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DECISION MAKING UNDER FUTURE CLIMATE UNCERTAINTY: ANALYSIS OF THE HYDROPOWER SECTOR IN THE MAGDALENA RIVER BASIN, COLOMBIA

TOMA DE DECISIONES BAJO INCERTIDUMBRE DE UN CLIMA FUTURO: ANÁLISIS DEL SECTOR HIDROENERGÉTICO EN LA CUENCA DEL RÍO MAGDALENA, COLOMBIA

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Abstract:

Engineers and decision makers face significant uncertainties in water resources management and planning as a result of climate change. While the availability of climate data is increasing, guidance for interpreting these data and communicating the uncertainty for decision making is lacking. This case study aims to address this need using a different planning approach, applying a bottom-up perspective instead of the traditional top-down one. The study demonstrates the use of climate data in decision making by applying the Collaborative Risk Informed Decision Analysis (CRIDA) method to the hydropower sector in the Magdalena River Basin of Colombia. CRIDA focuses on tailoring a traditional planning process to the problem at hand to avoid over- or under-investing in both the planning process and the final plan. Through a process referred to as the Level of Concern Analysis, the analyst assessed the climate risk and uncertainty involved in the problem at hand. CRIDA then provides guidance corresponding to this assessment.

While CRIDA is a starting point to bridge the gap between climate science and decision making, the Level of Concern Analysis contains a high level of subjectivity and examples are needed. This case study provides a detailed example of the Level of Concern analysis applied to the Magdalena River Basin hydropower system. The sensitivity of the sector to climate change versus other natural drivers, including climate variability and sedimentation, is evaluated, with the goal of determining whether or not climate change is indeed the main threat to the system. After determining that climate change is indeed the main threat, planning options are discussed such as building robustness or flexibility into the system in response to the assessed climate risk. As a result of this work, engineers will have an example application of the CRIDA method and how to communicate climate risks and their implications to decision makers.

Keywords: Decision making, collaborative risk informed decision making, level of concern analysis LOC, vulnerability assessment.

Resumen:

Ingenieros y tomadores de decisiones enfrentan incertidumbres significativas en el manejo y planeación de los recursos hídricos como resultado del cambio climático. Mientras que la disponibilidad de datos sobre el cambio climático incrementa, hacen falta guías para interpretarlos y comunicar su incertidumbre para toma de decisiones. Este estudio de caso pretende abordar esta necesidad desde una perspectiva ascendente, en vez de la tradicional descendente. El estudio demuestra el uso de datos climáticos en toma de decisiones mediante la aplicación de la metodología para toma de Decisiones Colaborativa e Informada del Riesgo (CRIDA por sus siglas en inglés) al sector hidroenergético en la cuenca del río Magdalena en Colombia. CRIDA se enfoca en personalizar el proceso de planeación tradicional del problema a mano para evitar sobre o subestimar invertir en el proceso de planeación y el plan final. A través del proceso denominado Análisis del Nivel de Preocupación, el analista evalúa el riesgo climático y la incertidumbre que implica el problema. CRIDA provee entonces la guía correspondiente a esta evaluación.

Mientras CRIDA es un punto de inicio para unir la brecha entre ciencias climáticas y la toma decisiones, el Análisis del Nivel de Preocupación contiene un alto nivel de subjetividad y se requiere de ejemplos. Este estudio de caso provee un ejemplo detallado del Análisis del Nivel de Preocupación aplicado al sistema hidroenergético de la cuenca del río Magdalena. La sensibilidad del sistema es evaluada frente al cambio climático en comparación con otros factores naturales, incluyendo variabilidad climática y sedimentación con el fin de determinar si el cambio climático es en efecto la mayor amenaza para el sistema. Luego de determinar que el cambio climático es de hecho la mayor amenaza, las opciones para planeación son discutidas como construir robustez o flexibilidad como respuesta al riesgo climático evaluado. Como resultado de este trabajo, los ingenieros tienen un ejemplo de aplicación del método CRIDA y cómo comunicar riesgos y sus implicaciones a los tomadores de decisiones.

Palabra clave: Toma de decisiones, toma de decisiones colaborativa e informada del riesgo, Nivel de Análisis de Preocupación LOC, evaluación de vulnerabilidad.

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1. INTRODUCTION:

Climate Changes raise several key challenges regarding social and sustainable economic development. However, decision-makers face some issues when understanding and giving an effective response to them. In fact, those changes imply non-stationary conditions on the climatic system, greatly affecting the decision-making processes by either the private or public sectors and bringing in to the equation an increase in uncertainty for GCMs projections and new climate scenarios. It is therefore necessary to understand better how to structure better the decisions made. Facing those uncertainties is not easy, especially because we have not been dealing with something even close before. It is a very complex problem with consequences within different time horizons, characterised by uncertainty and risks. However, that is the main goal: take the risk for a climate resilient strategy. Moreover, gathering science, management and policies is a must and it implies understanding first their correlation and thus, building methodologies in which every role-player could contribute from their responsibilities and perspective (UNESCO, 2016).

Nevertheless, in water management decision making processes, the dominant perspective have been done based on analysis like the cost-benefit ratio and multi-criteria decision analysis among others. This perspective has a limitation and is the bounded rationality that drives the decision-maker to use a hyerarchical division of the problem in order to solve them one by one (HFIDTC, 2007). Decision-making in water management is needed to involve risks and uncertainties to the whole context in order to have a clearer idea of the system and the implications of the decision made. This guarantees a better understanding of the system, the acceptation of the ranges within the uncertainty do the variables be and the risk that implies a future scenario that will be different from the past ones (Middelkoop, H et al., 2004). Therefore, if water managers keep applying a practical guidance for all the planning stages challenges, including a non-stationary climate condition, must not underestimate uncertainties that are intrinsic to them. In that sense, if a methodology is available involving those components, especially uncertainty, should also allow to revise the planning steps and in that case, reformulate actions if necessary in order to fend off an undesirable performance either current or expected (USACE; Deltares, 2016)

When basing on a stationary climate setup as a decision-making method, uncertainties are avoided and this assumption seems to oversimplify the problem. It has to be pointed out that most of the management ideas around a better hydrological knowledge are recent (less than 20 years) and that concepts such as trends, uncertainties, resource pressure, etc., have been developed based on the current climate comparison with the past one and the ongoing climate changes projected for the future (USACE; Deltares, 2016). That methodology is equivalent to the traditional planning method, also known as top-down planning approach. The bottom-up planning approach on the other hand is a novel method that, although starts its analysis in the same fashion the top-down approach does:1) identifies vulnerabilities, 2) accepts natural climate variability, 3) looks for key impacts and possible system stressors of concern and 4) identifies stakeholders participation at various stages, it does not seek for a deterministic assessment of uncertainties; rather, this approach gives an analytical framework useful for decision-makers to identify the impact of the uncertainties, which are important from their perspective and how the system is sensible to them, considering the whole range within climate information is (Brown, 2011), which is the one this article is focused on to apply.

