‘’Reading the Minds’’ for Quantitative Sustainability: Assessing Stakeholder Mental Models via Probabilistic Text Analysis

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Management of complex ecosystems is a difficult process that involves multiple factors and stakeholders. In most cases the interactions of these factors and stakeholders' trade-offs are not considered quantitatively in the design and management of ecosystems. To address these issues mental modeling is useful for eliciting stakeholder objectives and preferences in order to evaluate preliminary knowledge about structure and function of complex ecosystems. This is advantageous for ecosystem analysis, modeling, and management.

Here we provide an assessment of stakeholder preferences and mental models for the case study of a large-scale watershed in Costa Rica composed by two rivers basins and one wetland. Trade-offs are related to water management in relation to ecological, agricultural, energy, and tourism endpoints that are affected by potential sets of dam and canal configurations. We apply and further develop a network-based model for stakeholder text analysis. Our innovation is the introduction of Network Complexity (NC) as a metric to characterize the inferred influenced diagram and to monitor the variation of such diagram under perturbations in socio-ecological factors provided by stakeholders and related to ecosystems. Perturbation effects – innovatively determined and assessed by global sensitivity and uncertainty analyses may reveal fundamental factor importance and interactions of ecosystem factors and ecosystem resilience. The derived influence diagram can be considered as the mental model of stakeholders because its construction is based on the direct elicitation of stakeholder preferences and objective in ad-hoc workshops organized for this study.

The decision-analysis based mental modeling approach allows a transparent and participatory decision-making concerning ecosystem management. The approach facilitates the identification and balance of trade-offs among stakeholder groups. Thus, it is coherent with the sustainability paradigm that includes social factors into the analysis, design, and management of complex systems.

Introduction

Mental Models

Complex networks are graphs that inform about the physical or functional connections among components of a system and among systems. Mental models are representation of the reality of complex systems - for example ecosystems - based on stakeholders knowledge of systems. Mental models are often represented in the form of networks (undirected or directed) whose features can be analyzed with equivalent tools used for complex networks found in biological and technological systems. Thus, mental models can considered as socio-cognitive network of stakeholders.

Mental models are useful in natural resource management for quantifying preliminary evidence from data and stakeholder preferences. Mental models are widely used for any complex systems and they can be modeled used systems dynamics model (Kim, 2009; Kim et al., 2012) or combined system dynamics and decision science models (Convertino, 2012; Convertino et al., 2013; Convertino and Valverde, 2013). Preferences are beliefs about a set criteria related to the problem at hand. Thus, preferences possibly reveal subjective probabilities of criteria's weights used to evaluate the alternative solutions against each other for the problem investigated. Such preferences reveal a mental model of stakeholders and can shift the decision making process when they vary. Thus, preferences are not fixed in time, nor among stakeholder groups, and can be leveraged in order to change decision making.

Jones et al. (2011) and Wood et al. (2012a,b,c) reviewed a variety of elicitation methods for identifying and describing stakeholders' mental models that have been successfully deployed in a variety of natural resource management (NRM) contexts. These methods are broadly categorized into direct and indirect methods. *Direct elicitation methods* are those where stakeholders work in conjunction with an analyst to describe and produce a graphical representation of the model in an iterative and interactive fashion. *Indirect elicitation* methods are those where a research team utilizes textual information from interviews, websites, and other documents to extract a graphical model via content analysis and/or the help of ad hoc-designed computer programs. These models and programs can really help policy via informatics by translating qualitative conversations of stakeholders into numbers that can be used effectively for policy relevant decision-making. Such models can detect individual and group preferences of stakeholders, thus emphasizing differential needs and contrasts to balance. Thinking about a government organization dealing with a complex problem where social, environmental, and economic criteria can collide against each other – in a sustainability perspective - the proposed model can be useful to provide a balanced solution (Morgan et al., 2002; Wood et al., 2012a). Stakeholder weights for social, environmental, and economic criteria can be used to balance criteria value for the selection of the optimal highest scoring alternatives, thus providing a balanced objective and subjective solution for the system considered. Specifically, here we propose an indirect elicitation method based on directly elicited data for an ecoystem management problem in Costa Rica where multiple solutins and criteria are evaluted. The case-study is just for illustrative purpose of a model that can be applied in any settings, thus we prefer to keep the generality of the discussion in order to emphasize the utility of the model for broader complex systems.

The Costa Rican Case Study

We provide a post-hoc preliminary analysis and synthesis of the research questions formulated at the Palo Verde research workshop in Costa Rica about the management of the Tempisque-Bebedero-Palo Verde ecosystem (TBPV, hereafter). The participating stakeholders belong to two kinds of institutions: academic and non-profit private organizations (NGOs). These stakeholders were considered after selection of key people involved in the decision making of the water-related infrastructure project in the TBPV. Other stakeholder may exist b but they were not involved in such study; however, it is very important in to include, if possible, any stakeholder involved in the ecosystem management. Such stakeholders have been identified by the Organization for Tropical Studies that is currently monitoring the ecosystem and developing a network of scientists to tackle the ecosystem problems in this area.

By analyzing the research questions and their institutional origin we: (i) evaluate trade-offs among the objectives of the problem and researcher preferences; (ii) screen the most important factors of the problem; and (iii) elicit mental models for possible development of a probabilistic decision model and for guidance of a more sophisticated modeling effort. For instance, research questions can be used to build a utility function that considers the important factors composing the objective of the problem, and mental models can be used to evaluate land-management policies relevant to the TBPV. Hence, ultimately the analysis and quantification of stakeholders' information is useful for environmental management and for socio-cognitive research related to individual and collective response of stakeholders facing multicriteria decision problems (Morgan et al., 2002; Linkov et al., 2011; Sparrevik et al, 2011; Wood et al., 2012a).

Materials and Methods

The Tempisque – Bebedero – Palo Verde Ecosystem

The 5404 km^2 Costa Rican Tempisque basin extends from the Tilarán and Guanacaste Mountains (in the NE) to the Gulf of Nicoya (SW) (Figure 1). The Tempisque river and its tributaries, flow into the northern Gulf of Nicoya, Pacific Ocean. The basin outlet forms the Palo Verde wetland (PV), protected by the Palo Verde National Park and internationally recognized by the Ramsar Convention (http://ramsar.org). The Bebedero basin extends in the east area of the Tempisque basin. The region is a mixture of tropical dry forest and dry-with-transition to moist forest life zones (Bolaños and Watson 1999); hence water is a limiting factor for both natural and human systems.

