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Collaborative Risk Informed Decision Analysis: A water security case study in the Philippines

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A R T I C L E I N F O

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A B S T R A C T

More frequent and intense hydrologic events under climate change are expected to enhance challenges for water security and flood risk management worldwide. Traditional planning approaches must be adapted to address climate change and develop solutions with an appropriate level of robustness and flexibility. The Collaborative Risk Informed Decision Analysis (CRIDA) method is a novel planning approach embodying a suite of complementary methods, including decision scaling and adaptation pathways, in a stakeholder driven process which guides decision makers through the planning and decision process, taking into account how the confidence in the available science, the consequences in the system, and the capacity of institutions should influence strategy selection. The purpose of this study is to apply the CRIDA approach to a water supply case study in Central Cebu, the Philippines in order to evaluate the added benefits of the method for planning and design under climate change uncertainty. This work will equip practitioners and decision makers with an example of a structured process for decision making under climate uncertainty that can be scaled as needed to the problem at hand.

Practical Implications

Worldwide, water resources and flood risk managers; asset and infrastructure managers; private companies; and national, provincial, and local government planning authorities all face similar challenges when developing plans and investments to revitalize or expand water infrastructure and networks to meet future needs or adapt to increasing uncertain future risks like those of climate change. Climate services aim to cover the gap between climate science, climate data providers, and decision making to support this challenge. However, available climate services often focus on improving the climate data produced by climate modelling centres while ignoring how the climate data should be used to support decision making. The method of Collaborative Risk Informed Decision Analysis (CRIDA) presented in this article falls in the latter category of decision services. CRIDA reaches out to practitioners that want to incorporate long term future uncertainty, such as climate change, in water resources planning.

The CRIDA guidance has been developed by practitioners and applied scientists in the United States and the Netherlands, combining experiences and advances in water resources planning under climate change in both countries. It integrates the latest scientific tools for climate stress testing, decision scaling (Brown and Wilby, 2012), with adaptation strategy development, adaptation pathways (Haasnoot et al., 2013), into one planning guidance. The CRIDA method makes these tools accessible beyond the scientific community to a larger audience of practitioners in water resources planning.

CRIDA directly serves the *analyst,* an individual with a technical background in water resources management serving or working for the type of target audience organisations previously defined. The analyst has the difficult task of evaluating and communicating uncertainties to stakeholders and decision makers with often very little guidance or training for this role, particularly for complex uncertainties such as climate change. In the CRIDA process, the analyst is guided through an evaluation of system sensitivity to climate and non-climate drivers as well as the quality of available data. The results from this initial evaluation are then translated into three guidance matrices, which provide recommendations for the selection of a strategy direction (i.e. flexible vs. robust), an economic evaluation method, and funding and governance requirements needed to complete the planning process. This guidance allow the analyst to scale the level of effort or level of complexity

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needed to the problem at hand. In this format, CRIDA ensures that the wealth of climate data services available can better support effective decision making in water resources planning.

This case study presents the CRIDA method and its application to a water security planning study to be used as an example for practitioners worldwide facing the challenge of climate uncertainty in water resources planning.

1. Introduction

Worldwide water resources managers, and local planning authorities all face similar challenges when they want to make new plans and investments to develop and expand their water infrastructure and networks to meet future needs or to adapt to increasing uncertain future risks. Traditional water resource engineering is struggling with climate non-stationarity (unknowable uncertainty about future hydrologic conditions) and seeking new approaches to guide infrastructure planning and avenues for secure economic investment under a wide range of climate scenarios (Hallegate et al., 2012). There is need for planners to know "Can we invest while minimizing the risk to do too much nor too little?"; "And if I do so, how can I justify my decision" or "How do we plan for an action that is not too early nor too late?".

Collaborative Risk Informed Decision Analysis (CRIDA) (Mendoza et al., 2018) is specifically designed to address plan development when significant uncertainty exists about future conditions. CRIDA applies a step-by-step approach to planning (Gregory et al., 2012; USACE, 2000), with a "bottom-up" approach to risk assessment. CRIDA is compatible with international guidelines of Integrated Water Resources Management (IWRM, UN-Water, 2014). The areas of commonality include planning processes, the negotiation of multiple interests, and emphasis on system stressors caused by social, environmental, and economic changes.

CRIDA basically adds treatment of future uncertainty to IWRM. Multiple novel methods and tools to deal with uncertainty are developed by scholars worldwide (Willows and Connell, 2003; Walker et al., 2013). CRIDA is most related to the World Bank in the Decision Tree Methodology (Ray and Brown, 2015), decision scaling (Brown and Wilby, 2012) and the adaptive planning approach using adaptation pathways exercised in the Thames Estuary 2100 and Dutch Delta program (Reeder and Ranger, 2009; Bloemen, 2015; Haasnoot et al., 2013). In recent update of guidelines for IWRM by the Global Water Partnership among others the adaptation pathways approach was included (Nauta et al., 2016). CRIDA shares the same ideas of bottom up vulnerability assessment and development of robust and flexible strategies and applies it in a stepwise way and tailor made (scaled) for the decision problem at hand. The aim of providing scaled guidance is similar to the efforts by the World Bank Decision tree (Ray and Brown, 2015), the EU Adaptation support tool ("The Adaptation Support Tool – Getting Started") and the UKCIP Climate change risk-uncertainty-decision making framework (Willows and Connell, 2003).

While the need for an improved planning process, such as CRIDA, to address deep uncertainty is clear, an evaluation of the added benefits of such an approach is still needed.

1.1. Purpose of this study

The purpose of this study is to compare the CRIDA method to traditional water resources planning methods to review this above mentioned added value through a water supply case study in Central Cebu, the Philippines. In 2006, an IWRM planning process was applied to the Central Cebu region with the goal to meet demand for safe water supply and lay the foundation in addressing the related issues of water quality and watershed protection. The stakeholder led process resulted in the selection of a final water management strategy titled "Water for all Cebuanos" (Deltares, 2006). The 2006 planning study was successful in selecting a stakeholder approved water management strategy but was less focused on selecting a robust strategy across the uncertain drivers involved. This study will identify deviations between the two planning approaches and the added value of the CRIDA approach to planning under uncertainty. The result will be an updated recommended plan for the Central Cebu water supply system as well as one of the first applications of the CRIDA methodology to an existing planning process.