Thereupon, exists a framework able to deal with the current necessities decision-makers have and provide an approach different to the traditional paradigm denominated: Collaborative Risk Informed Decision Analysis – CRIDA. CRIDA has been developed to answer the decision-making necessities: provide the best possible insight being aware of the uncertainties, as well as look for an effective and risk-informed decision for water resources management (Mendoza et al. 2018). The method depends on a vulnerability assessment to the multiple dynamic factors that can be game changers when making decision such as changes in the hydrological cycle, population growth, changes in land-use and land-cover, etc. As well, CRIDA provides an analysis of the risks and inform the decision-makers about them, meaning that CRIDA acknowledges the implications of the decision-making process when the management is based on risk-based metrics under non-stationary conditions.

CRIDA provides the analyst with guidance to assess system vulnerability to drivers such as climate change and climate variability, and use this assessment to tailor the remaining steps in the water resources planning process as needed. For example, a system that is highly sensitive to climate, and has already observed changes in the local climate, should consider designing for a projected future climate rather than the observed climate, as would be advised in a standard water resources planning process. In the CRIDA method, this is referred to as a strategy direction that builds robustness into the system. On the other hand, a system that is moderately vulnerable to climate, but lacks an understanding of observed climate trends, might prefer to design adaptation pathways which would allow decision makers to implement measures over time while observing changes in the key system drivers, thus avoiding over- or under-investing. The CRIDA method refers to this approach as an adaptive strategy direction. With each strategy direction comes guidance for economic analyses as well as institutional and financial requirements. These three guidance elements are illustrated through the CRIDA decision matrices.

While the CRIDA method is a starting point to improve guidance for engineers and decision makers in water resources planning, available case studies demonstrating the CRIDA concepts are limited (Gilroy and Jeuken, 2018). The goal of this work is to demonstrate for readers the link between a climate vulnerability assessment and the CRIDA decision matrices and, therefore, decision making under uncertainty for water resources planning. This case study builds on the previously conducted vulnerability assessment for the hydropower sector in the Magdalena River Basin of Colombia (Gomez-Dueñas et al., 2019). Through examples, such as this case study, engineers and decision makers will become more skilled at incorporating uncertainties, such as climate change, into the decision making process for water resources planning through the CRIDA method.

2. METHODOLOGY:

The CRIDA method follows a standard planning cycle and inserts guidance matrices at three decision points throughout the process, as illustrated in Figure 1. As previously discussed, the Decision Points provide the analyst with guidance regarding strategy direction (i.e., robust vs flexible), economic analyses, as well as institutional and financial requirements for implementation. The guidance aims to tailor the planning process based on the system vulnerability to climate uncertainty. It also provides a mechanism for communicating the implications of uncertainty to decision makers. The CRIDA *Decision Matrices* are shown in Figure 2.

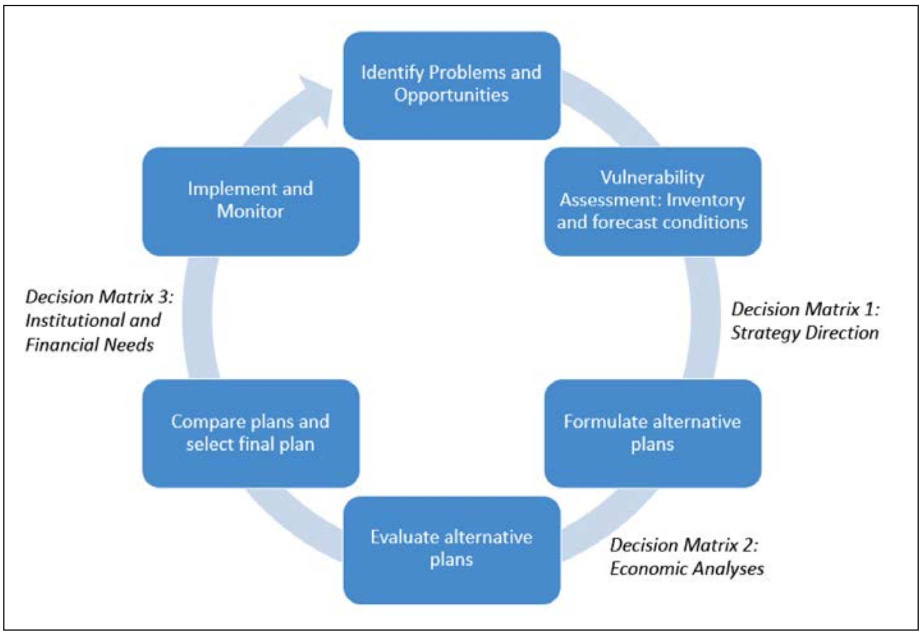


Figure 1. Traditional Water Resources Planning Cycle with CRIDA Decision Matrices

In addition to the *Decision Matrices*, the CRIDA vulnerability assessment deviates from traditional planning by following a *Stress Test* approach. Through a *Stress Test,* system performance is tested using driver values that extend beyond those previously observed or projected. Given the great amount of uncertainty in available data, this approach allows the analyst to better understand system vulnerability to drivers such as precipitation before limiting the range of values tested to the data available. The LOC Analysis uses the *Stress Test* results to determine (1) the *plausibility* of entering a vulnerable state or passing a defined performance threshold during the planning horizon; (2) the *consequences* of entering a vulnerable state; and (3) the *analytical uncertainty* in the data used to make these assessments. The *Level of Concern (LOC) Analysis* provides the link between the *Stress Test* and the *Decision Matrices*.

The *Consequences* of unacceptable system performance can often be defined based on the problem or opportunity statement. In general, consequences regarding a water supply project are less severe than flood risk management problems, as flooding occurs rapidly with little response time. Likewise, urban flood risk deals with life loss while agricultural flood risk may be more manageable through measures such as insurance. For hydropower, if an alternative energy source is not available, the consequences of system failure would be considered greater than if back-up plans are readily available. The analyst should consider these elements when assigning a low, medium, or high level of consequences to the problem at hand. If multiple projects are being assessed simultaneously, it is sometimes beneficial to report these assessments in relative terms across projects.

