Collaborative Research
Catalyzing New International Collaborations: Interdisciplinary workgroup on water sustainability in the Tempisque Basin, NW Costa Rica

End-of-Year One Report

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List of Abbreviations Used in this Report

ARCOSA	Centro de Generación Arenal Corobicí Sandillal (*Hydroelectric power generation center run by ICE*)
ASU	Arizona State University
CEDARENA	Centro de Derecho Ambiental y de los Recursos Naturales (*Center for Environmental and Natural Resource Law*)
CIDECAT	Comisión de Implementación y Desarrollo en la Cuenca Arenal Tempisque (*Commission for Implementation and Development in the Arenal-Tempisque Watershed*)
CIMAR - UCR	Centro de Investigación en Ciencias del Mar y Limnología – Universidad de Costa Rica (*Research Center in Marine and Limnological Sciences*)
CR	Costa Rica
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
ICE	Instituto Costarricense de Electricidad (*Costa Rican Institute of Electricity*)
ICOMVIS-UNA	Instituto Internacional en Conservación y Manejo de Vida Silvestre – Universidad Nacional (*International Institute for Wildlife Conservation and Management*)
IMN	Instituto Meteorológico de Costa Rica (*Costa Rican Meteorological Institute*)
INEC	Instituto Nacional de Estadística y Censos (*National Statistics and Census Institute*)
ITCR	Instituto Tecnológico de Costa Rica (*Technological Institute of Costa Rica*)
IRET – UNA	Instituto Regional de Estudios en Sustancias Tóxicas – Universidad Nacional (*Institute for Studies on Toxic Substances***)**
MINAET	Ministerio del Ambiente, Energía y Telecomunicaciones (*Ministry of Environment, Energy and Telecommunications)*
OTS	Organization for Tropical Studies
ProDUS-UCR	Programa de Investigación en Desarrollo Urbano Sostenible – Universidad de Costa Rica (*Research Program in Sustainable Urban Development)*
PVW	Palo Verde Wetlands (National Park)
PROGAI-UCR	Programa Institucional de Gestion Ambiental Integral – Universidad. de Costa Rica (*Institutional Program for Integrated Environmental Management)*)
SENARA	Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento (*National Groundwater, Irrigation and Drainage Service)*
UCR	Universidad de Costa Rica (*Universityof Costa Rica*)
UF	University of Florida
UNA	Universidad Nacional (*National University*)
US	United States of America
WI	UF Water Institute

1. Introduction

The Tempisque Basin in NW Costa Rica, focal site for this CNIC grant, represents a compelling place for studying water sustainability and climate interactions with wide application to many other regions. It is an excellent proxy site for Pacific Mesoamerica since it contains the basic land and water challenges of the region, including drier and hotter future climate scenarios.

This 5404 Km^2 basin extends from the Tilarán and Guanacaste Mountains to the Gulf of Nicoya, essentially from summit to sea (Figure 1). On the west side, the Basin ends in the Serranía de Nicoya, which separates it hydrologically from the Nicoya Coastal watershed. The Tempisque and its principal tributaries, the Bebedero, Cañas and Liberia rivers, flow into the northern Gulf of Nicoya, Pacific Ocean. The lower end of the basin forms the Palo Verde marsh, an internationally recognized Ramsar site, protected by the Palo Verde National Park and the International Convention on Wetlands (Ramsar, Iran, 1971, http://ramsar.org).