The basin was not significantly transformed until the 20th century, when forest gave way to pasturelands and cattle ranches. In the 1970s, a pivotal hydrological change occurred when the government created a large-scale irrigation district (Figure 1), funded by the International Development Bank, to provide agricultural land to low-income Costa Ricans and food security (rice, beans and sugar) for the country. The irrigation district receives water (30-65 m3/s) transferred from the Caribbean versant at Lake Arenal, and then directed to a hydroelectrical dam that generates 12% of the country´s electrical power (Figure 1). Upon discharging neat the town of Cañas, the water feeds a network of channels that spread through the middle Tempisque basin irrigating 44,000 hectares of agricultural lands (Jiménez et al. 2001). It eventually flows through the lower wetland-dominated basin, and into the Pacific at the Gulf of Nicoya. This large addition of water has transformed the middle and lower sections of the Tempisque basin. It modified the hydrology and thus the physical environment of both natural and human systems, and allowed the establishment of a new and extensive land use (agriculture and aquaculture). It also changed the TBPV dynamics by altering how the different ecosystems interact with each other. Direct links are now established through the transport and transfer of energy and materials among them, such as sediments, species propagules, agrochemicals, and other pollutants. While the extent of water contamination and its impact on human health are unknown, some manifestations are already visible in the protected wetlands in the lower basin (Daniels and Cumming 2008).

The wetlands of the lower Tempisque basin historically supported regionally important populations of waterbirds, including ducks, ibises, wood storks (*Mycteria americana*) and regionally endangered Jabiru storks (*Jabiru mycteria*), hence the site´s recognition as a Ramsar Wetland of International Importance. However, beginning in the late 1980s, there has been a large reduction (>90%) in the numbers of aquatic birds supported. Temporal observations and experimental evidence suggest that this change was precipitated by a vegetative regime shift, towards massive overdominance of cattails (*Typha domingensis*), resulting in stands so dense that birds cannot land or feed.

While the current situation already yields many environmental, socio-economic and institutional problems, these conditions are likely to be exacerbated by climatic variability and change. The 2007 Intergovernmental Panel on Climate Change (IPCC) report indicates strong consensus among climate models for increasing temperature and decreasing precipitation for much of Pacific Central America. Unless greenhouse gas trends change, average temperatures are expected to increase 2- 6 °C in the region, possibly with more extreme hydro-climatological events. Wet season precipitation is expected to decrease as much as 27% with associated drier soils and loss of water storage for irrigation, hydropower production and protected wetlands. Dry season river flow is also expected to decrease due to reduced cloud cover on the mountain ridges. These changes may unfold in as little as two decades, with a trend towards increasing aridity already evident in NW Costa Rica (Birkel and Demuth 2006). Recent and regional scale weather patterns appear to be consistent with long-term and global climate scenarios that portend severe impacts on agriculture, biodiversity, and land use (Murcia et al. 2012).

The gradual destruction of the Palo Verde wetland (Figure 2), the Sardinal conflict, pressures for new irrigation development and the proposed Rio Piedras Dam and its unintended consequences, illustrate how individualistic actions to acquire water have created a dysfunctional and unsustainable water system. They emphasize the urgency of conducting an integrative analysis of the situation that informs strategies to reach a consensual agreement on new policy that simultaneously considers all stakeholders interests. This is the motivation for which in this study different management actions are preliminary investigated by evaluating stakeholder preferences, trade-offs, and objectives for the TBPV ecosystem. The topic categories are: climate behavior (1), climate on vegetation (2), governance (3), human impact on natural systems (4), human impacts of natural systems on climate/production (5), impacts on water system behavior (6), natural system behavior (7), use/decision processes (8), water system behavior (9), natural system sustainability (10), water sustainability (11), incentive mechanisms (12), governance structure (13), institutions (14), laws and policy (15), stakeholders (16), water use (17). The time categories are: historic trends (1), current status (2), expected behavior (3). G=0.62 and 0.25 for the two frequency distributions of topic and time categories of NGOs and Academics, respectively. The G-test value is proportional to the Kullback–Leibler divergence of the two distributions that are compared; thus, the higher G the more dissimilar are the two distributions that are compared. The frequency distributions are normalized considering the different number of stakeholders in stakeholder groups.

Palo Verde Workshop

Objectives

A four-day workshop was held at the OTS Palo Verde Biological Field Station, Costa Rica, from April 24 to April 27, 2012. The goals of this workshop were to: (1) formulate and refine compelling research questions and hypotheses on water sustainability and climate for ensuing research collaborative proposals and infer stakeholder preferences; (2) define the teams that will prepare research proposals; (3) identify funding sources; and (4) agree on the mechanisms for communication and integration among the different working teams.

Participants included 20 researchers from the four participating US universities and organizations (UF, ASU, Columbia and OTS) and 5 Costa Rican collaborators from UCR, ITCR, MarViva, Texas A&M's Soltis Center, and ProDesarrollo Internacional.

Activities

On the first day of the workshop, participants were taken on a day-long field trip in the Tempisque River Basin so that they could get to know the basin first-hand and become familiar with key components of this system, in terms of water management and water use. Driving out of the Palo Verde field station, participants were shown rice and sugarcane fields, the two major agricultural crops grown in the Tempisque Basin. They were then taken to the Sandillal hydropower generating station, managed by the Costa Rican Electricity Institute (ICE), where they were given an hour-long tour by ICE staff. This is one of two power generating stations below the Arenal Dam, and once passed through the station; this water is diverted into the two primary irrigation canals of the Tempisque Basin at the Miguel Pablo Dengo Diverting Station, the third stop of our tour. The group was then taken to a large tilapia fish farm and given a tour of the facilities by its staff, where each phase of production was explained in detail. Finally, in the afternoon, they were driven to the Pacific coast (Playas del Coco) to get a feel of the tourism industry (a major component in terms of water use in the region). On the way to the coast, they stopped at the La Guardia gauging station, the only gauging station in the Tempisque River. The group then returned to the Palo Verde field station in the evening, better prepared to discuss water management challenges faced in the region the following morning.

From Wednesday to Friday (April 26 to 28 2012), the group stayed at the Palo Verde field station. The days consisted of multiple plenary and group break-out sessions to address the goals of the workshop. These included presentations on the analysis of current conditions in the basin, discussions on the elements of a social model and defining the long-term goals of the project. Participants also identified research questions, discussed potential funding sources as well as possible stakeholder engagement strategies.