Energy output ratio

In regards to *plausibility*, the analyst must assess the likelihood that the system will perform unacceptably during the defined planning horizon based on all available data and information. Often times, the system is already failing, hence the call for a project. In this case, the analyst is evaluating how sensitive the system performance is to each driver and, therefore, how important uncertainty is in the decision making process. Can we plan based on observed data and feel confident in the system performance for the planning horizon? Or should we consider flexible plans, such as adaptation pathways, or more robust plans which are designed for a future climate?

The analyst can assess plausibility by answering the following questions: (1) Does the stress test suggest that a climate change metric is the most sensitive driver? If no, then drivers with less uncertainty are of greater concern and plausibility is low. Traditional planning approaches based on observed data would be appropriate. If yes, then: (2) Do observed data suggest a shift in towards a more vulnerable climate? And (3) Do projected data suggest a shift towards a more vulnerable climate? The more the data suggests a shift towards a vulnerable climate, the greater the plausibility score. The combination of *Consequences* and *Plausibility* provides the analyst with a low, medium, or high ranking of *Future Risk*, which is the y-axis of the Decision matrices.

The purpose of assessing the *Analytical Uncertainty* is to determine the reliability of the data upon which decisions are being made. For example, observed data has lower uncertainty than projected data. Projected temperature data has lower uncertainty than projected precipitation data. And projected annual means have lower uncertainty then projected extreme events. *Analytical Uncertainty* can also be assessed based on the agreement between all available data sources. If the available general circulation models are not an agreement, then there is a high analytical uncertainty regarding future projections. The low, medium, or high assessment of *Analytical Uncertainty* places the problem along the x-axis of the decision matrices, with higher A*nalytical Uncertainty* leaning towards more adaptive strategies.

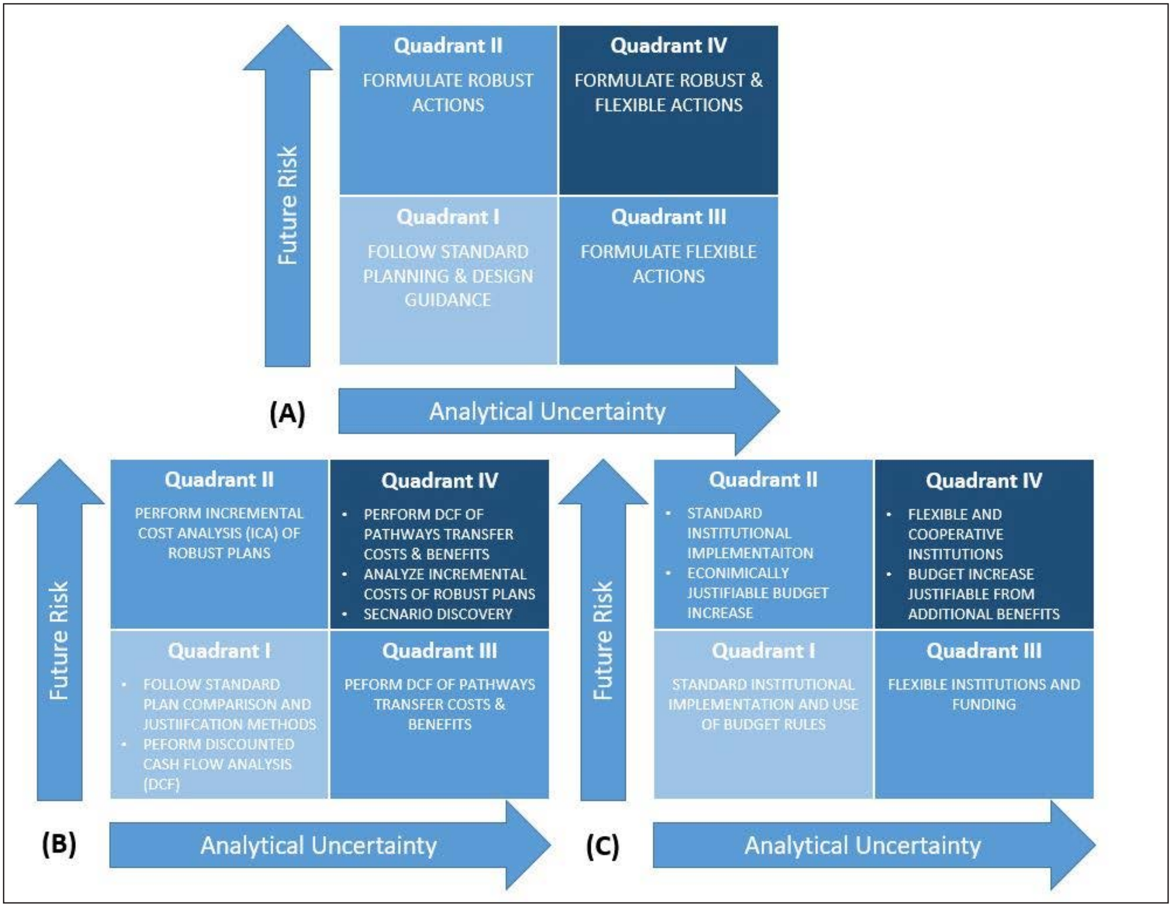


Figure 2. CRIDA Decision Matrices: (A) Strategic Direction (B) Economic Analyses (C) Institutional and Financial Requirements

As a result of the level of concern analysis, the engineer or analyst is then able to place the problem at hand into one of four quadrants in the CRIDA decision matrices, shown in Figure 2. These decision matrices guide the analyst or engineer through the development of a strategic direction best fit to the problem at hand as well as the necessary economic analysis method and institutional as well as financial requirements to implement the developed plan (Mendoza et al., 2018). As previously mentioned, this paper focuses on the Level of Concern Analysis based on a previously conducted vulnerability assessment for the hydropower sector in the Magdalena River Basin in Colombia. As the Level of Concern Analysis contains a significant amount of subjectivity, examples such as this case study will be critical to aid analysts and engineers who are required to consider uncertainties, such as climate change, in the water resources planning process.

3. RESULTS AND DISCUSSION

Hydropower is the main energy source in Colombia and has strategically positioned the country as a referent in terms of energy production in Latin America (Foro Nacional Internacional, 2012). The country takes advantage of its geographical position, topographical conditions and water availability to base its production applying a clean energy matrix and that bases the production on the usage of water for that purpose, leaving oil and coal fields as a system backup rather than being the primary energy source. Additionally, there are plans to upgrade the current infrastructure with some works in order to increase income discharges to the reservoirs (ACOLGEN, 2012) due to unexpected lower performances (Mariño, 2007). Consequently, Colombia has been looking to increase the investments in the hydropower sector and accomplish the plans proposed. Most of the new contemplated hydropower infrastructure will be located over the Magdalena Basin as shown in Figure 3. The Magdalena River's length is 1,612 Km, and the whole drainage area is approximately equal to one fourth of the total country area, hence the main fluvial branch of Colombia (Restrepo, 2000).

