any theme chosen by the user, not only regarding geographic information (vector layers or raster), but including also documents, photographs, infopackages, etc. The system can also pre-organize relevant information in different categories (e.g. the Determinant Pressure State Impact and Response scheme) and calculate indices based on measured variables to express judgments in qualitative scales and therefore, providing a synthetic view of the often overwhelming environmental information, but ensuring full transparency (as it is always possible to rise the aggregation tree up to the original data).

Most of the information required for the Historical mode can be obtained from official sources in the country using the SIMA interoperability capacity. However, the system allows the assimilation of data from other sources as well (form academia, NGOs, research institutes, among others), providing a suitable metadata file used to identify and describe the characteristics of the data and its reliability. It depends on the user to use or filtrate official and non-official data.

The *Future* mode has been designed to allow exploring the expected consequences of possible (hypothetical) interventions in the basin. Two components play hence a key role in the Future mode of SIMA: *scenarios* (variables that are beyond the scope of decision-makers) and *alternatives* (of sectorial and integrated plans), that, when combined (together with additional pieces of *context* information (e.g. the value of models parameters; or geographic feature like topography), create a *Case study*. A scenario, as mentioned, is a time pattern of the set of variables that affect the system under consideration, but that cannot be controlled (at least not by the decision-maker involved with the DSS): the user can only adopt the most credible, representative, optimistic, or rather critical or accepted scenario, depending on his particular interest. Some examples of variables that are categorized under a *scenario* are: climate, sea level, land use, energy demand and demography (population growth). On the other hand, an *alternative* is defined as a set of decisions under the control of the decision-maker(s) and from which the effects are to be explored if implemented. Examples of variables under the alternative category in the DSS are: siting and sizing of hydroelectric plants (both reservoir and run-of-river), agricultural development, forest exploitation, mining exploitation and wetlands management. The Case engine that is mentioned in Figure 2, under the category of informatic tool, represents the capability of the system to administrate this configuration of scenarios and alternatives and its combination to create study cases.

2.3 Analysis framework

Due to the multiple benefits and impacts that any alternative can have at the macro-basin scale, the assessment must be based on a multicriteria, comparative framework. A specific alternative could rate well under a certain point of view (criterion), but may rate bad under other criteria. Additionally, the comparative approach somehow confines the uncertainties of the models, as the differentials are what counts more.

Defining and implementing a meaningful cause-effect network of relationships between a case and the relevant, possible effects (cumulative impacts) is not an easy task at all. To address this challenge, we started by identifying the key problems considered relevant in the Magdalena basin (might be different in another instance) as well as the set of significant possible causes, including anthropogenic interventions (i.e. alternative plans) - like infrastructural projects, land use change or management practices- and non-controllable causes, like climate change or population growth, (i.e. "scenario" variables). Then we identified the main processes and phenomena linking causes (non-controllable and controllable variables) to effects (worsening or improvement of problems, i.e. cumulative impacts). Several of such relationships have then be formalized and modeled, as explained in section 3.

The cause-effect relationships network incorporated in SIMA, in its current version, is presented in Figure 4, showing the complexity of the different interactions in the system. The tier 1 tools are focused on three types of impacts: i) Fragmentation of river systems, ii) downstream effects associated with changes in the flow and sediment regime and iii) footprint of flooding on environmental, social and cultural values. The first two types are mainly associated with freshwater systems, where the impacts of the different infrastructures are accumulated from the upper parts to the lower parts of the basin through the river network. The third type of impact is associated with cumulative footprint of flooded areas on terrestrial or aquatic systems.