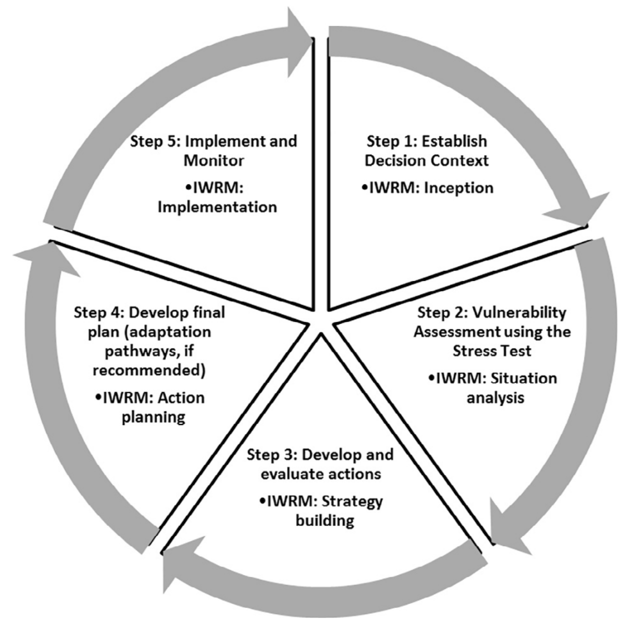

Fig. 1. Comparison between the CRIDA planning process steps and the IWRM Planning Process (Deltares, 2006) steps, identified in the bulleted descriptions.

2. Methodology

A comparison between the IWRM planning steps used in the Central Cebu Water Supply Study and the CRIDA planning steps is provided in Fig. 1. Both processes are cyclical, representing the dynamic aspects of our water management systems and the need for iterative planning. While the number of steps in each process may vary, the following concepts are covered in all of the processes:

1. Defining the problem, goals and objectives of the planning process, and decision criteria to define acceptable system performance
2. Evaluating the existing system based on the defined criteria and expected future conditions
3. Evaluating strategies to improve system performance and meet goals and objectives
4. Developing a final plan
5. Implementing the selected plan

The differences in the CRIDA and the IWRM planning process are discussed herein in terms of the CRIDA Method Steps outlined in Fig. 1.

2.1. Comparison of IWRM and CRIDA methods

While the IWRM and CRIDA planning processes are complementary, CRIDA contains deviations with the goal of tailoring the planning process to the problem at hand. The main deviation from traditional planning occurs in the *Step 2: Vulnerability Assessment*. Both the Situation Analysis in IWRM and the Vulnerability Assessment in CRIDA require the evaluation of system performance under current and future conditions. However, CRIDA does a more thorough uncertainty analysis, referred to as a Stress Test, than the traditional scenario analysis recommended by IWRM. In a traditional "predict and act" planning approach, as used in the Central Cebu case study, a vulnerability assessment is completed using observed climate data (USACE, 2000), which does not consider uncertainties under climate change. Even with a traditional scenario analysis, the range of climate under which a decision is made is limited to the available information. CRIDA, like other bottom-up methods (Brown and Wilby, 2012, Kwadijk et al., 2010) analyses performance over a wide range of plausible futures, not a priori limited by available scenarios. This focus on performance and its potential improvement by measures avoids the possibility of overlooking alternatives which would make the system more robust with little to no additional negative impacts or costs. While traditional scenarios can still be used to guide the discussion, the decision maker is provided with a wider decision space with which to evaluate alternatives.

The second major deviation within the *Step 2: Vulnerability Assessment* is CRIDA's Level of Concern Analysis. A key aspect of CRIDA is to tailor the process to the problem at hand, based on the Level of Concern analysis. In this phase of the process, the analyst evaluates the sensitivity of the system performance to multiple drivers (i.e., population growth, climate, etc.) and the *plausibility* of the system being exposed to driver conditions under which performance is unacceptable, referred to as vulnerable driver states, within the planning horizon. The analyst then evaluates the level of *future risk*, which is a function of (1) the *plausibility* of entering vulnerable driver states and (2) the *consequences* within the system. Then, based on a combination of the *future risk* and the level *of Analytical Uncertainty* associated with the available information, the analyst selects one of the four quadrants from the decision matrices shown in Fig. 2 within which to continue the planning process.

The decision matrices shown in Fig. 2 provide guidance to the analyst throughout the remainder of the planning process in order to tailor the process to the problem at hand. Decision Matrix A provides recommendations for the strategy direction, ranging from traditional planning approaches to an emphasis on flexible and/or robust strategy development. If flexibility is recommended, the CRIDA process encourages the use of Adaptation Pathways (Haasnoot et al., 2013). This guidance may result in deviations from traditional planning in the *Strategy Building Phase* of IWRM. Decision Matrix B then recommends the type of economic analysis with which to evaluate the developed strategies in the *Action Planning Phase*. Finally, Matric C provides insight into the likely funding and institutional needs to implement the planning process, which is necessary to complete the *Implementation Phase*. The Decision Matrices inform the analyst if and how the remainder of the steps in the planning process deviate from traditional IWRM planning. Furthermore, the guidance provided by the Level of Concern Analysis and Decision Matrices is what CRIDA adds to other bottom-up approaches for water resources planning.

In summary, the CRIDA approach complements the IWRM approach but adds the following key components to improve the decision making process: (1) a focus on objective based thresholds; (2) a broader vulnerability assessment through a *Stress Test* which does not limit decision space to available and selected scenarios; and (3) guidance on deviations from traditional planning. This guidance includes: (1) strategy emphasis on robustness and/or flexibility, for which adaptation pathways are recommended; (2) economic evaluation methods; and (3) institutional capacity requirements to implement process. Each of these components will be explained in further detail and their added value