Workshop Outputs

Participants were asked to submit (individually or in small disciplinary groups) an unlimited number of research questions to address one or more of the three main objectives identified above. A total of 85 questions on a diversity of topics, from hydrology and natural ecosystems, to social and governance issues were proposed (these are available at http://www.tc.umn.edu/~matteoc/). These were mapped to the specific goals of the project, and will form the core of the research grant proposals that will be generated by this group. They are also mapped to the five thematic groups (listed above), indicating where additional inter-group coordination will be required. In the next section, we present a *post-hoc* preliminary analysis based on these questions, to explore further gaps in the project´s research framework, and trends of thought.

Elicitation of Stakeholder Preferences

Stakeholder preferences have been analyzed as a function of two categories (i.e., topic and time categories) assigned by stakeholders to the questions formulated during the workshop. The topic categories are: climate behavior (1), climate on vegetation (2), governance (3), human impact on natural systems (4), human impacts of natural systems on climate/production (5), impacts on water system behavior (6), natural system behavior (7), use/decision processes (8), water system behavior (9), natural system sustainability (10), water sustainability (11), incentive mechanisms (12), governance structure (13), institutions (14), laws and policy (15), stakeholders (16), water use (17). The time categories are: historic trends (1), current status (2), expected behavior (3).

The selection of a topic or time class independently of the questions represents a preference formulation of stakeholders. All stakeholders (with the exception of stakeholders from governmental organizations) selected topic and time classes for the same set of questions.

Considering the selection of stakeholders we assessed the frequency distributions of selected topic and time classes for academics and NGOs. In our case the number of stakeholders for each stakeholder group is different; however, this is a common situation that does not affect the inter-comparison of stakeholder groups' preferences. More participation was observed for academics.

Semantic Network Extraction Model

The inference of the semantic network from a text is useful for assessing the potential mental model of stakeholders for a given problem. Aggregated mental models of stakeholders can be useful for the construction of probabilistic decision networks (i.e., influence diagrams) for the evaluation of policy options through the integrations of data, decisions, and model predictions. Here we use a textual analysis for all questions formulated in the Palo Verde workshop. Thus, the analysis is considering all questions for all the goals assembled together.

The text mining functionality of the model provides support for creating *term maps* based on a corpus of a text. In this case the corpus is composed by all workshop questions together. A *term map* is a two-dimensional map in which terms are located in such a way that the distance between two terms can be interpreted as an indication of the relatedness of the terms. In general, the smaller the distance between two terms, the stronger the terms are related to each other. The relatedness of terms is determined based on co-occurrences in documents or in the same text analyzed; this means that two closed nodes (terms) are mentioned closely in the text.

To create a term map based on a corpus of text, the model distinguishes the following steps:

1. *Identification of noun phrases*. The approach that we take is similar to what is reported in papers available in the literature (Van Eck et al., 2010a). We first perform part-of-speech tagging (i.e., identification of verbs, nouns, adjectives, etc.). The Apache OpenNLP toolkit (http://incubator.apache.org/opennlp/) is used for this purpose. We then use a linguistic filter to identify noun phrases. The filter selects all word sequences that consist exclusively of nouns and adjectives and that end with a noun (e.g., *change, basin,* but not *variability of climate* and *highly critical areas).* Finally, we convert plural noun phrases into singular ones.

2. *Selection of the most relevant noun phrases*. The selected noun phrases are referred to as *terms*. The essence of the technique for selecting the most relevant noun phrase is as follows. For each noun phrase, the distribution of (second-order) co-occurrences over all noun phrases is determined. This distribution is compared with the overall distribution of

co-occurrences over noun phrases. The larger the difference between the two distributions (measured using the Kullback-Leibler distance), the higher the relevance of a noun phrase. Intuitively, the idea is that noun phrases with a low relevance (or noun phrases with a general meaning), such as *change, basin,* and *new method* in this case study, have a more or less equal distribution of their (second-order) co-occurrences. On the other hand, noun phrases with a high relevance (or noun phrases with a specific meaning), such as *variability of climate* and *highly critical areas,* have a distribution of their (second-order) co-occurrences that is significantly biased towards certain other noun phrases. Hence, it is assumed that in a co-occurrence network noun phrases with a high relevance are grouped together into clusters. Each cluster may be seen as a topic. The criterion for a noun phrase to be included in the lexicon was that a fragment of the noun phrase (e.g., ``Basin level'') occurs at least three times in the text.

3. *Mapping and clustering of the terms*. We use the unified framework for mapping and clustering defined in Van Eck et al., (2010b), and in Waltman et al., (2010). Mapping and clustering are complementary to each other. Mapping is used to obtain a fairly detailed picture of the structure of a semantic network; while clustering is used to obtain a fairly detailed picture of the clusters of topics in a semantic network. Note that the clusters are determined by a statistical technique and not by an a priori delineation of topics. Naturally, it is hoped that the clustering technique leads to recognizable topics, but it has to be explicitly investigated whether this is actually the case.

4. *Visualization of the mapping and clustering results*. The model can ``zoom'' and scroll on a term map, and it allows term search functionality to support a detailed examination of a term map. Other relevant network variables can be calculated and represented.

Influence Diagram Construction

The direction of each arrow is assessed by the analysis of the sequence of terms in the text. The point of the arrow is directed from each term to the most frequent term in the text that appears after the term considered. The analysis is repeated for each combination of the most important terms (Table 1). The frequency of the repetition of the term ``A'' after the term ``B' in the text (all questions together) is calculated. Thus, the arrow is drawn from A to B. In this way potential casual relationships among factors of the system can be assessed.

Network Complexity as Objective Function

The Network Complexity (NC) is introduced here as a metric to characterize the inferred influenced diagram. NC is used as a metric to monitor the variation of the influenced diagram under changes in the text provided by the stakeholders. Thus, in absence of an objective function defined by the stakeholders – in which the nodes of the influence diagrams are the criteria and the weights are their relative frequency – we measure the stability of the influence diagram with a topological metric that characterize its overall structure; a variation in NC reflects a variation of any objective function. Yet, variations of NC are dictated by variations of stakeholder preferences. This metric is defined as $\mathrm{NC} = \frac{A}{L} = \frac{\sum_{i=1}^{V}\sum_{j=1}^{V} a_{ij}}{\sum_{i=1}^{Z}\sum_{j=1}^{Z} l_{ij}}$ that is the ratio between network connectivity (A is the number of connected nodes where V is the total number of nodes) and length (L is the length of each link that is here defined as the number of words that separate the connected words i,j in the stakeholder text, where Z is the total number of links). NC varies between 0 and 1. Networks with high complexity are characterized by both high node-node connectedness and small node-node separation. This definition of NC is equivalent to the definition of network complexity of Bonchev and Buck (2005). Variations in stakeholder preferences are induced by global sensitivity and uncertainty analyses assuming a uniform distribution with a standard deviation of +- 20% around the average frequency.