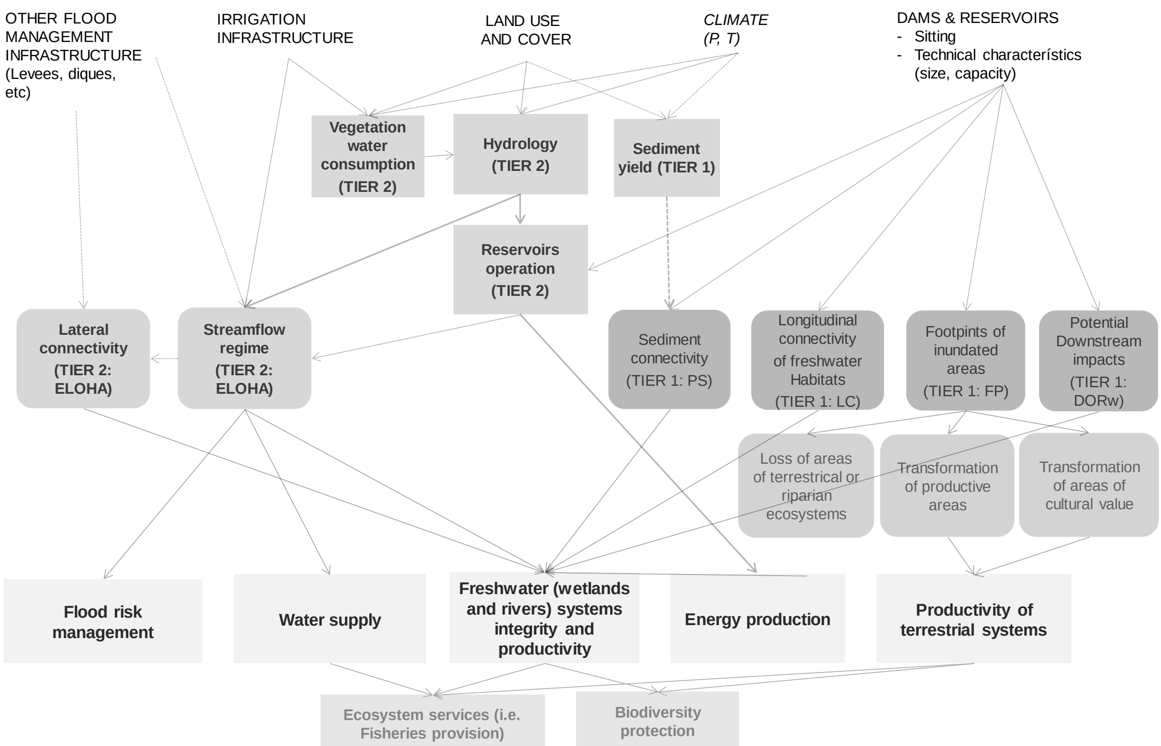

Figure 4. Cause-effect relationships incorporated in SIMA. Note that tier 1 analysis tools do not depend on hydrological modelling and are tools for quick assessment. Tier 2 tools are more complex analysis that need hydrological modelling.

Fragmentation refers to the loss of natural connectivity in fluvial systems, limiting the transfer of organisms, sediments and nutrients. The connectivity in fluvial systems covers different aspects: longitudinal, which refers to the connection upstream and downstream of the ecosystems, lateral, which refers to the relationship between fluvial systems with their wetlands and floodplains, and vertical that connects surface water with groundwater flows [3]. In the case of hydroelectric infrastructure, the analysis focuses on longitudinal connectivity (Lc), given that reservoirs, dams and deviations are generally barriers that prevent the migration and dispersion of species and the continuity of sediment and nutrient transfer between sections located upstream and downstream.

Downstream impacts refer to the cumulative effect of reservoirs on the artificial regulation of flow rates and entrapment of sediments. For example, peaks of seasonal flow with annual frequencies stop occurring in regulated rivers due to the damping effect of reservoirs. Likewise, downstream, the extension of floodable areas, wetlands and riparian zones are reduced [4]. As a result, processes of redistribution of sediments, biomass and nutrients along the stream and flood zones are disrupted, destroying corridors of connectivity between lotic and lentic systems [5] [6]. These alterations in the hydrological and sediment regimes can cause interruption of the vital cycles of freshwater species [7] and loss of lateral connectivity and transport of organic and inorganic matter towards the riparian flood plains [8] [9].

In order to measure the alteration of the flow regime at a Tier 1 level of analysis, the weighted degree of regulation (DOR_w) presented by Angarita, *et al.* [10] has been adopted in SIMA. DOR_w is defined as the relationship between the cumulative reservoir storage upstream and the total annual river flow in a river section, weighted by the percentage of upstream runoff effectively controlled by artificial storage [10]. In the same way, a tool to estimate suspended sediment entrapment is also incorporated in SIMA-Core as a tier 1 approximation using an indicator of relative loss of sediments as defined by Angarita, *et al*. [10].