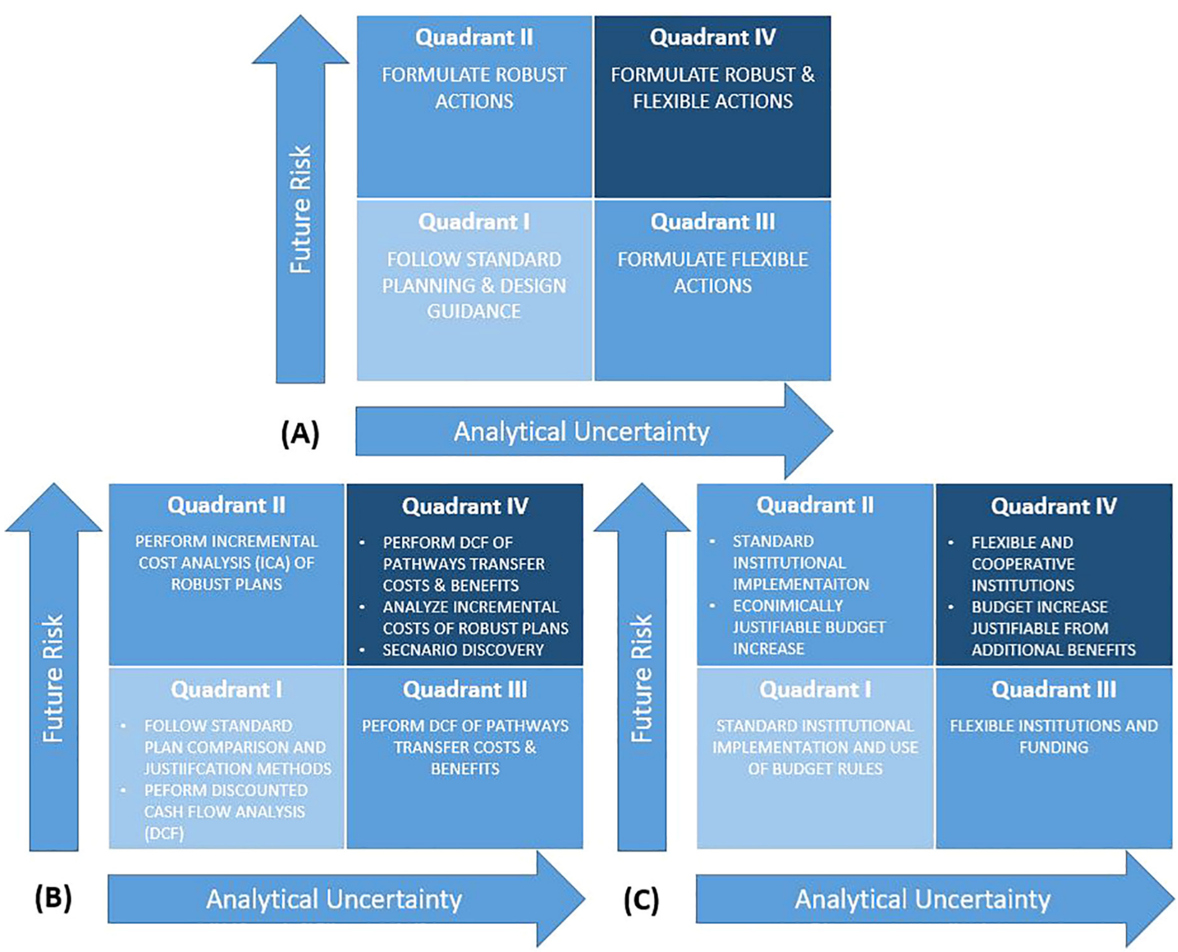

Fig. 2. Decision matrics for (A) Strategy direction (B) Level of economic analysis and (C) Institutional and financial requirements.

assessed with an application to the Central Cebu case study.

It is important to emphasize that this study does not determine whether the CRIDA method would result in a different decision than traditional IWRM planning. Neither process is a decision *making* method, rather they are decision *support* methods. This application, however, illustrates where CRIDA would provide additional information to support the analyst and decision makers and if recommended final strategies differ from in the IWRM approach. Additional engagement with the original decision makers was outside the scope of this study to determine whether the final decision would vary as a result of the CRIDA method.

3. Results: Application to Central Cebu case study

Growing water demands and increasing water degradation due to saltwater intrusion are stressing the water supply system in Central Cebu, the Philippines. Traditionally, water resources management in the region has only been conducted on a short term basis. However, these changing conditions require more long term planning as well as large scale collaboration across cities and municipalities in the region. In 2006, a traditional Integrated Water Resources Management (IWRM) planning process was applied to the Central Cebu region with the goal to meet demand for safe municipal water supply and lay the foundation in addressing the related issues of water quality and watershed protection (Deltares, 2006).

3.1. Decision context

The purpose of *Step 1: Decision Context* is to: (1) outline the problem statement and objective of the planning study, (2) identify the performance metrics and thresholds to evaluate whether objectives are met, (3) select relevant system drivers, and (4) develop a system model. As previously stated, Central Cebu faces the challenge of managing water supply for a growing population with minimal impacts on the environment. The objective is to ensure the continuous availability of good quality water to all existing and future uses in Central Cebu at an affordable cost and in an environmentally friendly and sustainable way for a 25 year planning horizon (2005–2030).

Regarding performance metrics, the original 2006 study project team used a multi-criteria scorecard approach containing five criteria: technical effectivity, cost-efficiency, health and socio-environmental aspects, and institutional and organizational aspects. For the CRIDA application, the same performance metrics were considered; however, as the vulnerability assessment *Stress Test* requires quantitative metrics, technical effectivity, defined as unmet demand (mcm/year), was selected as the main CRIDA study performance metric. A target threshold for unmet demand equal to 0 mcm/year at 97% reliability was selected. Additional qualitative social and environmental metrics were considered in the evaluation phase of the process as in the case of the original study.

The system drivers considered in the original 2006 Cebu Study included observed climate and future population growth scenarios which would influence water demands. For the CRIDA application, the same demand scenarios were used; however, the application also explored the following climate change drivers based on stakeholders' concerns regarding more severe droughts (Deltares, 2006):

1) Reduction in average annual precipitation and an increase in temperature and, therefore, evaporation. This change will lead to a reduction in average annual water availability within the system and was expressed in terms of the Aridity Index, or the ratio between precipitation and potential evapotranspiration (P/PET).
2) An increase in inter-annual variability, meaning that dry years become drier, but wet years become wetter, with the average annual precipitation remaining the same.

Because the existing system is predominantly supported by groundwater, the assumption was made that the groundwater system would be less sensitive to intra-annual variability than inter-annual variability, due to the longer residence time of groundwater systems as compared to surface water systems. Therefore, shifts in seasonal precipitation were not explored for the purpose of this study. The selection of ranges for each analysis will be discussed in *Step 2: Vulnerability Assessment*.