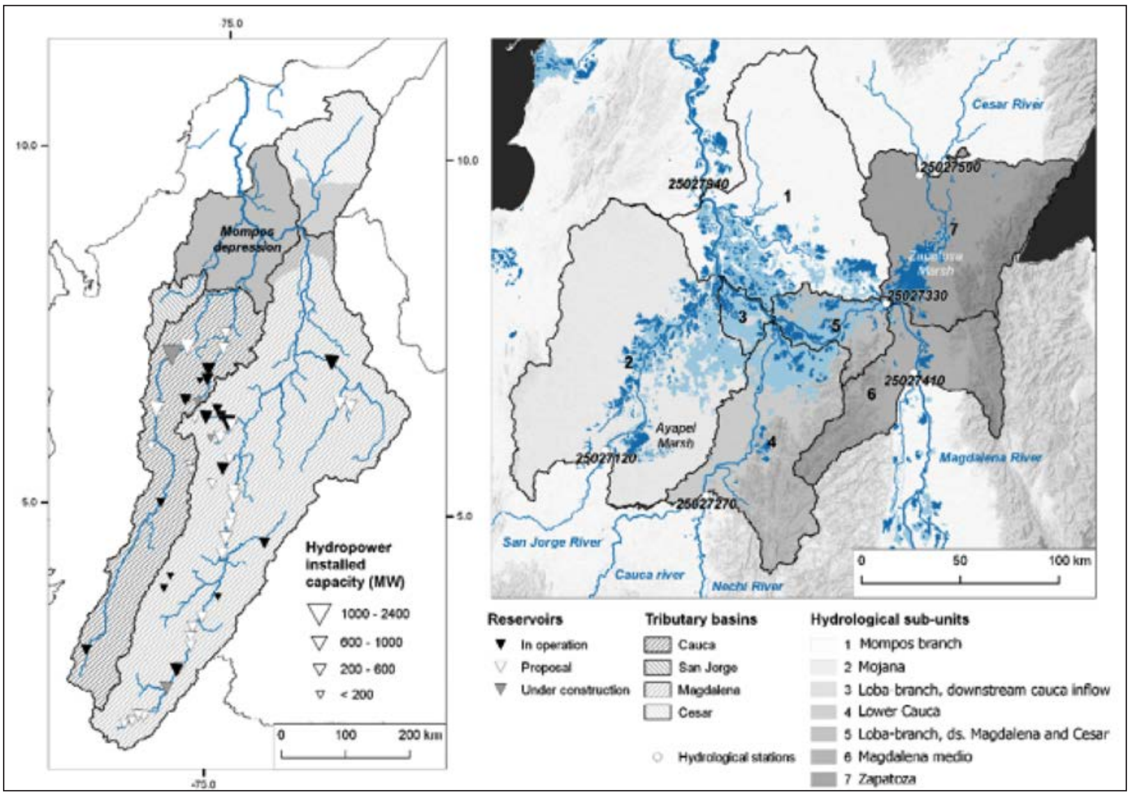


Figure 3. Hydropower infrastructure: current and projected over the Magdalena river basin (Angarita et al., 2015)

The tropical South American region is influenced by the ENSO extreme phases, affecting primarily the interannual hydro-climatological conditions and several studies support that statement (Restrepo, 2000). However, since many studies have been carried out focusing on the interannual variability and the ENSO effects on rainfall and river discharges, the Magdalena have received scarce attention and still the impacts on the basin remain uncertain, adding to the well-known climate change effects. Additionally, the Magdalena basin is naturally susceptible to erosion (Restrepo et al., 2006), being orography the major controller. The sediment yield varies parallel to the rainfall patterns and thus for a non-stationary climate, a non-stationary sediment transport. Furthermore, as the reservoirs are located at the upper-basin in the mountainous area, they act like a sediment trap and their influence is considerable for the sediment balance along in the reaches; however, as sediment is retained in the reservoirs, their storage diminishes and hence the energy production.

It is useful to know when the system breaks based on the external drivers mentioned above: climate change, climate variability and reservoir sediment retention. By varying the parameters, a vulnerability assessment is carried out by comparing results and determining to which driver the system is more sensitive. Stress test results indicating that the main system driver is not climate change will greatly simplify the planning process and decision making. Otherwise, the level of concern decision matrices can be used to guide the analyst through the planning process.

A. Stress Test Results

As previously mentioned, an in-depth explanation of the Stress Test methodology will be provided in (Gomez-Dueñas et al. 2019). The goal of this research is to demonstrate interpreting the results for decision making. The results are shown in Figure 4 and Figure 5 for climate and sediment drivers, respectively. Figure 4 shows the climate response surface, with the X-axis representing climate change and the Y-axis representing climate variability. Climate change was simulated by incrementally reducing the annual mean precipitation of the reference record (1970-2013) to represent a drier climate. Climate variability was simulated by bootstrapping the reference record to explore the system sensitivity to observed precipitation events with different frequencies. For example, if the most severe drought occurred multiple times in the period of record, how would the system performance change? 10 000 samples were bootstrapped and percentiles were calculated based on the severity of the droughts in each bootstrapped sample. The colour bar represents the energy ratio of the scenario modelled energy output over the reference case, with white representing almost no change from the reference scenario and dark red representing up to a 30% reduction in energy production.

Selection of any point within the response surface represents the energy output ratio resulting from the corresponding climate change reduction on the X-axis and climate variability percentile on the Y-axis. A comparison of the colour grade change in the horizontal direction vs. the vertical direction indicates that the system is significantly more sensitive to the range in climate change tested than to the climate variability scenarios. This indicates that climate change is the more important of the two drivers and should not be ignored in the planning and decision making process. However, this conclusion depends on entirely on the plausibility of the ranges selected for the climate change variable. This will be evaluated in the Level of Concern Analysis.