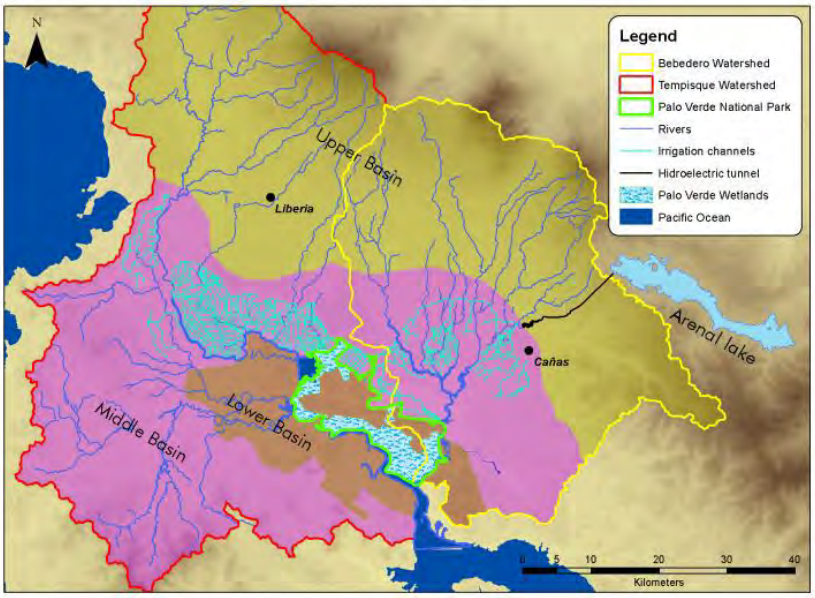


Figure 1.Map with upper/mid/lower Tempisque Basin

Originally a cattle ranching dry forest and savannah landscape, the basin has experienced a significant transformation in the past 40 years. With funding from the Inter-American Development Bank, the Costa Rican Government launched, in the mid-1970s, a project to provide land and agricultural options to low-income Costa Ricans. This infrastructure project collects water from the Caribbean versant and dumps 30-65 m3/s of water via canals, from Lake Arenal (Caribbean basin) into the Tempisque´s mid and lower basin, irrigating 44,000 Hectares of seasonally dry land for agriculture (Jimenez et al. 2001). In spite of its original social intent, this large-scale irrigation project (Figure 1) currently benefits mostly owners of extensive rice and sugarcane fields, and Tilapia fish farms. In addition, it is causing an unintended but possible significant degradation of the natural ecosystems that abut the productive lands.

The irrigation channels collect, as they pass through the agricultural plots and fish farms, pesticides, excess nutrients, hormones, antibiotics, parasites and feces, delivering them eventually into rivers and wetlands. 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 as they get converted from wetland to other land uses (Daniels and Cumming 2008). Because of its location within the watershed, the Palo Verde marsh is suffering from severe habitat modification, manifested by invasion of dense cattail (*Typha dominguensis*) stands, which are thought to be responding to hydroperiod modification and excess phosphorus loading from upstream agriculture, and by a concomitant loss of the waterfowl that earned the wetland its Ramsar status. The lower basin therefore integrates the good" and "bad" land use practices of the whole basin (Pringle 2001).

The water eventually reaches the Gulf of Nicoya, where further impacts occur. The Gulf of Nicoya harbors 75% of the artisanal fisheries of the country, representing 25% of the country´s fish landing. The most affected area is the estuary and upper part of the gulf that holds the nurseries for most of the important fish populations of the gulf. Four thousand artisanal fishermen families depend on this resource. Water pollution is already reducing the fish populations of 140 species (Jorge Jiménez, pers. comm.).

In addition to water contamination, unmanaged demands and mismanagement of the resource throughout Costa Rica are affecting water availability and sustainable use. This mostly agrarian basin benefits little from the significant international tourism industry that characterizes Costa Rica, because the tourism developments are concentrated on the beaches on the other side of the Coastal range. Yet, rather than contribute to the local economy, tourism poses an additional strain due to their high water demand.

Water, a critical resource for human activities and natural ecosystems in this basin, is subject to the pressures of external factors, and at the same time drives internal processes either facilitating or negatively affecting the different components of this system. The complexity of the water-mediated interactions in the Tempisque is described in the preliminary conceptual model shown in Figure 2.