And finally, a system model in the form of an annual water balance was developed for the 2006 study to evaluate the threat of saltwater intrusion of the groundwater supply system as a result of proposed water management investments. The water supply system consisted largely of coastal groundwater abstraction; however, the groundwater system was supplemented by the Buhisan surface water reservoir, two small desalination plants, and the Jacuplan groundwater reservoir. For the original system, salt water intrusion from the sea was not considered a risk due to the hydraulic gradient of the ground water table and limited transmissivity of the soils. However, to avoid future salt water intrusion, specialists from the 2006 study recommended that proposed increased abstractions from surface or groundwater sources be limited a maximum of 60% of the natural inflow into the groundwater system. For the CRIDA analysis, this system model was used to explore the impact of changes in demand and climate. Any combination of demand, precipitation, and temperature that violated the groundwater constraints assigned to prevent saltwater intrusion or resulted in unmet demand was considered a vulnerable system state.

3.2. Vulnerability assessment

The vulnerability analysis, consisting of the stress test and level of concern analysis, is one of the main deviations from the traditional planning process used in the original study. The Stress Test provides the user with an understanding of system sensitivity to drivers, such as climate variability and/or change. It informs the analyst and decision maker of the magnitude of climate change and/or variability under which the system would no longer perform acceptably. However, more information is needed to make this information useful to the decision maker. The Level of Concern Analysis provides that information through a qualitative evaluation of *future risk* (a function of *consequences* in the system and *plausibility* of entering a vulnerable climate state) and *analytical uncertainty* in the available information. This additional information directs the analyst to a quadrant in the Decision Matrices for further guidance throughout the planning process.

Consequences in the system are assessed based on the type of problem being addressed. In general, drought occurs slowly, allowing time for adaptation to avoid severe consequences, such as fatalities, whereas flooding occurs more rapidly, with a much greater chance of fatalities. In addition, there is the possibility to truck water from other parts of the island in the event of a drought. Therefore, consequences were considered moderate for the Central Cebu case study.

To evaluate *plausibility,* available observed and projected information is gathered and evaluated. Based on observed values, observed trends, and projected values, the analyst can assess whether there is evidence that the system will enter a vulnerable driver state. Following the assessment of *plausibility*¸ the analyst must then determine the analytical uncertainty in these available data. For example, is the observed trend statistically significant? How much certainty does the IPCC place in the climatic variable evaluated? And are the data sources in agreement? *Plausibility* and *Analytical Uncertainty* were evaluated for each driver analysed.

For the two climate change conditions considered, the selection of ranges, resulting stress test, and level of concern analysis are discussed herein.

3.2.1. Analysis one: Reduction in aridity index

The first climate change driver, the annual average Aridity Index

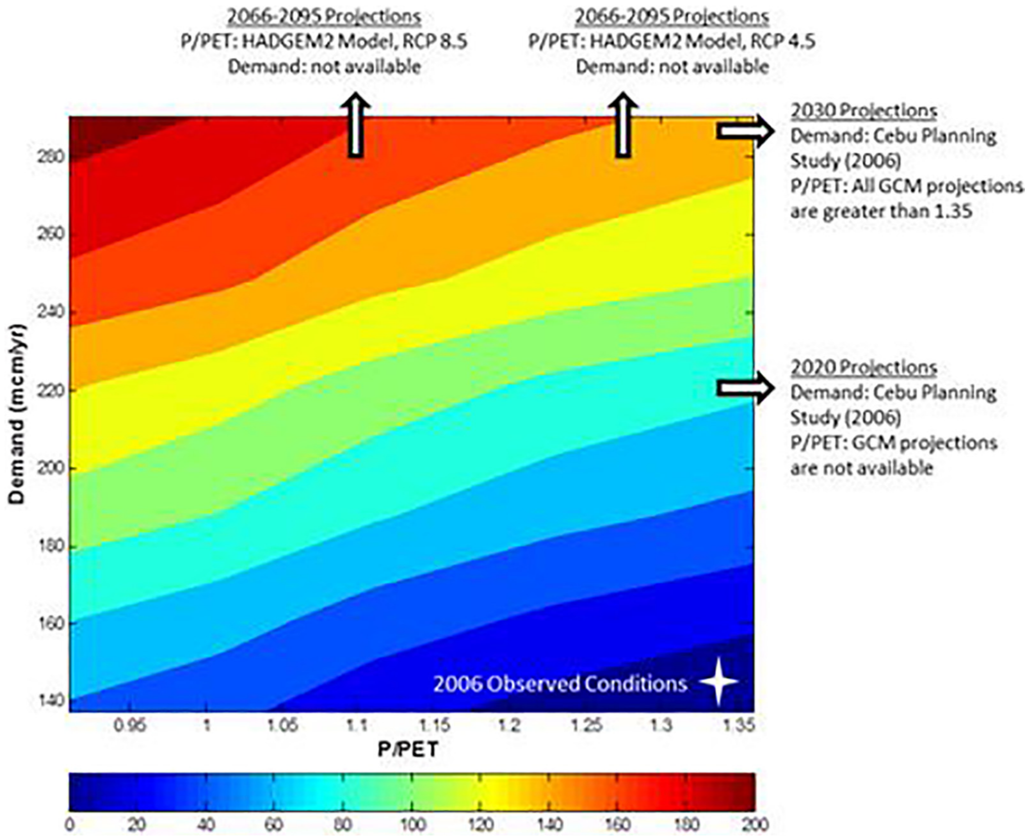

Fig. 3. Stress test response surface to demand and aridity index. response surface colors correspond to system unmet demand (MCM/YR).

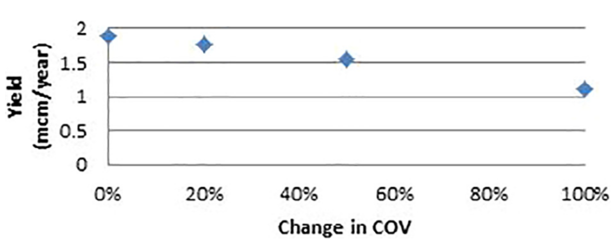

Fig. 4. Average annual precipitation for all watersheds.

(P/PET), considers the combined impacts of changing annual temperatures and precipitation. The plausible range analysed for decreases in annual precipitation was selected based on the coefficient of variation of the observed average annual precipitation data for all watersheds. Incremental reductions up to 20% were applied to the observed period of record on an annual basis for the Stress Test application. Based on the same approach, a plausible range for increased PET was also identified as 20%. This assessment was limited, however, by the lack of observed temperature data available, from which PET is normally derived. Instead, the observed actual evaporation data were analysed, acknowledging that the variability would likely be higher than for PET; however, for the purpose of setting a range, it was determined suitable. Thus the Aridity Index values analysed ranged from 1.36 (observed) to 0.91. The selected range in P/PET was considered a realistic shift relative to the observed values, but significant enough to stress the system.