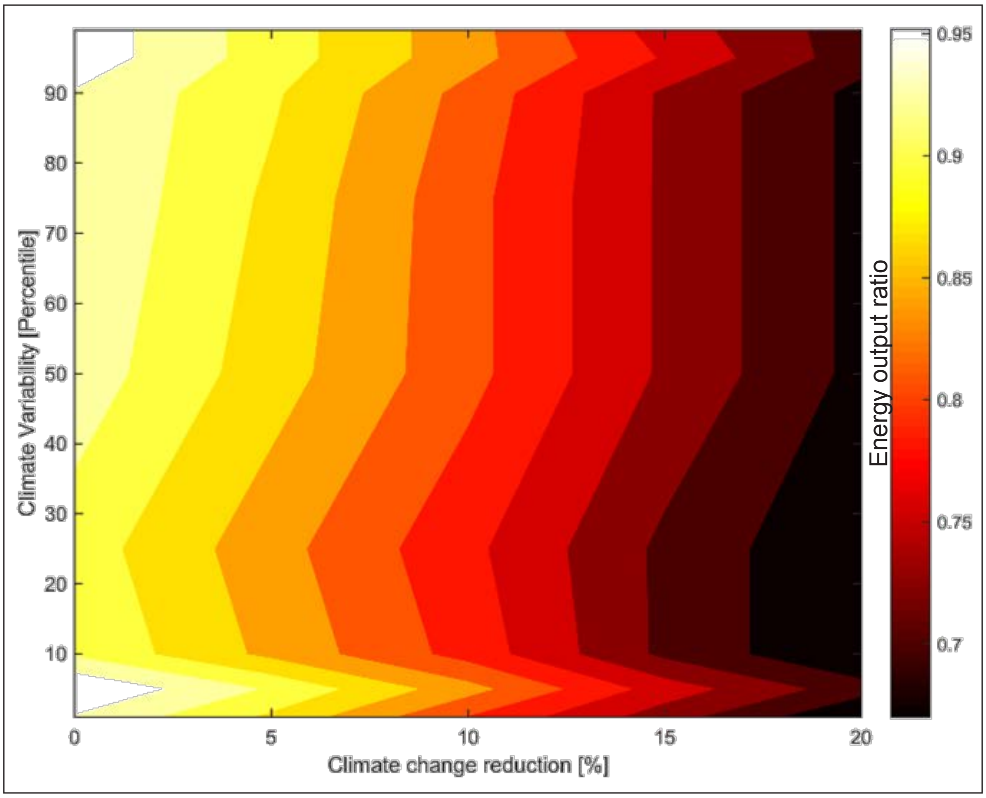


Figure 4. Climate Stress Test. Average – Mean annual method

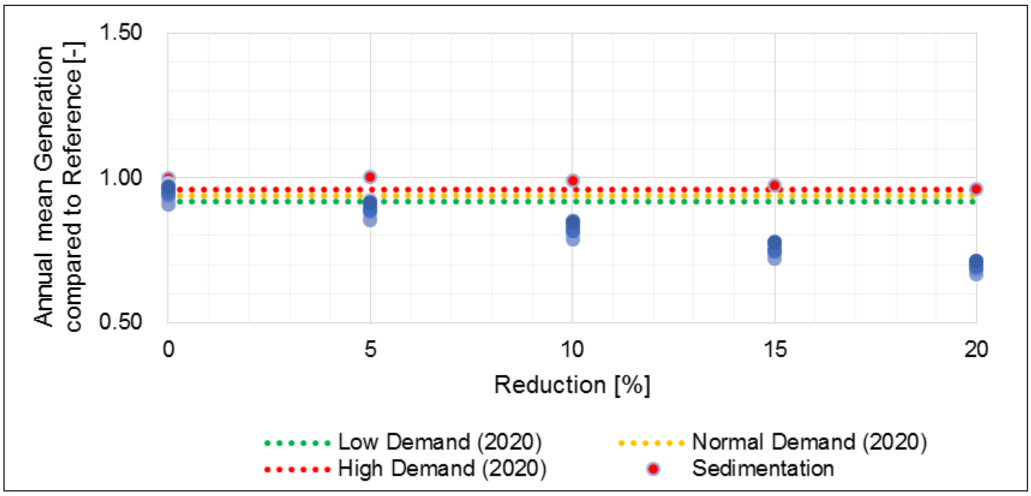


Figure 5. Stress test among the natural drivers. Average – Mean annual method

The next step in the stress test phase was to compare climate change (the main driver of the two climate variables) to sedimentation, illustrated in Figure 5. The x-axis refers to the reduction in the driver ranging from 0 to 20%. For the red dot series, this reduction refers to the reservoir storage due to sedimentation. For the blue dot series, this reduction refers to precipitation to illustrate the climate change and their climate variability percentile scenarios from the first stress test. In order to see the results compared to a threshold, the low, normal, and high energy demand scenarios for 2020 are plotted. Note that later year energy demand projections have energy ratio-demands significantly greater than the values contained in Figure 5, meaning that the system is already failing to meet demand projected for 2020.

The sedimentation stress test indicates that climate drivers have a lower energy ratio than the sediment retention drivers. In the worst scenario possible for sediment retention, the values are below just 6% compared to the Reference case, while climate drivers for the same reduction percentage (20%), show a difference by 31% to 37%, around 5 time less. For the other reduction percentages (0% to 15%, the performance is acceptable even for the highest demand scenario. Hence, based on the results and comparing different system vulnerabilities can be concluded that the main natural driver is the climate change over the sediment retention in the reservoirs. Again, this conclusion depends entirely on the plausibility of the climate change range analysed, which will be evaluated in the Level of Concern Analysis.

B. Plausibility Assessment

The goal of the Level of Concern Analysis is to evaluate the Future Risk and Analytical Uncertainty of the problem at hand in order to select one of the four quadrants in the Decision Matrices. The preliminary evaluation of the stress test indicates that climate change is the main variable driving system vulnerability. By evaluating the plausibility of the ranges evaluated, an assessment of future risk can be made. The followings are the analysis carried out for the natural drivers involved.

Climate variability is the one that controls intensity and frequency of the extreme events such as heavy rainfalls, overflows, flood-drought conditions, etc. that cause great social and economic impact to the country (IDEAM-UNAL, 2018). Its interannual variation is caused by El Niño Southern Oscillation – ENSO. During El Niño Events, there is a diminishment in precipitation in the Caribbean and mid-Andean and north-Pacific regions, whereas in the Orinoquian and Amazonican foothill regions, happens the opposite. Due to the nature of the business, hydropower's main input is water and during El Niño events, is when the most critical conditions occur. In Fig. 6 can be seen the most recent available studies for anomalies effects due to El Niño events. Along the Andean region, where the hydropower plants are located, it is expected to have a deficit in precipitation within 40 to 80%, showing that the infrastructure is susceptible to water shortages.

On the other hand, the most recent version of the Climate Atlas for Colombia (IDEAM, 2018) concludes that for precipitation, it is expected to decrease within 5 – 10% in the Caribbean and centre and northern Andean regions, where overlaps with some hydropower facilities for the period 2011-2070. For the southern Andean and Pacific regions, the expected increase will range between 5-15% for the same period. Additionally, after a warm-day analysis, these tend to increase all over the country, creating a drier context for hydropower plants to be performing on. The climate change projections were obtained using the new RCP scenarios (2.6, 4.5, 6.0 and 8.5) available for the CMIP5 project and for precipitation, a REA assemble was carried out for the four scenarios. In the Fig. 7 and 8, it can be seen the general precipitation trends for the 2011-2040 and 2040-2070 periods.