Global Sensitivity and Uncertainty Analyses

The goal of the sensitivity analysis is to identify which variables (or input factors) in the influence diagram have the highest effect on NC, thus to measure the relative importance of the variables that constitute any potential objective function that depends on NC. For the global sensitivity analysis we adopted the Morris method (Morris, 1991) for screening variable importance by varying all the variables simultaneously. The Morris method is composed of individually randomized variable designed models. Each variable may assume a discrete number of values that are selected randomly within an allocated range of variation. Then, the Morris method calculates the importance of each variable and the interaction of each variable with all the others for NC. The former is the mean of the elementary effect μ^* (i.e., the local derivative of output NC, with respect to input factors for values sampled at each level of factor Xi in the k-dimensional inputs space), and the latter is the variation of the mean elementary effect, σ. The elementary effect di(x) for factor Xi is defined as

$$d_i(x) \ = \ \frac{y(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, x_k) - y(x)}{\Delta}$$

where xi + Δ is the perturbed value of xi; k is the number of factors, i = 1, ..., k. di(x) is considering the ratio between the variation of the output, y = NC, and the variation of the input factors, xi. The resulting probability distribution of the elementary effects of factor Xi is characterized with its mean μ^* (absolute values) and standard deviation σ. Although elementary effects are local measures, the method, is considered global, as the final measure μ^* is obtained by averaging the elementary effects which eliminates the need to consider the specific points at which they are computed (Saltelli et al., 2005). The higher μ^* the higher the absolute importance of each variable for NC. The number of simulations, N, required to perform the Morris analysis is given as $N = r(k + 1)$, where r is the sampling size for each trajectory ($r = 10$ produces satisfactory results (Saltelli et al., 2005)). The variables with μ^* values close to zero can be considered as negligible ones. The variables with the largest value of μ^* are the most important variables. However, the value of this measure for a given variable does not provide any quantitative information on its own and needs to be interpreted qualitatively, i.e. relatively to other variables values. The meaning of σ can be interpreted as follows: if the value for σ is high for a variable, Xi, the elementary effects relative to this variable are implied to be substantially different from each other. In other words, the choice of the point in the input space at which an elementary effect is calculated strongly affects its value. Conversely, a low σ value for a variable implies that the values for the elementary effects are relatively consistent, and that the effect is almost independent of the values for the other input variables (i.e. no interaction). The uncertainty analysis is performed by assigning a probability distribution to each variable. Thus, the calculation of NC is repeated via Monte Carlo simulations of the textual analysis model for sets of values of each variable according to their distribution. In the uncertainty analysis the probability of occurrence of each variable value is related to the assigned distribution.

Results and Discussion

The first and easiest analysis to be performed is the analysis of the frequency distribution of the choices made by stakeholders during the workshop. Figure 2A shows that academics have a predominant preference toward climate behavior (topic 1), human impacts on natural systems

(4), impacts on water system behavior (6), water sustainability (11), and institutions (14). NGOs and other private organizations have a very different set of preferences; namely, these preferences are about use/decision processes (8), law and policy (15), and water use (17). However NGOs consider important also the topics 4, 10, 11, 13 and 16 as academics.

As for the time component of the ecosystem management, in Figure 2B it appears that NGOs and private organizations strongly believe in investing more analysis and plans for the future of the TBPV ecosystem (time class 3) rather than investing in analysis about the past. Academics consider the present situation more important than the future, even though the difference is minimal. Academics believe more than NGOs in analysis about the past of the TBPV ecosystem. These preferences about the future of the basin can prioritize research and development activities, and increase efforts toward solutions with different time horizons in terms of their potential effects. Overall, from the workshop questions it seems there is an agreement toward a strategic planning for the future.

The term map derived from textual analysis (Methods) is shown in Figure 3. The total terms are 317 and after the minimum threshold for the occurrences (equal to 3) the total terms are 29. Table 3 shows the occurrence of the 29 terms in the text analyzed (all questions together) and their relevance. Low relevance is for the terms with general meaning and viceversa. Thus, relevance should not be confused with absolute importance of the word in the problem at hand. The overall importance of each term that can is a factor of the environmental problem considered is captured by the occurrence of each term.

Terms that are located close to each other in the map often occur together in the same text, while terms that are located far away from each other do not or almost not occur together. In general, terms in the center of the map co-occur with many different terms and are therefore related to various topics. In contrast, terms at the edges of the map tend to co-occur only with a small number of other terms. Terms at the edges therefore often belong to relatively isolated fields. The color of a term indicates the cluster to which the term has been assigned, and the size of a term indicates the frequency with which the term occurs in the editorials. The color of an item is determined by the score of the item, where by default colors range from blue (score of 0) to green (score of 1) to red (score of 2). The size of a cluster in the map is influenced by many factors (e.g., the number of terms in the cluster, the frequency of occurrence of the terms and the strength with which the terms are related to each other) and therefore does not have a straightforward interpretation. The density of an area in the map is determined by the number of terms in the area and by the frequency with which the terms occur in the text.

Of great importance is the potential influence diagram show in Figure 4. The influence diagram is built from the term network in Figure 3 by considering the occurrence and frequency of pairs of terms in the text. The width of a link in the influence diagram is proportional to the frequency of the pair of terms that are connected. The distribution of nodes (terms) is random, so the length of links has no meaning. The direction of the arrow is related to the sequential appearance of terms in the text. In this case, the inferred causal relationships are related to all stakeholders. In fact, we investigated the text of answers of all stakeholders for the questions formulated during the workshop. Hence, the semantic network in Figure 4 can be used as an influence diagram for preliminary modeling of the TBPV ecosystem problem. This can be done after assigning the marginal and conditional probability distribution functions.

Conclusions

The consideration of stakeholder preferences, objectives, and mental models is a worthwhile effort for the analysis and management of complex ecosystems. We show that by realizing workshops of stakeholders it is possible to use workshop material to infer stakeholder preferences and their knowledge about the ecosystem for which different management strategies are evaluated. Certainly mental modeling is a costly effort but the payoff of this effort is also related to engage stakeholder since the very beginning of the planning process that makes easier future communication of results, request of feedbacks and/or more data, and building community capacity. Community capacity is also education of stakeholders to unknown problem and trade-offs among ecosystem factors and needs. Moreover, mental modeling and textual analysis of workshop products facilitate model constructions and the integration of models of different research groups. We emphasize that ecosystem and society should coexist and the proposed direct and indirect mental modeling effort is a preliminary tool to enhance this linkage. In the Costa Rica case study we show that academic stakeholders are more focused on the current and past dynamics of natural and human processes, while NGO stakeholders are focused on the future socio-legal aspects of ecosystem management. Mental modeling is a way to unify these parts which need to be address together necessarily for the sustainability of ecosystems.