With the driver ranges identified, the system model was run with different combinations of demand and climate to produce the resulting stress test response surface, shown in Fig. 3. The x- and y-axes display the selected ranges in P/PET and demand, respectively. The performance threshold, equal to unmet demand greater than 0 mcm/year, is represented in dark blue in the lower right corner of the stress test. Anything to the upper-left of this region indicates the system is not performing as expected.

The response surface shown in Fig. 3 reveals that for one value of P/PET the water shortage values resulting from the range in demand span 200 mcm/yr whereas for one demand value, the range of climate states only span about 40 mcm/yr. This suggests that a decision maker should be more concerned with the demand than the changes in climate. However, this assessment is based on the assumption that the selected ranges for the stress test are appropriate. While there is a high level of understanding of changes in demand, it is necessary to look at all of the available climate information to determine whether it is plausible that the future climate might surpass the analysed range in the aridity index.

Starting with observed data, the average aridity index for the entire period of record equals 1.34, at the highest range considered. Fig. 4 illustrates the average annual precipitation for all watersheds within the study area. The figure does not suggest any observed decline in annual precipitation; rather it suggests a slight, but statistically insignificant increase in average annual precipitation in the study area. This information suggests that there is no available observed information indicating that P/PET is decreasing and, therefore, the selected range in P/PET is sufficient for decision making. This indicates that relative to demand, it is not highly plausible that a decrease in the aridity index would have a significant impact on the system in the planning horizon.

The available GCM data, summarized in Table 1 and consisting of two RCP scenarios and two planning horizons for the HADGEM2 and EC Earth 2 models, also suggest that it is unlikely the study area will experience a decline in annual precipitation in the project planning horizon. For the year 2035, which is closest to the study planning horizon, zero out of the four GCM and RCP combinations indicate a P/PET less than 1.35, meaning that water availability will actually increase. This is due to the slight increase in precipitation projected, which dominates the increase in temperature. For the 2066–2090 time horizon, both RCP scenarios for the EC Earth 2 model continue to suggest an increase in P/

Table 1
GCM Projected P/PET Values for 2006–2035. Values were calculated using the delta method: the ratio of the GCM Outputs for the projected time periods (2006–2035 and 2066–2096) and the historic time period 1976–2005 were multiplied by the observed P/PET in Central Cebu, the Philippines (1.35). Evaporation is calculated based on the penman formula. The highlighted values represent projections of a drier future.

GCM: Projection Year	RCP 4.5	RCP 8.5
HADGEM2: 2035	1.43	1.35
HADGEM2: 2095	1.27	1.12
EC Earth 2: 2035	2.32	2.31
EC Earth 2: 2095	2.03	1.76

PET. The HADGCM2 model suggests a decrease in P/PET for both RCP scenarios, as illustrated in Fig. 3; however, this is well beyond the selected planning horizon and also still falls within our selected range, indicating that our initial conclusions still stand: relative to demand, it is not highly plausible that a decrease in the aridity index would have a significant impact on the system in the planning horizon.

The implications of this level of concern analysis will be discussed in greater detail in Section 3.2.3.

3.2.2. *Analysis two: Increase in inter-annual variability*

Inter-annual variability evaluates the change in precipitation from year to year, as opposed to within a single year. It can be measured based on the coefficient of variation of the annual precipitation values. Note that this differs from the previous analysis which assessed the changes in the mean annual precipitation. Analysis of observed data showed a 50% increase in the coefficient of variation between the first and second halves of the annual precipitation record. Based on this point of reference, the inter-annual variability was increased incrementally up to 100% for the Stress Test.

The assumption was made that only a decline in average annual precipitation and evaporation (Analysis 1) would influence groundwater supplies and that the inter-annual variability (Analysis 2) would only affect the surface water sources. The Buhisan Reservoir is the only surface water reservoir in the existing system and is designed to provide less than 1% of the total water supply (1.8 mcm); however, surface water reservoirs are included in the proposed measures. To ensure that the sensitivity of proposed surface water sources to climate change and/or variability is not overlooked, the Analysis Two stress test was applied only to the Buhisan Reservoir, as opposed to the entire system.

Fig. 5 shows the sensitivity of the Buhisan Reservoir yield (mcm/yr) to an increase in inter-annual variability. The reservoir is designed to provide 1.8 mcm/year at 88% reliability based on the observed inflows into the system. Doubling the inter-annual variability results in a 38.8% reduction from the design yield. Since the Buhisan reservoir only provides 1% of the total water supply in the existing system, this reduction in water supply would not have an impact on the overall system. However, it does suggest that any proposed surface water sources is sensitive to inter-annual variability.

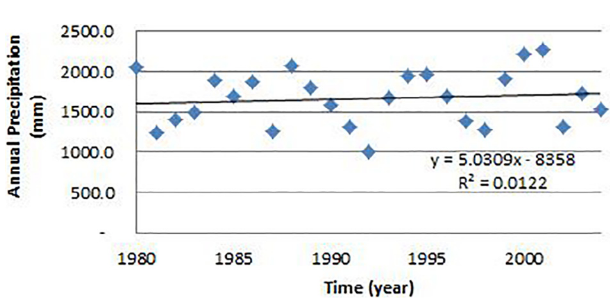

Fig. 5. Change in annual yield for buhisan reservoir with increase in inter-annual variability, measured by cov. system should provide 1.8 MCM/YEAR.

Table 2
Level of concern analysis findings.