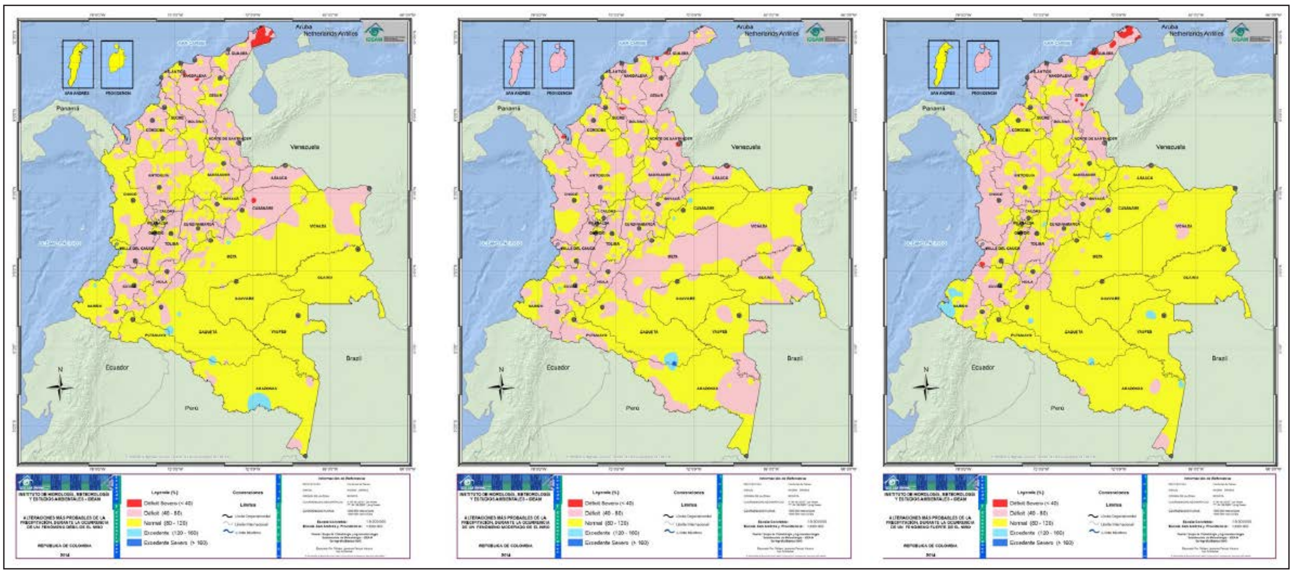


Figure 6. Precipitation anomalies distribution due to a weak (left), moderate (centre) and strong (right) El Niño event (Montealegre, 2014)

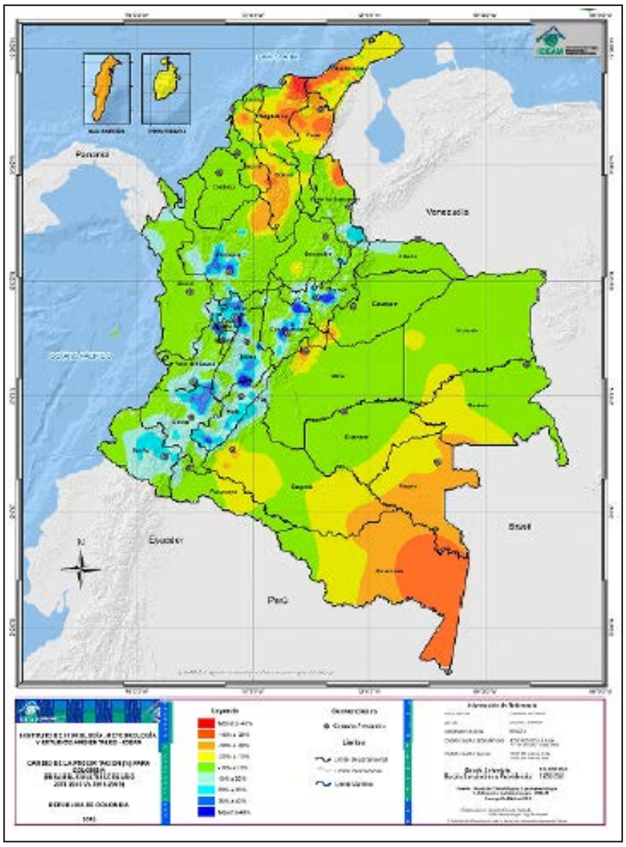


Figure 7. Precipitation change (%) for the period 2011-2040 (IDEAM, 2018)

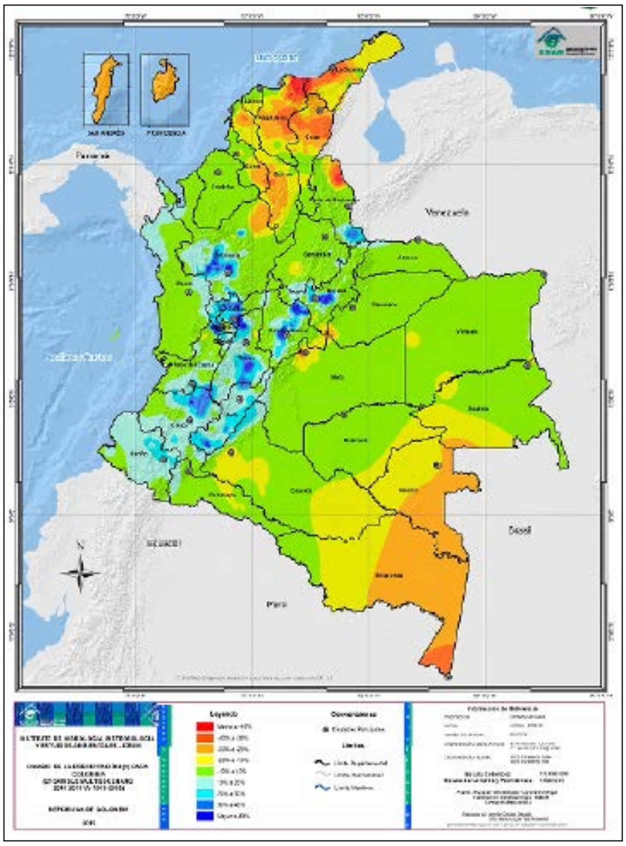


Figure 8. Precipitation change (%) for the period 2040-2070 (IDEAM, 2018)

On the other hand, GOTTA (2016) did a geomorphological characterization of the streams, as well as they computed the whole sediments balance over the Magdalena basin. For reservoir retention – Rx were compared the methodologies developed by Brune's empirical curve (1953) which is a very well-known method with almost 44 different records used for this study, Morris (1963) that proposed a relationship between the retention efficiency (TE) over the ratio between storage and income discharge(C/I) and Heineman (1981) who modified Morris' expression based on whether the reservoir drainage area is larger or smaller than 38.85 Km^2 (15 Mi^2) and therefore the Brune's curve has smaller or larger retention efficiencies respectively. Fig. 9 represents the computed Rx for the 1970-2013 time period.