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Table Captions

Table 1. Mapping of all questions formulated in the workshop. Terms are listed with their occurrence and relevance. Low and high relevance terms are noun phrases with a general and with a specific meaning, respectively. The occurrence is related to the frequency of terms.

Figure Captions

Figure 1. Tempisque-Bebedero-Palo Verde ecosystem.

Figure 2. Stakeholder preferences for topic and time categories related to the workshop questions.

Figure 3. Inferred mental model from textual analysis. The vidualized network does not take in account the sequence of words in workshop's questions. Node distance and color are related to the relevance and occurrence in Table 1, respectively.

Figure 4. Probabilistic decision network for the TBPV ecosystem problem. The influence diagram is assessed by considering the terms/factors of the TBPV ecosystem workshop and the

order in which they occur in the text. In general, the smaller the distance between two terms, the stronger the terms are related to each other.

Figure 5. Mental models of academics and NGOs. The influence diagram is assessed by considering the terms/factors of the TBPV for the two different group of stakehoders: NGO and private, and academics.

Figure 6. Network complexity and global sensitivity and uncertainty analyses. Network Complexity (NC) (upper plot) is a metric to characterize the inferred influenced diagram and to monitor the variation of such diagram under perturbations in socio-ecological factors provided by stakeholders. Perturbation effects are assessed by global sensitivity and uncertainty analyses (GSUA) that reveal factor importance and interaction of ecosystem factors for NC as output variable (bottom plot).

Term	Occurrences	Relevance
basin level	3	2.14
prediction	4	2.09
current pattern	3	1.81
institution	7	1.62
local scale	3	1.56
sustainability	3	1.56
approach	4	1.47
enso	4	1.43
large scale atmospheric driver	4	1.44
water use	6	1.34
phase	6	1.25
local precipitation	6	1.14
future climate scenario	4	1.01
statistical relationship	4	0.95
asadas	3	0.83
watershed	4	0.79
tempisque basin	6	0.60
pvw	7	0.56
water	5	0.52
hydrology	3	0.48
impact	6	0.46
groundwater	3	0.41
climate change	8	0.33
change	15	0.28

Table 1:

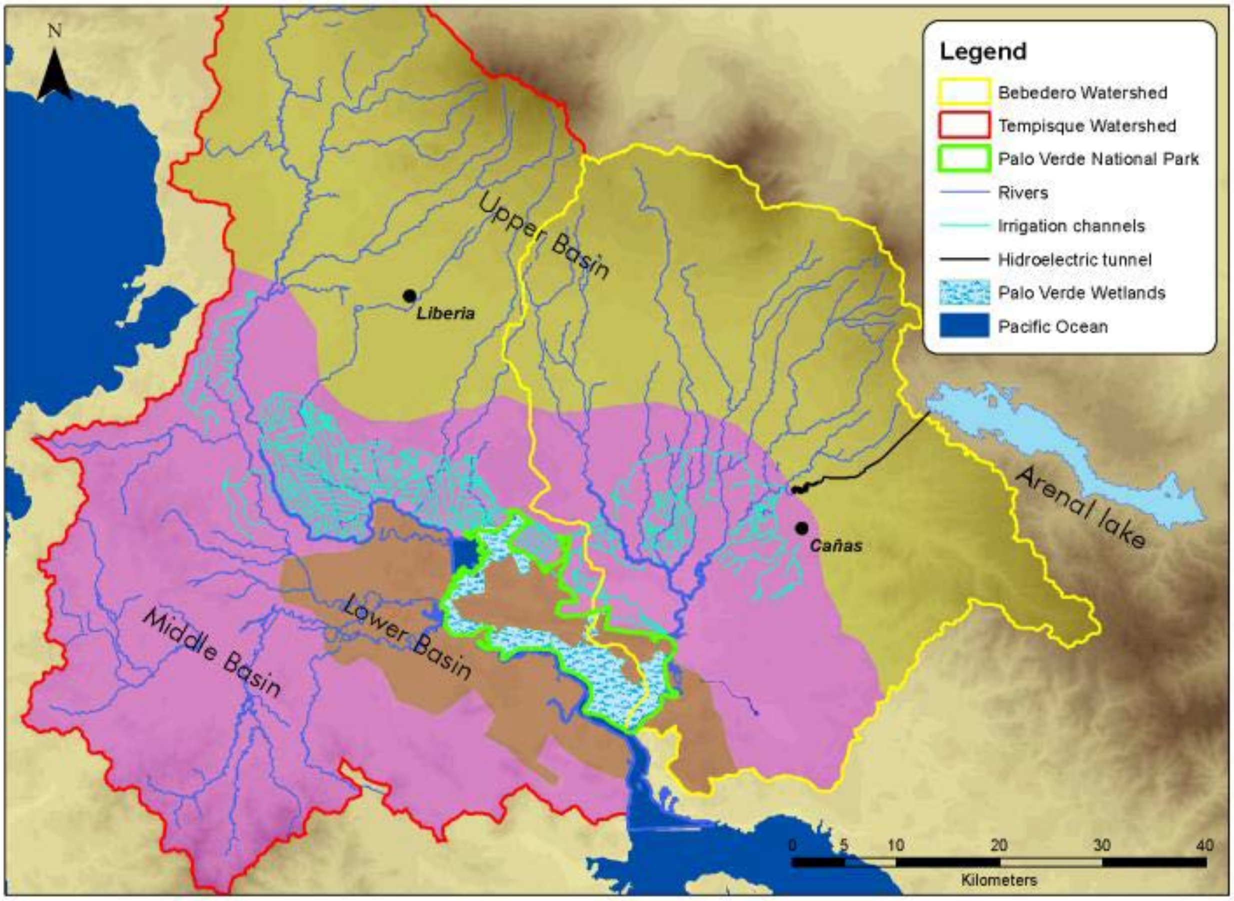

N
Legend
Bebedero Watershed
Tempisque Watershed
Palo Verde National Park
Rivers
Irrigation channels
Hidroelectric tunnel
Palo Verde Wetlands
Pacific Ocean
Upper Basin
Liberia
Arenal lake
Cañas
Middle Basin
Lower Basin
0 5 10 20 30 40
Kilometers

Figure 1.