Driver Analysis	Plausibility	Future risk (Plausibility × Consequences)	Analytical Uncertainty	Implication
Demand	High	Medium-High	Low	Main Driver. Cannot be ignored, but still would not require deviation from traditional planning, as demand is already included.
Climate Option 1: Decrease in P/PET	*Observed data:* Low Plausibility. There is no observed trend in P/PET. *Projected data:* 2030 projections have a low plausibility, due to an increase in precipitation. 2066 projections, however, have a medium plausibility due to an increase in temperature. The projected values, however, still provide less change in the system then the demand projections for 2030 and are well outside the planning horizon. *Sensitivity:* Low relative to the projected changes in demand and the ranges of P/PET analysed. *Overall: Low*	Low-Medium	*Observed data:* Low, due to the short planning horizon *Projected data:* 2030 projections have high uncertainty because P/PET is driven by precipitation projections, which do not have high confidence. The 2066 projections, however, have a medium level of uncertainty because annual temperature is considered a more reliable variable in GCMs. *Overall: Medium*	Low-medium future risk, so no need to shift to Quadrants II or IV. However, uncertainty level suggests Quadrant III should be considered. Analyst should not invest extensive additional resources in the remainder of the process. He or she should select one P/PET scenario which stresses the system to test measures and inform decisions.
Climate Option 2: Increase in Inter-Annual Variability (only evaluated for Buhisan Reservoir)	*Observed Data:* Moderately Plausible *Projected Data:* not available *Sensitivity:* High *Overall: Medium*	Medium	*Observed Data:* Medium Uncertainty due to the sensitivity of the significance of the findings to where the record is divided. *Projected Data:* Not available *Overall: Medium-High*	Medium future risk, so no need to shift to Quadrants II or IV. However, uncertainty level suggests Quadrant III should be considered. Similar to P/PET, select one scenario and test measures and inform decisions.

Given the already observed increase in inter-annual variability, it is highly plausible that future increases in inter-annual variability could result in any proposed surface waters sources performing unacceptably. However, it is important to note that this statistic is highly dependent on whether or not the year 1992, which is the driest year on record, is placed in the first or second half of the record. This sensitivity increases the analytical uncertainty in the level of concern analysis. The implications of this level of concern analysis will be discussed in greater detail in Section 3.2.3.

3.2.3. Discussion of level of concern analysis implications

The findings from the level of concern analysis, summarized in Table 2, suggest that the current system is more sensitive to expected changes in demand than to climate change. Demand is a fairly well understood variable, especially considering agriculture is not a factor and the scenario is supported by observed data. Therefore, our level of analytical uncertainty is low in our assessment of demand. As a result of these findings, demand is considered the main driver and will be analysed throughout the remainder of the analysis. These initial results place the planning process in Quadrant I of the Decision Matrixes. Quadrant I does not suggest a deviation from traditional planning, which already incorporates demand changes, and allows the user to exit the CRIDA process.

Despite demand being the main driver, the system is not *insensitive* to P/PET changes; however, the available data do not suggest a decrease until 2066–2090, which is well outside the planning horizon. That said, precipitation projections are the driver of P/PET changes, which contain high levels of uncertainty. Based on this combination of low-medium future risk and high uncertainty, the analyst may consider shifting from quadrant I to quadrant III in the Decision Matrix and consider flexible measures or strategies to allow more time for monitoring.

Likewise, the sensitivity of the surface water sources to precipitation inter-annual variability cannot be ignored. While 99% of the current system relies on groundwater, proposed surface water sources should consider climate change. However, as the increase in inter-annual variability detected is highly sensitive when the observed record is divided, a medium-high level of analytical uncertainty was assigned. Therefore, as with P/PET, the analyst should consider flexible measures or strategies.

In regards to strategy direction, the outcome of the level of concern analysis places emphasis between Quadrants I and III in the decision matrix. In addition to these findings, the original study noted that the existing institution prefers an adaptive management approach. This is often preferred if the institutional or financial capacity is insufficient to implement major projects upfront altogether. Therefore, consideration of flexible measures and strategies (Quadrant III) were recommended from both a level of concern and institutional capacity perspective.

3.3. Develop and evaluate actions

In Step 3 of the CRIDA planning process as with IWRM, the analyst develops and evaluates potential actions to include in a final strategy to meet the planning objectives. In CRIDA, however, the analyst should consider robustness and/or flexibility depending on the level of concern analysis recommendations. To consider robustness, measures are designed and evaluated over a range of future climate conditions. For flexibility, expandable or reversible actions as well as adaptation pathway strategies can be considered and both were included in this study. In addition, given the level of analytical uncertainty in both climate drivers, actions were evaluated under the observed climate and as well as one extreme future climate condition for each of the two climate variables considered to provide additional information to decision makers for strategy selection.

The 2006 study selected multiple actions ranging from groundwater to surface water to desalination plants, listed in Column 1 of Table 3.

Table 3
Strategy development based on CRIDA criteria.

Actions	1	2	3	4	5
	IWRM	Flexibility	Economically Beneficial (Highest NPV)		
			Current Climate	Extreme P/PET	Extreme Interannual Variability
Lusaran Dam	2030	2030	2020	2020	2020
GW Wells within MCWD	2020	2020	2020		2020
Mananga Dam	2020	2030	2030	2030	2030
GW Wells outside MCWD	2020	2020	2030		2030
Kotkot Weir		2020	2030	2020	2030
Desalination (small)	2030			2020	
Desalination (medium)	2030			2030	
Southern Wells Project		2020		2030	
Luyang Dam					
Desalination (large)					

The study team then developed four different strategies by combining actions meeting the following objectives: (1) maximize use of groundwater; (2) mix of surface water and groundwater; (3) maximize use of surface water; and (4) most likely projects based on existing political support. Each strategy consisted of two phases: 2020 and 2030 implementations. For the CRIDA analysis, the same actions were evaluated without changing design yields from the original study; however, actions were evaluated and strategies were developed based on the criteria identified in Columns 2 through 6 in Table 3. Criterion 1, an integrated water resources management (IWRM) index, was developed based on social, environmental, and economic impact scores provided by the 2006 study and aligns the process with the traditional IWRM planning process criteria. Criterion 2, flexibility of action, allows the analyst to consider flexibility in terms of individual measures rather than through adaptation pathways. Criterion 3, economic benefits under current climate based on net present value (NPV) represents more traditional planning evaluation methods based on the highest NPV under observed climate. Finally, Criteria 4 and 5, economic benefits under two different potential extreme future climates, provides insight into the impact of climate change consideration on strategy selection. Actions were evaluated based on the net present value of each measure under the extreme future climate illustrated by (1) the P/PET resulting from HADGCM2 RCP 8.5 for 2066–2090 and (2) a 100% increase in inter-annual variability. The higher the net present value, the better the measure will perform under extreme future climates.

Five strategies (combinations of actions) were then developed in which incremental investments based on the highest ranking actions for each criterion were combined until demand requirements for Phase I (2020) and then Phase II (2030) were met. The strategies, actions, and corresponding implementation times are outlined in Table 3.