Plausibility

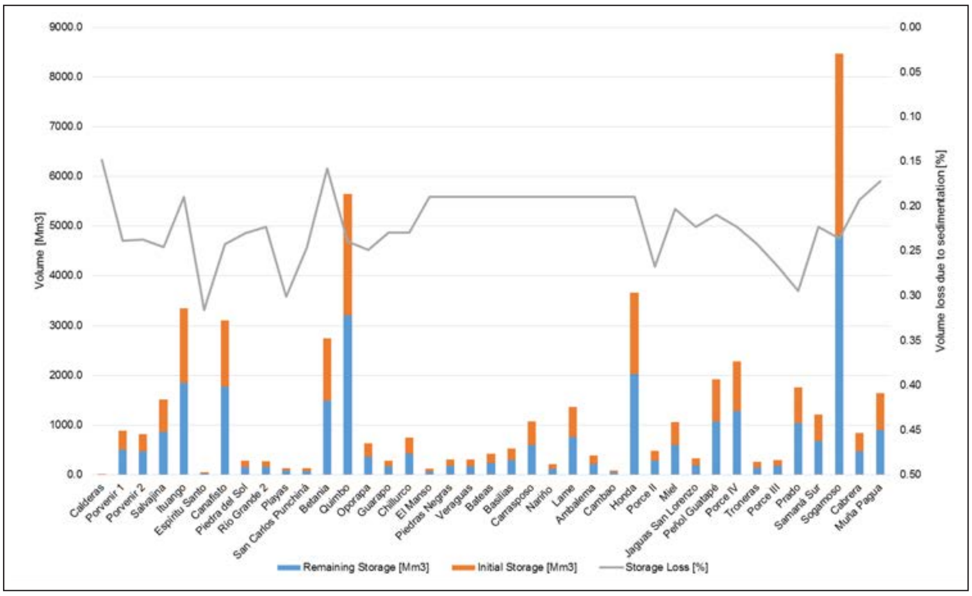
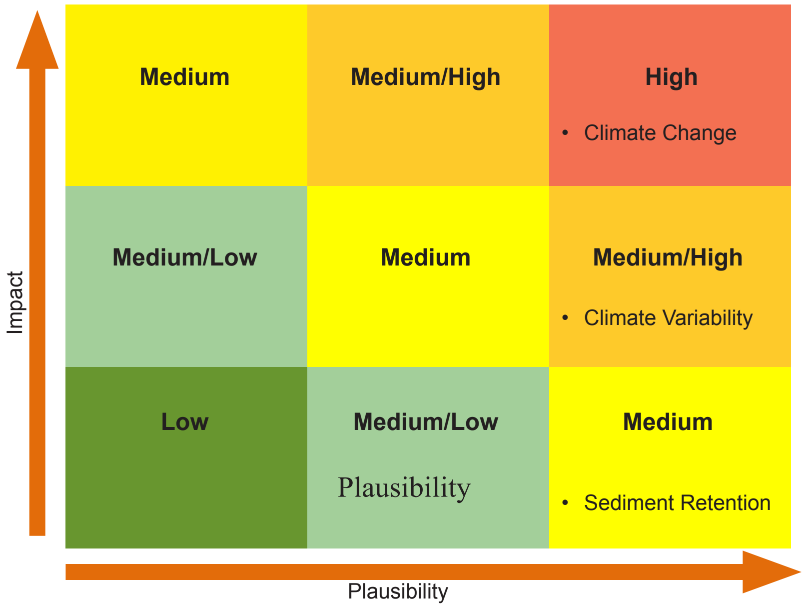


Figure 9. Sediment retention for each reservoir for the period 1970 – 2013. (Gómez-Dueñas et al, 2017)

Level of Concern Analysis

As CRIDA is a risk-based approach, the first step is, in a qualitative way, to put together the elements that involves the risk concept from a bottom-up vulnerability perspective. Thus, impacts, plausibility and uncertainty are assessed in this step. Impacts assessment depends on the thresholds surpassing brought off in the performance metrics assessment. Plausibility are based on how likely the variables ranges are based on the available information (or the methodology used to get the system stress ranges. Uncertainty is based on the quality of the data used to make this assessment. Table 1 provides an overview of the level of concern analysis for each variable analysed.

Based on the summary provided in the Table 1, the next step is to plot each driver in the Level of Concern Risk matrix, shown in Figure 10. As the plausibility is high for all three natural drivers, all variables are plotted on the right of the figure. However, the impact varies significantly across the three drivers, as was discussed in the stress test results. As a result, climate change poses a high future risk, climate variability a medium/high future risk, and sediment retention a medium future risk.



Medium	**Medium/High**	**High** • Climate Change
Medium/Low	**Medium**	**Medium/High** • Climate Variability
Low	**Medium/Low** Plausibility	**Medium** • Sediment Retention

Figure 10. Level of Concern Risk matrix

Table 1. Level of concern matrix

Variable	Impact	Plausibility	Uncertainty
Sediment retention	Acceptable performance. Although the results show 6% less energy production than in the Reference case, it is not as representative as for the climate drivers. The energy generation will not depend on the sedimentation rates but in the climate conditions and reservoir network setup.	High. The sediment rates computed for the reservoirs within the basin range within 15% to 30% for the time period chosen for the modelling. That means that the reported rates (GOTTA, 2016) are greater than the scenarios modelled. Hence, it has to be run the model with greater values in order to stress the system beyond the reports.	Low. Based on bathymetries already carried out in the basin, the sediment retention rates have been calibrated.
Climate Variability	Mostly acceptable performance. The performance does not depend on a drier-wetter climate condition. For wetter climates the energy production is greater than for the Reference case	High. Bootstrapping carried out based on already seen climate.	Very Low. This climate has been already seen in the basin.
Climate Change	Unacceptable performance. Is the main climate driver, among the different rainfall reduction scenarios the system was being more unable to meet any current or projected demand	High. The GCMs for precipitation, it is expected to decrease within 5 – 10% in the Caribbean and centre and northern Andean regions, where overlaps with some hydropower facilities for the period 2011-2070. For the southern Andean and Pacific regions, the expected increase will range between 5-15% for the same period. The climate change projections were obtained using the new RCP scenarios (2.6, 4.5, 6.0 and 8.5) available for the CMIP5 project and for precipitation, a REA assemble was carried out for the four scenarios (IDEAM, 2018) Additionally what adds plausibility to this driver is the fact that when comparing the energy ratio between the percentiles for climate variability and the values obtained for climate change, the values from the mid/lower percentiles are the values for the immediate following climate change scenario in its higher percentiles. This means that not necessarily the impact may be seen only from a vertical or a horizontal perspective, but also what is a drier climate at a certain rainfall reduction scenario, can be a wetter climate in the following climate change scenario and still have the same performance.	High. The scenarios are likely to happen. The reference GCM information is for the RCP scenarios (2.6, 4.5, 6.0 and 8.5). However, it is difficult to determine whether a climate anomaly is due to climate variability or climate change.