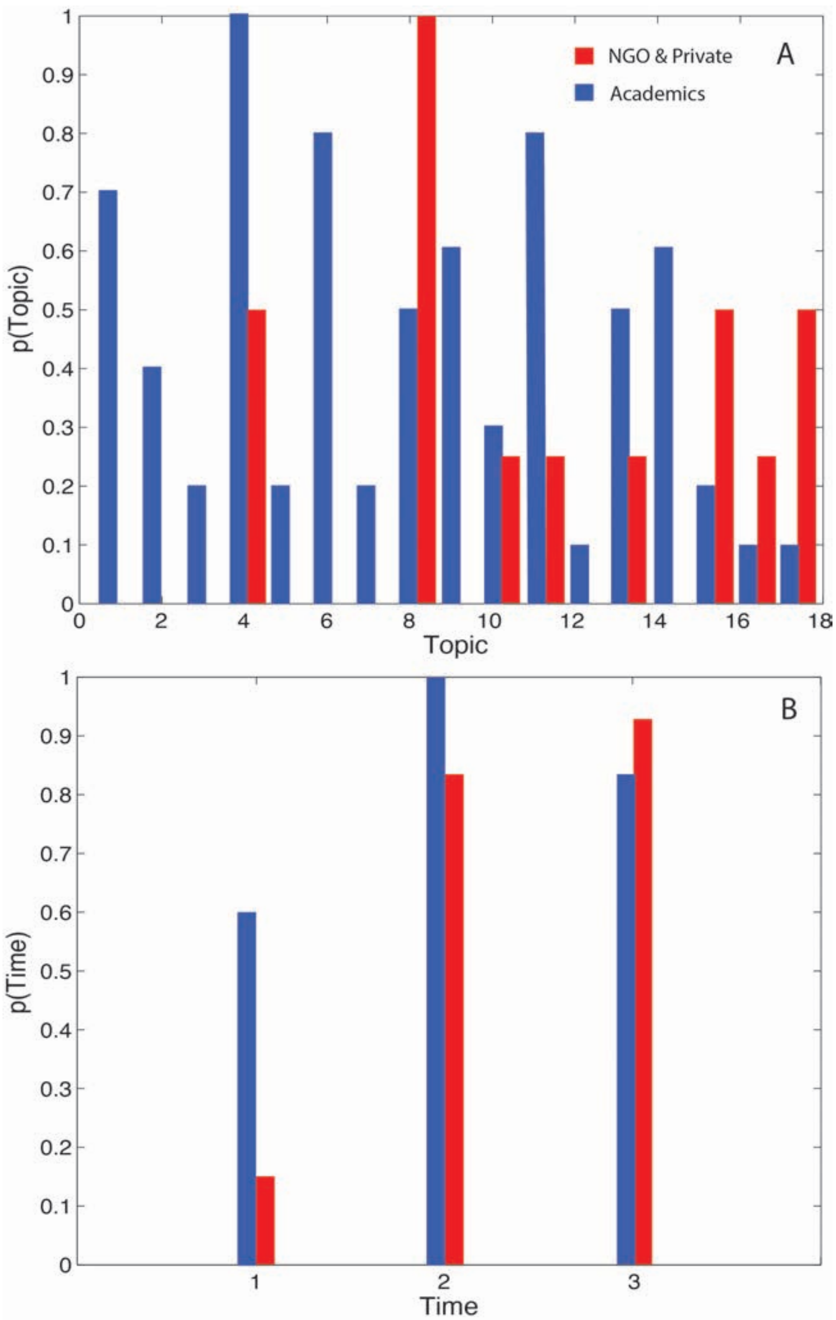
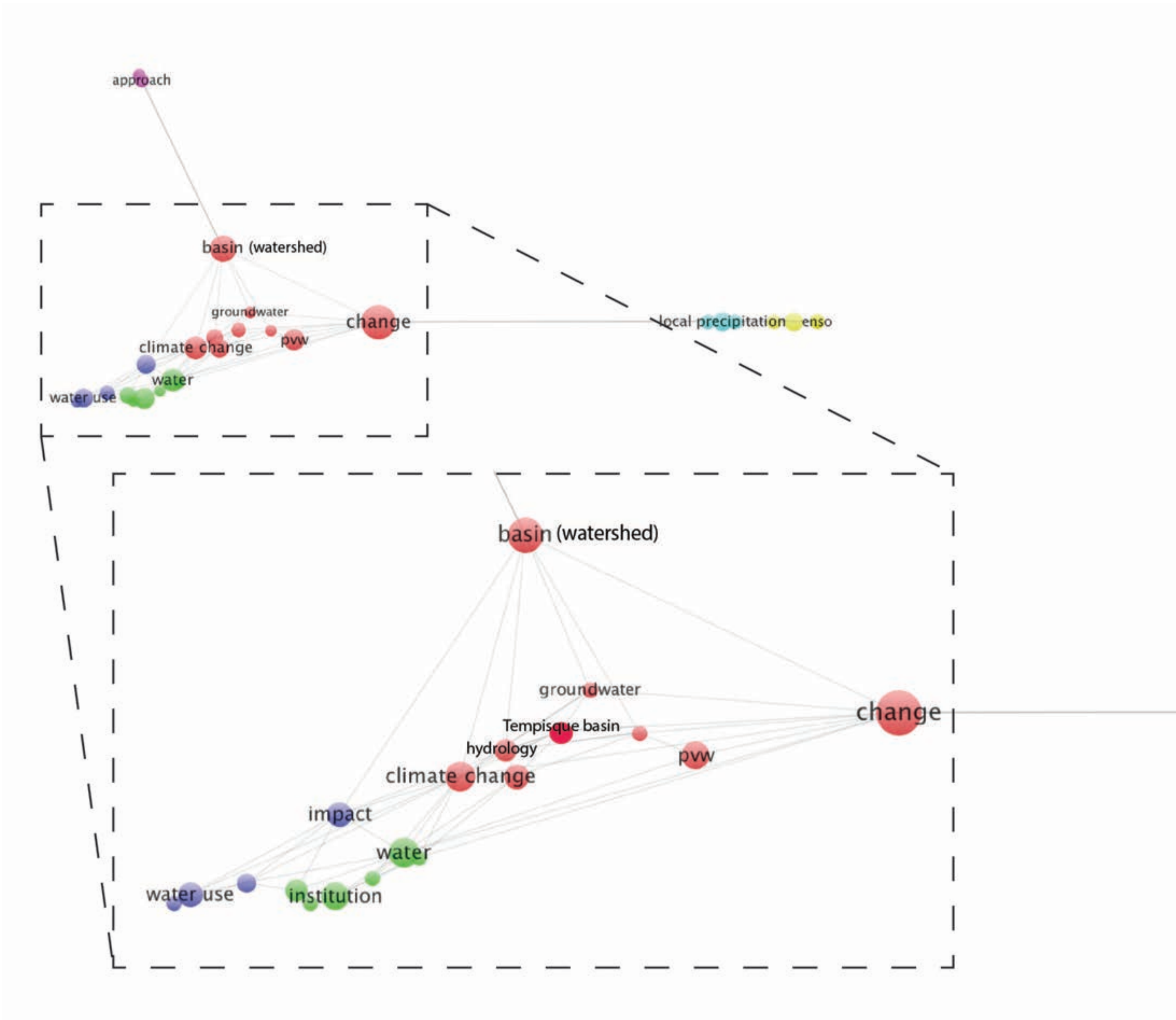