Through an initial analysis of the resulting strategies described in Table 3, the analyst is able to eliminate some strategies immediately to make decision making easier. Ultimately, the analyst is trying to determine whether or not it may be necessary to deviate from traditional planning, which often times selects strategies based on the NPV, or economic benefits, under current climate (Criterion 3). The resulting strategies in Table 3 suggest that Criterion 5, which tests robustness to increased interannual variability, would not differ from Criterion 3. Therefore, the analyst can eliminate the inter-annual variability strategy from the decision making process. Likewise, the only difference in the Criterion 2 (flexibility) strategy and the Criterion 3 strategy is a large groundwater project which is not included in the Criterion 4 (robust to P/PET) strategy. Considering the benefit of choosing flexible measures is to be able to switch approaches if climate does change, implementing a measure that is not in the Criterion 4 (robust to P/PET) strategy does not have added value. Therefore, the flexibility strategy was also eliminated from the evaluation process.

3.4. Develop final plan

Following the evaluation of actions and development of strategies, the next step in both standard planning and CRIDA is to evaluate each strategy and ultimately make a selection. In the 2006 study, a strategy was selected using multi-criteria decision making to optimize the IWRM criteria. In standard planning, decisions are often made based on the highest economic performance, normally based on a discounted cash flow analysis (DCF), as is mentioned in the Decision Matrix B, Quadrant III, or other economic evaluation criteria of choice. This type of economic evaluation becomes difficult under uncertainty, however, because it is unclear under which climate conditions the net present value should be calculated. CRIDA recommends evaluating the pathways under an observed and extreme future climate and determining if there is a single pathway or a single first step which outperforms all other options under both conditions. If this is the case, the decision is simplified despite the uncertainty because there is a low-regret option or “clear winner”. However, if this is not the case, the next best approach is to identify pathways or first steps which can be eliminated based on poor performance under both conditions. This process of elimination makes selecting a Phase I approach easier for decision makers dealing with uncertainty.

After the initial evaluation of actions and development of strategies, the remaining three strategies are presented using adaptation pathways as shown in Fig. 6. The benefit of flexibility through adaptation pathways is avoiding over- or under-investing for climate change by making investments incrementally, starting with the lowest regret options with which the most future options remain open. Both the Economically Beneficial and the IWRM pathway are able to transfer to the More Climate Change Robust pathway after Phase I if a drier climate has been detected. The presentation of strategies in this manner allows the decision maker to evaluate and select a first step (Phase I) that has the lowest regrets.

The net present value of each pathway, including pathways with a transfer to the More Climate Robust pathway at Phase I, under both the current and the future extreme climate used in Step 4 for P/PET are shown in Fig. 7. As expected, the economically beneficial pathway outperforms all pathways under the current climate. However, it also outperforms even the pathway developed to be more robust to climate change under an extreme climate. This is due to the delay of more expensive investments. Additionally, beginning with the Economically Beneficial pathway and then transferring to More Climate Robust measures still outperforms starting directly with More Climate Robust measures. As a decision maker, this means that implementing the Economically Beneficial Pathway for Phase I is a no-regret option, regardless of whether or not climate change is observed before Phase II begins. In the event that a clear winner did not exist, additional climate scenarios could be analysed to develop more sophisticated climate robustness statistics or qualitative IWRM metrics could be incorporated into the decision making process. In comparison to the original 2006 study, all strategies considered economically outperformed the selected study in 2006 as a result of the multi-criteria decision analysis approach to strategy selection.

3.5. Implementation and monitoring

The CRIDA approach allows the decision maker to select a Phase I implementation strategy with the option to transfer if deemed necessary to a strategy containing more climate robust measures at Phase II. The remaining challenge, as is the case with any adaptive management option, is to continue monitoring the system climate. In addition to monitoring, financial decisions need to be made to ensure a transfer is possible if determined necessary. Finally, as the 2006 study stated, shifting the focus from supply to demand reduction measures may also be considered rather than requiring a transfer if the financials are too difficult to implement. Each of these elements should be considered by the decision maker to ensure that adaptation pathways are used to their full benefit under an uncertain climate.

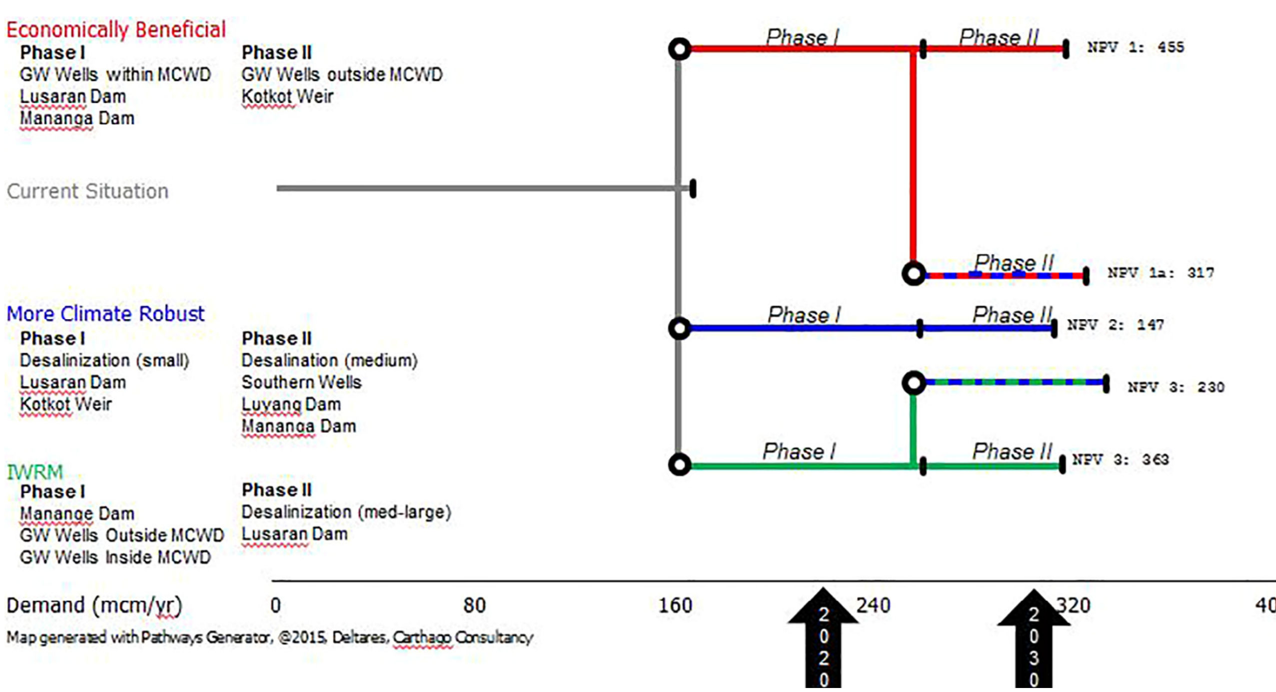

Fig. 6. Adaptation pathways for water supply in Central Cebu. Transitions are allowed after the first implementation phase from the IWRM and economically beneficial pathways to the more climate robust pathway if decision makers deem necessary. The net present value scores are calculated under observed climate.