The last stage of the Level of Concern Analysis is the Decision matrix. It complements the risk assessment by adding the analytical uncertainty element. The final quadrant selected for each driver will provide recommendations for future planning stages. Figure 11 shows the decision quadrants outcome for each driver analysed.

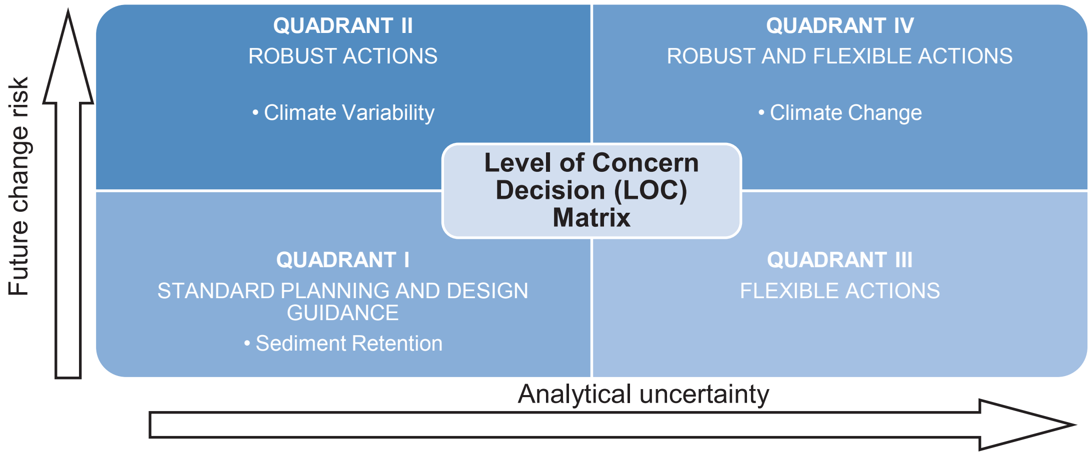


Figure 11. Level of Concern Decision Matrix

The results show a scattered behaviour for the natural drivers taken into account for this research. For the climate drivers the action must be to follow a robust decision making. This means that investments may be more costly due to the high risk they represent for the system performance.

Sediment retention represents a lower risk for the system than the climate drivers. There is a limited evidence that in the future either the risk will change from the values modelled. Compared to climate drivers, the effects this driver has on the system performance is low. In addition, the changes in storage are well understood, because observed data is available for the sediment driver from bathymetries since the reservoirs started to be built around the 70s, as well as suspended solid measurements over the river that indicate the ranges within the sediment balance is varying. Hence, the strategy direction for sediment retention is not required to be deviated from the standard planning approach and for future planning stages CRIDA is not the right approach to be applied.

In the case of the Climate Variability driver, the results indicate medium/high future risk conditions. However, the data used to for this assessment were observed, resulting in low uncertainty. Therefore, the strategy direction for Climate Variability is placed in Quadrant II, recommending slightly more robust solutions than would otherwise be designed. However, since traditional planning often already plans for uncertainty in the climate data, the decision maker could still consider a standard planning process where both certain and uncertain futures are involved at the same time and, therefore, the system risks can be handled.

The Decision Matrix quadrant differs significantly, however, for the Climate Change driver due to the high uncertainty and high impact this driver has on the system. For this reason, a combination of robust and flexible actions would be recommended. Flexible actions allow shifts from one decision to another at any stage through the planning horizon and still keep and be able to meet the objective function. Robust actions mean that decision making was made by analysing both observed and future climates to determine whether no regret options were available. Consequently, the strategy direction for Climate Change might be given for different scenarios and possible linkages between them, allowing the flexibility to follow a certain decision path until there is enough evidence either to confirm the decision correctness or to change for a more accepted one regardless.

4. CONCLUSIONS

A new approach to project planning was put into practice by determining a set of thresholds to enhance the hydropower generation in the study area. The method better incorporates inherent uncertainties, such as climate variability or change, into the decision-making process. Traditional approaches favor a “predict and act” method, meaning the analyst evaluates the performance of the system according to available observed data, or in some cases future projections if available or specified be existing policy. However, this limits the decision space to the available information which is known to contain uncertainties. As a result, the decision maker risks over- or under-designing the system under both current and future conditions.

After having applied the CRIDA method for this vulnerability assessment, there are some remarks that are necessary to call to. Is important to point out the role the analyst has when applying these concepts, due to will be the one assessing the multiple variables considered among the project. Because the aim is not to neglect climate information available so a relevancy analysis is carried out afterwards, the process depends on how experienced the analyst is, how much the analyst knows the system, its particularities and concern events that may lead to a better understanding of it. Once the problem is understood, opposite to the traditional planning framework, it is required from the analyst to formulate alternative plans and evaluate them, instead of formulating directly robust and flexible actions and then evaluate alternative plans. In conclusion, from the involvement degree of the analyst, as well as from his/her understanding of the problem and how to deal with the concerns in order to reach the best possible decision, depends the success of the methodology. However, CRIDA gives the tools that will guide him/her to approach better the project.

While the CRIDA method itself is a novel approach, few real-world applications exist. This study also provides greater depth to the Level of Concern Analysis than currently exists in the CRIDA guidance manual. In addition, the application to the Magdalena River Basin builds on the existing method by incorporating climate variability/change to hydropower production, as well as reservoir sediment retention. Next assessments will involve to carry out a temperature and rainfall records available analysis (43 years) at an inter-annual basis which is when the system gets more stressed and define the natural driver to which the system is more vulnerable combined with the natural parameter that makes more sensitive the system. In conclusion, it is necessary to keep elaborating on this research in order to integrate water management methods for decision-making to a study case that aims to be improved in the following years given the alarming expected infrastructure expansion.

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