Figure 2.



approach
basin (watershed)
groundwater
change
local precipitation
enso
climate change
pvw
water
water use
basin (watershed)
groundwater
Tempisque basin
change
hydrology
pvw
climate change
impact
water
water use
institution

Figure 3.

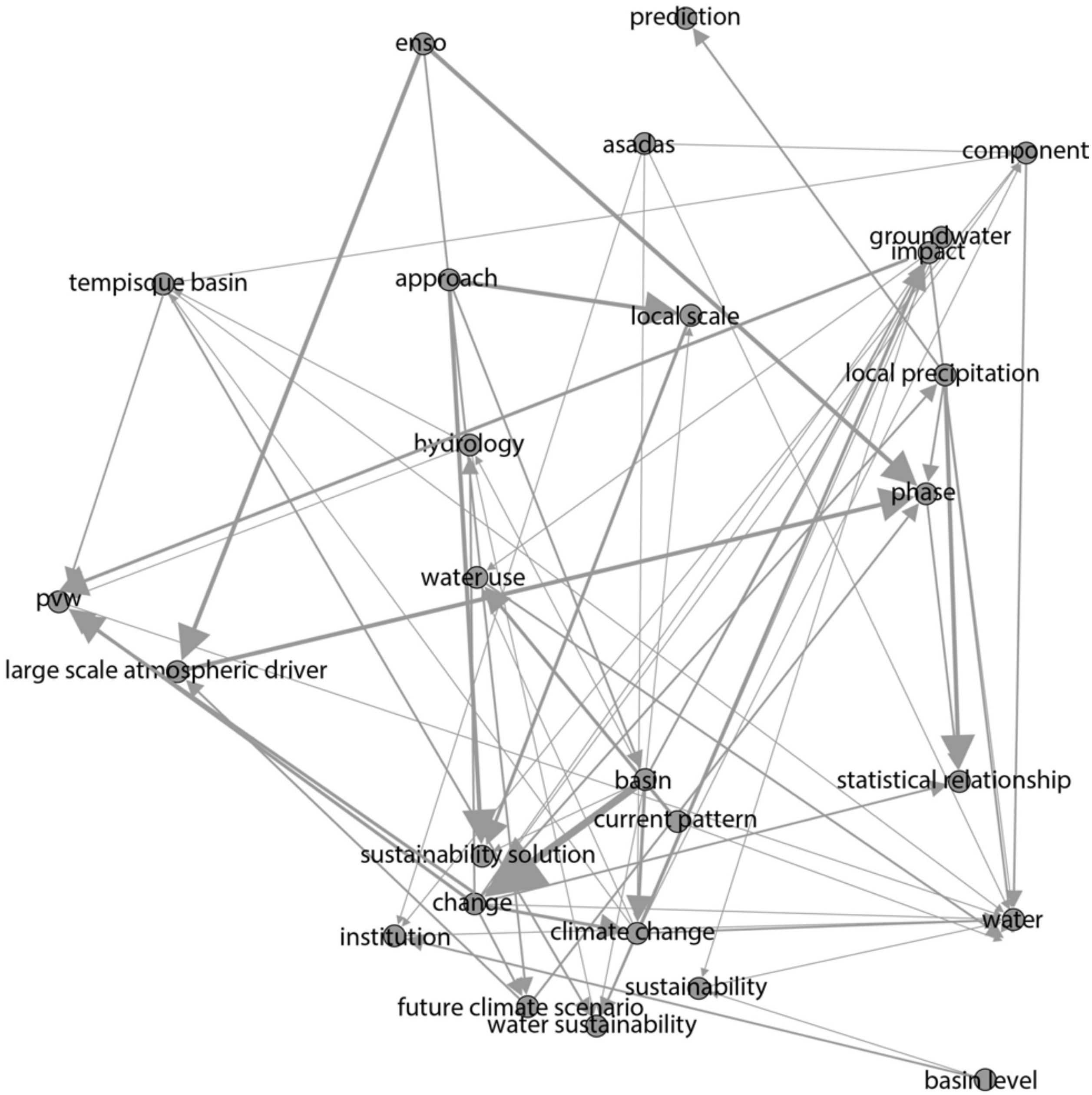

prediction
enso
asadas
component
groundwater
impact
tempisque basin
approach
local scale
local precipitation
hydrology
phase
water use
pvw
large scale atmospheric driver
basin
statistical relationship
current pattern
sustainability solution
change
water
institution
climate change
sustainability
future climate scenario
water sustainability
basin level

Figure 4.