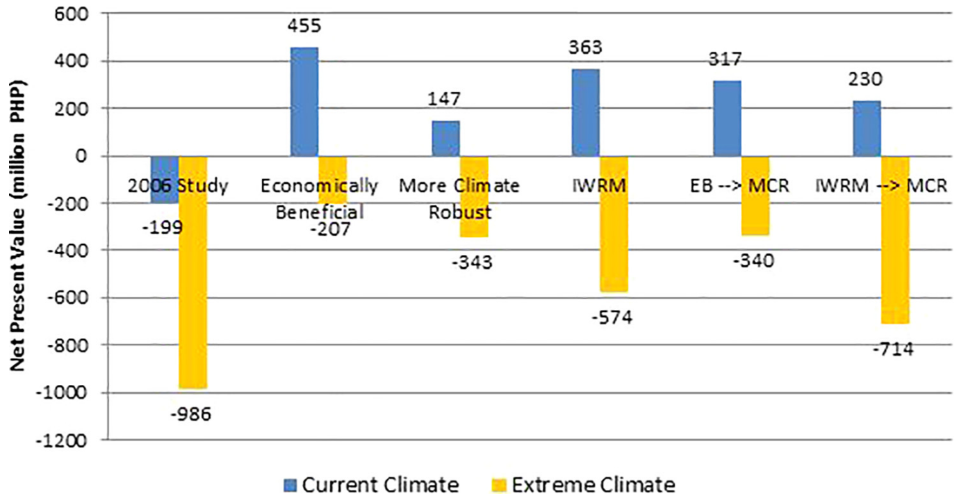

Fig. 7. DCF Analysis of each pathway under current and extreme future climate.

4. Discussion

The purpose of this study was to apply CRIDA, a novel planning process which takes into account the impact of climate uncertainties on the planning process, to an existing planning case study in Central Cebu, the Philippines. The study demonstrated the following key differences between CRIDA and traditional planning: (1) consideration of climate change as a system driver through a bottom-up vulnerability assessment; (2) evaluation of the Level of Concern Analysis and quadrant placement in the CRIDA decision matrices; (3) development of a flexible strategy direction; and (4) a more sophisticated economic analysis to evaluate adaptation pathways.

While the CRIDA approach required additional processing time in the stress test, the level of effort for the remainder of the planning process was tailored to the outcome of the stress test. The stress test level of concern analysis showed that while the system is sensitive to climate change, the magnitude of change necessary to shift the dominant driver from demand to climate was not plausible in the study planning horizon. However, uncertainty in the available data as well as the existing institutional capacity led to the recommendation of a flexible water supply strategy. The flexibility strategy recommendation represents a second tier level of effort in a planning process. It is more intensive than traditional planning, which is often based on observed climate and a single net present value analysis. Flexible arrangements also often do not match with institutional habits like budget cycles. However, it is less intensive then the recommendation for a more climate robust strategy. This would be required if both the system is climate sensitive and the required magnitude of change were deemed plausible in the planning horizon. The evaluation of more robust strategies would require analysing additional climate scenarios, possibly including downscaling, and an incremental cost analysis of each strategy. Therefore, while the initial vulnerability assessment required more analysis than traditional planning, the analyst is able to tailor the remainder of the process to the problem at hand.

An additional benefit of the CRIDA application is the use of adaptation pathways to demonstrate flexible strategies. The original study employed adaptive management by implementing investments incrementally over the planning horizon. However, the study did not provide transfer options if the climate situation were to change in the future as is done via CRIDA and the adaptation pathways approach. The pathways allow decision makers to select a Phase I effort which does not lock the overall water supply strategy into one climate state, rather it leaves future options open as our uncertainty decreases over time.

And finally, in terms of compatibility with traditional planning approaches, the use of the net present value as a strategy selection metric aligns with many current planning methods (USACE, 2000); however, to better align with IWRM, the analyst should provide a discussion of IWRM scores for each pathway, not only for the IWRM pathway, for decision makers. These can act as “tie-breakers” in the event that a “clear winner” does not exist.

5. Conclusions and recommendations

The CRIDA method is a novel planning approach embodying a suite of complementary methods, including decision scaling and adaptation pathways, while remaining compatible with existing planning approaches. Decision scaling offers a bottom-up approach to assess risk and tailors the complexity of the analysis to the problem at hand based on the CRIDA Decision Matrices. Through adaptation pathways, an array of future strategies towards climate robustness are developed, ranging in flexibility and immediacy of investments. Flexible pathways include transfer points to other strategies to ensure that the system can be adapted if future conditions vary from those expected. CRIDA combines these two approaches in a stakeholder driven process which guides decision makers through the planning and decision process, taking into account how the uncertainty in the available science, the consequences in the system, and the capacity of institutions should influence strategy selection.

This study provides an application of the CRIDA method to the Central Cebu Water Supply Planning Study completed by Deltares in 2006 using a traditional IWRM process. The study offers a general overview of the additional planning guidance provided by the CRIDA approach and a specific application to a planning process which falls in Quadrant III, with an emphasis on flexible planning strategies. Additional case studies are being developed to demonstrate the application of Quadrants II and IV, which incorporate robustness into the strategy direction.

While this case study demonstrates the deviations and added value of the CRIDA method when uncertainty is of concern, future research is still recommended both for the case study and the overall CRIDA Method. For the Cebu City stress test, additional climate metrics such as persistence and intra-annual variability may be of interest to decision makers. For the purpose of this study, however, only two metrics were selected in order to demonstrate the CRIDA approach. In regards to the overall CRIDA Method, the Level of Concern Analysis remains fairly subjective and is challenging for the analyst to interpret. Further research and case studies are currently being conducted to provide more structured guidance for future applications of the CRIDA process in water resources planning under uncertainty.

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