The connectivity and the condition of naturalness of the flow regime are determining factors of the integrity and productivity of freshwater systems, since the availability and quality of the habitats depend on them.

The third group of cumulative impacts refers to the footprint of flooded areas on sites or areas of social, environmental and economic value. From a cumulative impact analysis perspective, we seek to know and compare the aggregate impacts of flooded areas by groups of projects in relation to the abundance or relative scarcity of social, environmental or economic values at the macro-basin scale. In this way it is possible, for example, to identify combinations of projects that completely avoid, or reduce to a minimum, the effects in areas of productive zones, heritage sites, areas of conservation, among others.

At Tier 2, the analysis of the hydrological answer of the catchments (affected by both climate change and land use) and the alteration of flow regime due to that factor together with management actions (reservoirs, withdrawals, levees,. etc.) has been incorporated within SIMA by implementing a WEAP [11] application (Water Evaluation And Planning) for the whole basin. Owing to its complexity, this kind of tools usually has to be developed for the specific area where the instance has been created.

Finally, considering additional results that a tier 2 model can provide, SIMA also incorporates analysis using the scientific process proposed by Poff *et al.* [12] as part of the Ecological Limits of Hydrologic Alteration (ELOHA). In the ELOHA framework, to develop flow alteration – ecological response relationships-, a procedure based on 4 steps is proposed. In step 1 a hydrological foundation is built using available data and mathematical modelling to represent both baseline (pre-development) and developed conditions. For this step a tier 2 hydrological model in SIMA is required to be incorporated as a central tool for the analysis in the DSS. In step 2, a classification of river segments is performed based on similarity of flow regimes using relevant flow statistics computed in step 1 and geomorphology characteristics to define river types. In step 3, hydrological alteration is calculated as the percentage deviation of developed condition compare to baseline condition, focusing on a small set of flow statistics strongly linked to ecological conditions. Finally, in step 4, flow alteration and ecology response relationships are developed using flow – ecology linkages. Through monitor and social information, the ecological data used to develop these relationships can be validated [12].

3 EXAMPLE OF THE DSS IMPLEMENTATION IN SIMA-MAGDALENA

The first SIMA instance was implemented in the Magdalena river macro-basin in Colombia. This river is the 5th largest in South America and holds important environmental, social and cultural assets. It supports a large range of habitats, from paramos to dry tropics, which are home to over 250 species of mammals, 800 species of birds, 400 species of amphibians and more than 200 species of fish [13]. The basin supports water provision, food security and other services to more than 70% of the Colombian population [14]. It is also the heart of the national energy system with 60% of current national hydropower capacity of the country [15]. Hydropower is the main source of electricity of the country representing around 70% of the national installed capacity [16]. Most projected hydropower expansion will occur within this macro-basin [17]. Due to the social, economic and environmental values of the Magdalena river, the effective management of the basin is a national development priority. Therefore, the avoidance and minimization of impacts from hydroelectric development is key for the sustainability of the basin. SIMA-Magdalena instance provides an integrated vision of sectorial development in the macro-basin with emphasis on hydroelectric infrastructure.

Hydroelectric development, as well as agriculture sectorial development and wetland management actions, mainly related with food risk management, are incorporated in SIMA-Magdalena as possible alternatives for the user to model interventions in the basin management. The impacts derived from the alternatives to be analyzed are modeled in tools arranged in the two tiers described in section 2.2. The base data used by the models includes spatial information of environmental and social valuable areas, climate scenarios and long term sectorial plans. Underlying datasets are mainly based on official information but also includes non-official datasets produced by academic and research institutions that complies with certain quality standards that are communicated to users.