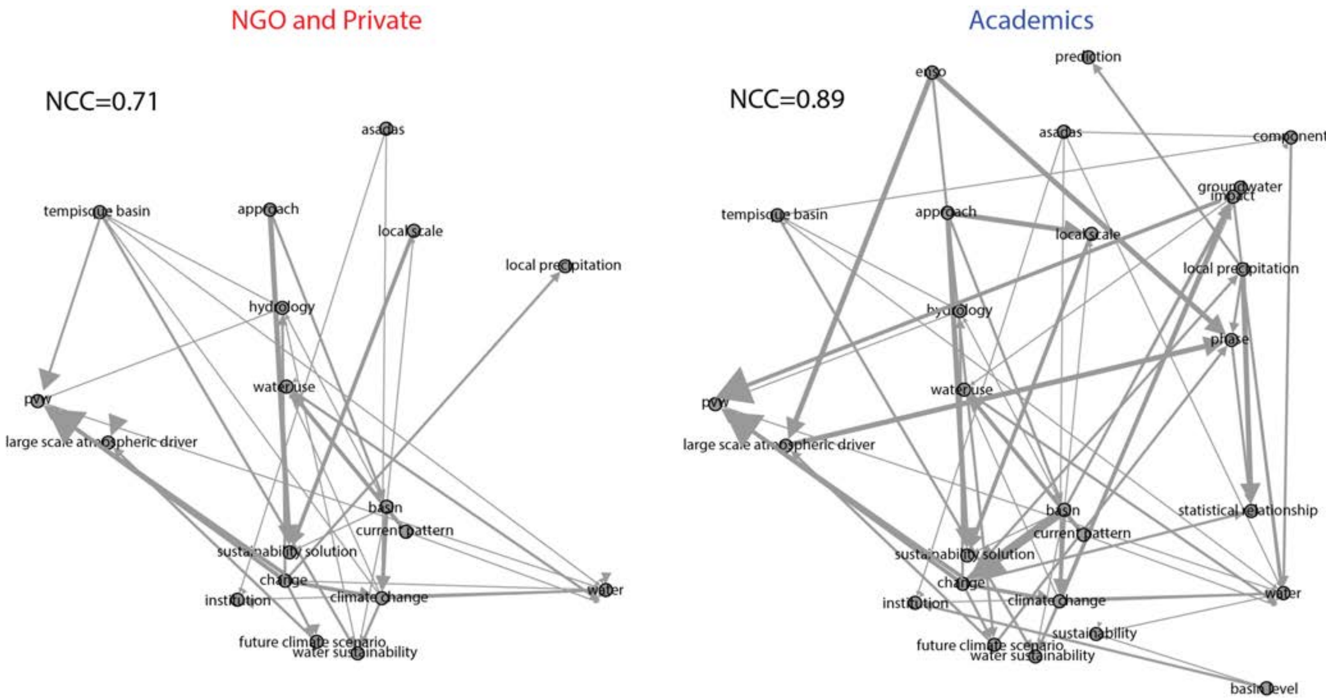
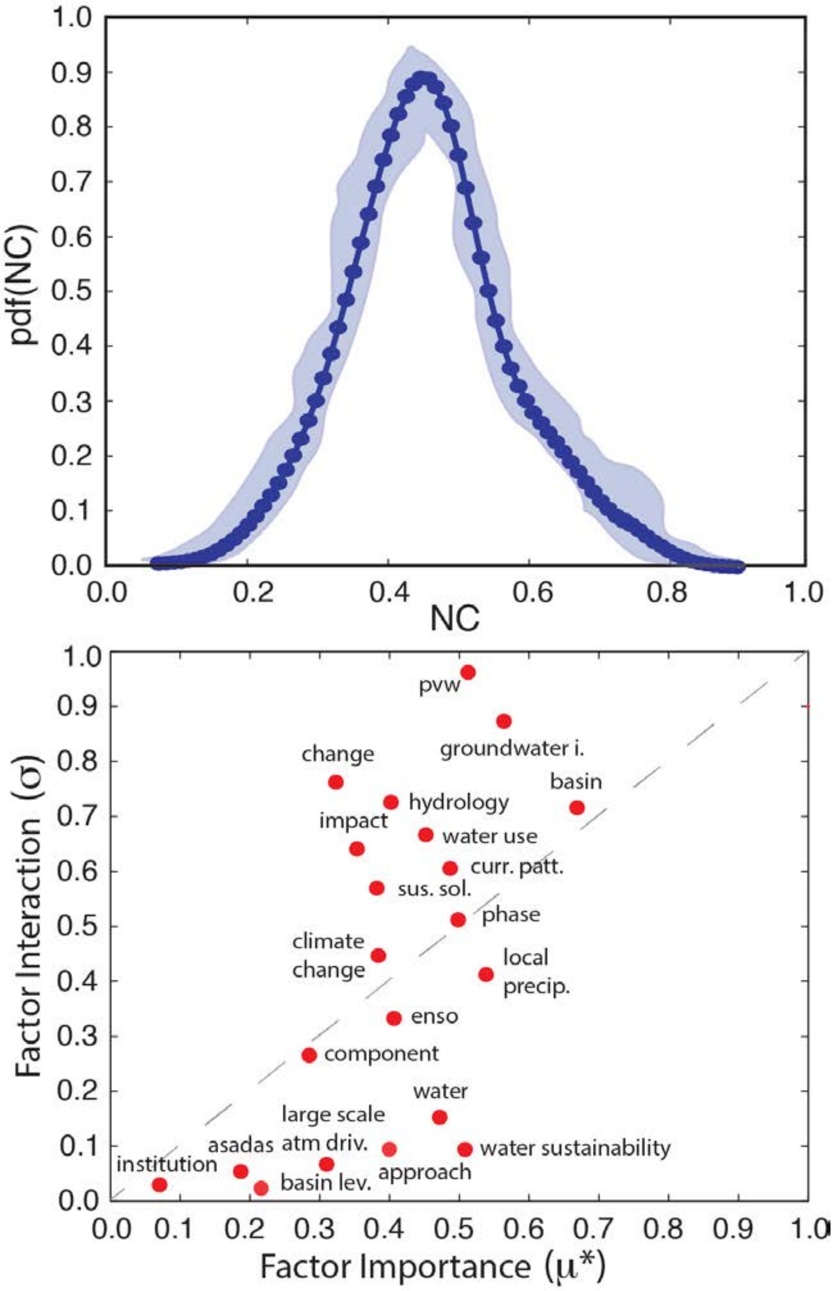

NGO and Private
NCC=0.71
asadas
tempisque basin
approach
local scale
local precipitation
hydrology
water use
pvw
large scale atmospheric driver
basin
current pattern
sustainability solution
change
institution
climate change
water
future climate scenario
water sustainability
Academics
NCC=0.89
enso
prediction
asadas
component
groundwater
impact
tempisque basin
approach
local scale
local precipitation
hydrology
phase
water use
pvw
large scale atmospheric driver
statistical relationship
basin
current pattern
sustainability solution
change
institution
climate change
water
sustainability
future climate scenario
water sustainability
basin level

Figure 5.



pdf(NC)
NC
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Factor Interaction (σ)
Factor Importance (μ*)
pvw
groundwater i.
change
basin
hydrology
impact
water use
curr. patt.
sus. sol.
phase
climate
change
local
precip.
enso
component
water
large scale
atm driv.
asadas
water sustainability
institution
approach
basin lev.

Figure 6.