For the SIMA-Magdalena instance, tier 1 tools include models for analysis of river fragmentation, downstream impacts and footprint impact. Outputs modeled by SIMA-Magdalena fragmentation tools can be combined with related tools like bio-models (e.g. spawn grounds modeling for migratory fishes) to deliver meaningful information for integrated analyses accruing environmental, social and economic impacts. Regarding downstream impacts, tier 1 tools estimate DOR_w and sediment regime alterations that can also be related with effects on freshwater fauna. The third group of tier 1 models capture direct effects by flooded area. The variables to be measured cover a wide range of environmental, social and economic values and can be easily extended by disposing additional geographic information of interest. Footprint models can appraise impacts on natural protected areas, identified areas of high biodiversity, priority ecosystems, areas of high potential for economic activities, indigenous and community protected areas. It is also possible to incorporate a carbon emission estimation due to flooded area.

On the other hand, tier 2 analysis in SIMA-Magdalena rely on a WEAP model specifically developed for the macro-basin. Tier 2 is able to execute deeper analysis with higher detail since it performs simulations with all capabilities of WEAP [11] with a calibrated and validated model of the Magdalena macro-basin.

SIMA-Magdalena has mainly been used to evaluate possible futures represented as alternatives of hydropower development. Figure 5 shows the effect of dams, in operation and under construction, in the Magdalena basin on four key variables: River fragmentation, DOR_W, sediment regime alteration and richness of migratory and commercial fishes. From this baseline, possible alternatives for future developments have been assessed following a collaborative approach to gather system-scale visions of relevant decision makers. In this way, the alternatives to be assessed in a prospective case in SIMA-Magdalena future mode are built in collaboration with regional and national stakeholders.

With this context, The Nature Conservancy (TNC), Fundación CREACUA and the National Authority for Environmental Licensing (ANLA) developed a two-workshop series called *Baseline and prospective evaluation of socio-environmental cumulative impacts of hydropower projects* with the participation of the main stakeholders of the Magdalena Basin, the Ministry of Environment and Sustainable Development (MADS), Ministry of Mining and Energy (MINMINAS), the National Energy Planning Unit (UPME), and representatives of mayor energy companies. The main objective of the workshops was to create—at a pilot level—prospective hydroelectric expansion scenarios, and compare the cumulative system-level benefits and impacts in the medium and long term. Given the current institutional design of energy expansion, which relies on the initiative of developers, the workshop was focused on basin-wide environmental and social considerations that could inform project siting without specific project identification. In Table 1, different basin-level policy scenarios – or narratives - that resulted from the discussion sessions between the actors are presented.

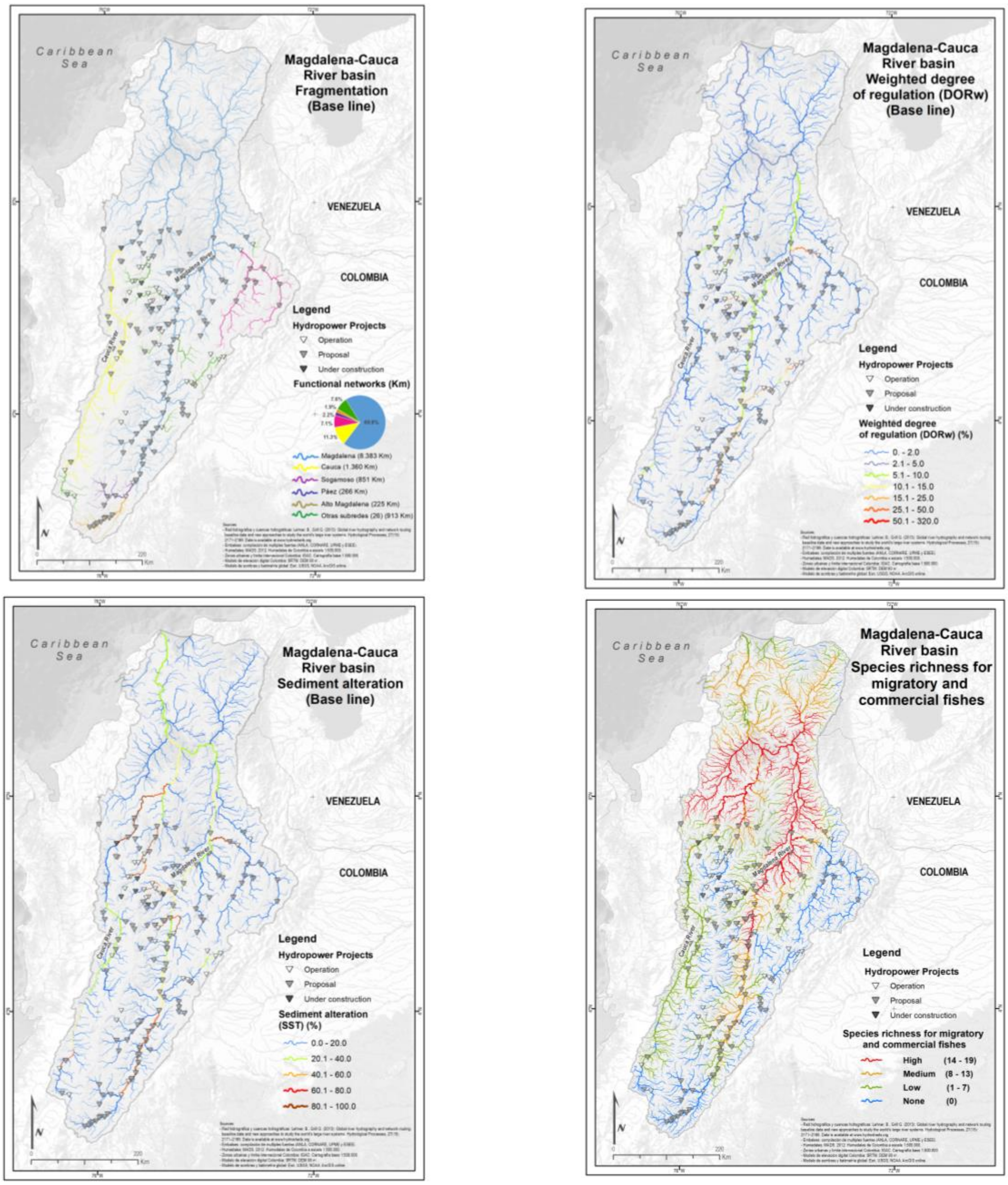

Figure 5. Base line in the Magdalena macro-basin as a result of hydropower development in key variables.

Table 1. Strategic policy guidelines proposed by stakeholders for cumulative impact analysis scenarios

Policy Name	Description
Narrative A	Develop identified projects in the Antioquia region.
Narrative B	Define the main functional network, currently the Magdalena river and is main free tributaries as rivers free of hydroelectric development.
Narrative C	Same as Narrative B, plus avoid projects located in the mainstem of remaining connected important river networks
Narrative D	Only allow projects with estimated affected population lower than 300 inhabitants
Narrative E	Same as Narrative D, plus only allow projects with affected productive areas lower than 300 ha

All narratives were analyzed respect to the range of potential basin-level energy benefits and impacts, as shown in Figure 6. These graphs show how some scenarios are much more effective than others at reducing multiple social or environmental impacts while achieving energy expansion goals. Other policy proposals reduce local impacts and meet capacity goals, but are still quite detrimental at the system level. Some proposals neither meet capacity goals, nor avoid basin-level impacts. This analysis demonstrated that policy guidelines based on a few simple rules can help create a landscape that is favorable to current developers given the current institutional design, while maintaining basin-level conservation values and avoiding impacts or conflicts on areas of social or economic importance. Positive impacts are measured in Megawatts of installed capacity, while negative impacts are quantified in indexes and are represented in the vertical axis. Figure to the left shows impacts on non-regulated free river length and to the right, the level of impacts on social, cultural and economic values were normalized in a multicriteria index. In these graphics, each dot represents a possible future modeled as a combination of new hydroelectric projects starting at a common baseline. In the presented cases, the futures were modeled randomly, only constrained to the defined narrative rules.

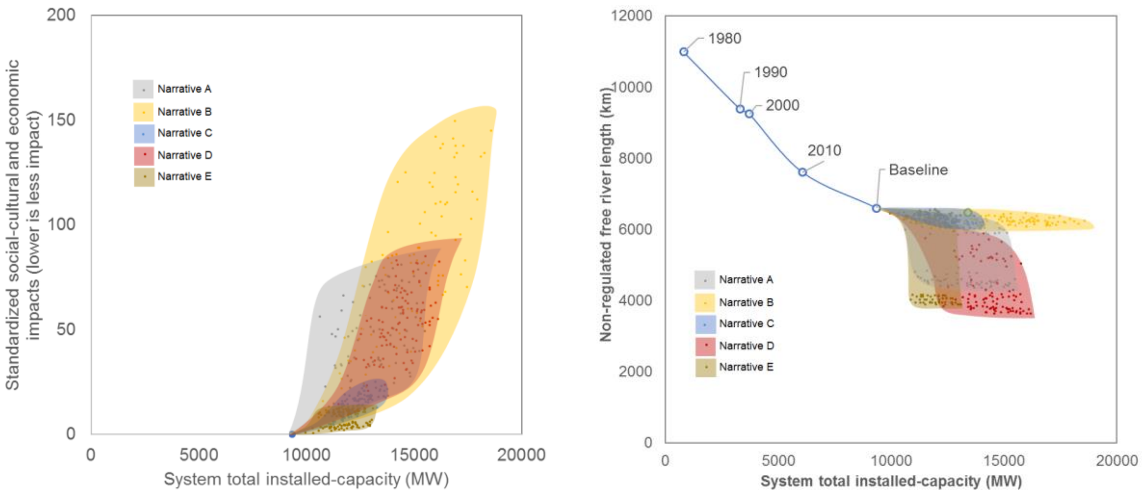

Figure 6. Historical trajectory and domain of impacts and benefits of different strategic policy guidelines. Left. Non-regulated free river length and Right. Standardized index of added social-cultural and economic impact.

The color envelopes represent the potential range of impacts and benefits of each narrative. The directional trend and the width of the envelop are pointers of how effective a development rule is as for steering possible futures in relation to the measured negative impact. The boundaries of the envelop can help to identify the limits of impacts and the levels of benefits that a high-level policy might determine.

Results can illustrate trade-offs in impacts from the selection of a given narrative. This means that a narrative might be effective for regulating negative effects in terms of a variable while being less useful to preventing impacts in other variables. For instance, Narrative B leads to a flat and long shaped group of possible futures in terms of impacts for non-regulated free rivers. This is highly desirable, as it implies that Narrative B can lead to large installed capacity development with no significant further impacts in non-regulated river length variable. However, the same Narrative B fails to effectively prevent social-cultural and economic impacts as its alternatives entail a huge vertical range for the standardized index to the right.

4 CONCLUSIONS

The Support System for Decision Making at Macro-Basin Scale (SIMA) and the instance for the Magdalena macro-basin in Colombia (SIMA-Magdalena) can be an efficient DSS to be appropriated within national private and public decision makers. An open environment determined the set-up for building collaborative vision for its effective use among stakeholders. Similarly, identification of key technical partners in academia and research institutions has enrichened its continuous development. Currently the system counts with a comprehensive set of tools with different levels of complexity that respond to pragmatic needs of IWRM in the Magdalena macro-basin. Moreover, the selection of hydroelectric sector for the construction of technical and strategic capabilities boosted the development and mainstreaming of SIMA given the relative importance and addressability of basin scale cumulative impacts for public and private stakeholders within the sector.

The success of the prospective analysis exercises developed up to now with stakeholder largely relies in the rigorous selection of the parameters to run prospective scenarios in a joint work. It is key for the use of SIMA to include detailed information of relevant territory values at different scales and to involve relevant stakeholder's vision in narratives and variables for an efficient and meaningful appraisal and consequent minimization of impacts from infrastructure development.

SIMA has been shown as a useful DSS to promote dialogue among stakeholders with an integrated, transparent and coherent vision at macro-basin scale. In the particular case of the hydropower sector, the coordination of independent stakeholders to minimize impacts can be possible using the proposed DSS as it allows to the users to analyze and share their alternatives. It is also a scalable system to other geographies with the opportunity to be develop in a free, community-based environment.

5 ACKNOWLEDGMENTS

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