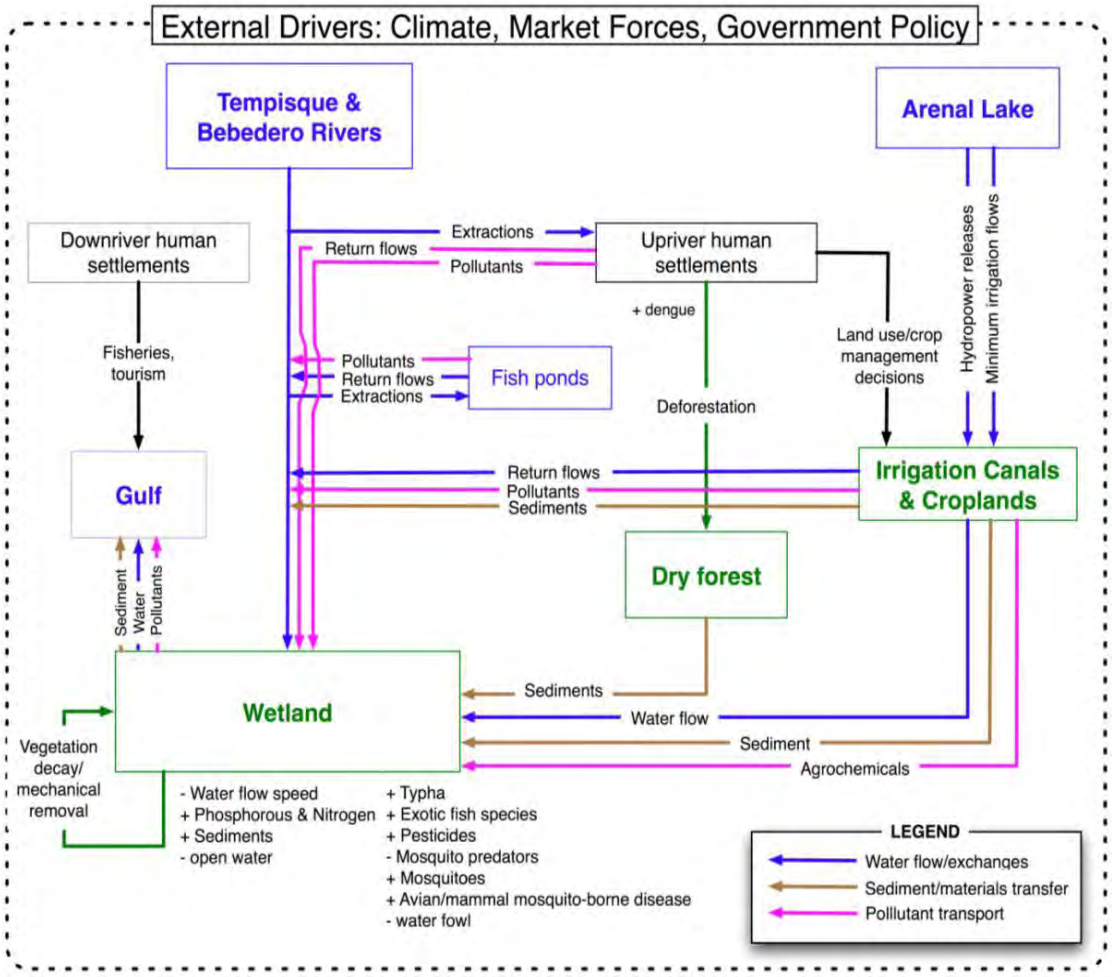


Figure 2. Preliminary conceptual model of the Tempisque Basin.

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, especially the anticipated drier and hotter conditions. 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 (Magrin et al. 2007). These results are supported by downscaled regional climate models (Anderson et al. 2008). Unless trends in greenhouse gas emissions change, average temperatures are expected to increase 2- 6 °C in the region, possibly with more extreme hydro-climatological events, particularly drought periods. Wet season precipitation is expected to decrease as much as 27% with associated soil moisture deficits 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 (Karlmalkar et al.2008). 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 therefore appear to be consistent with long-term global climate scenarios, and portend severe impacts on agriculture, biodiversity, and land use (Poveda et al. 2006; Waylen et al. 1996 a,b).

Landowners and government ministries are aware of the climate predictions, and are already working on strategies to adapt. Many of the former intend to replace rice with sugarcane and pineapple that require less water, while the latter recently announced plans to build more irrigation channels to respond to a growing demand from agriculture and the burgeoning tourism industry (República de Costa Rica 2010). These initiatives are designed to address individual challenges, but do not adopt an integrated view of all the issues, and are therefore likely to produce unintended consequences and be ineffective for the sustainability of the basin. For example, the government's plan to provide more water for irrigation may discourage landowners from adopting more water-conserving crops and in turn increase pollutant load inputs into the endangered wetland ecosystems.

Our **long-term goals** (to be achieved over the next 5-10 years) are to understand the causes and consequences of current water availability and use in NW Costa Rica; to forecast how water allocations will change as temperature rises, rainfall diminishes and land use changes; and identify what adaptive governance measures may be taken to ensure regional sustainability while protecting endangered ecological sites of international importance. The **specific goal of this CNIC grant** was to consolidate an international interdisciplinary inter-institutional group that would pursue the long-term goal of the project. The initial participants of this team belong to several US and Costa Rican institutions, namely, the University of Florida's *Water Institute* (WI), Arizona State University's *Global Institute of Sustainability*, the Duke-based *Organization for Tropical Studies* (OTS), Universidad de Costa Rica (UCR), Instituto Tecnológico de Costa Rica (ITCR), and Universidad Nacional de Costa Rica (UNA). This team addresses the intersection of land and water use in the context of climate change through the integrated disciplinary perspectives of ecology, hydrology, climatology, economics, law, and rural sociology. Funds were requested primarily to consolidate this large group through two coordination and exchange meetings and to conduct preliminary data analysis and synthesis to support the workgroup meetings and proposal development activities.

2. Catalyzing New International Collaborations

2.1 Proposal goals and specific objectives

The objectives of this grant were to: (a) bring together an international interdisciplinary team, and (b) consolidate and organize the team, to tackle the long-term goals described above. We proposed to accomplish this in three steps:

1. Hold a coordinating workshop of a core group of US and Costa Rican researchers to define how to collect and integrate available but fragmented information, revise a preliminary conceptual model, and agree on tasks and working groups in preparation for a second and larger international workshop.
2. Prepare a systems analysis model (developed as a result of the first workshop and refined conceptual model) to be used as a framework of discussion during the second workshop.
3. Organize an international workshop to include all Principal Investigators (PIs) and Senior Personnel (SPs) from US and Costa Rica named in the CNIC proposal, as well as invited staff from Costa Rican institutions with jurisdiction and expertise in the region.

The purpose of the second workshop was to formulate and refine compelling research questions and hypotheses on water sustainability and climate for ensuing research collaborative proposals, define the teams that will prepare these proposals, identify the funding sources for which these proposals will be prepared, and agree on the mechanisms for communication and integration among the different working teams.

In this international collaborative initiative, various institutions and countries brought different strengths to the table. UF researchers contribute their expertise on agro-ecological systems, hydrology, geography, climate change analysis, and social, economic and political drivers. OTS provides 40 years of accumulated ecological research and wetland management in the area, as well as being the liaison between US and CR institutions. Costa Rican partners contributed with hydrology and complementary aspects such as ecology, ecotoxicology and limnology. ASU faculty brought expertise in sustainability and wetland management, as well as expertise in managing large interdisciplinary groups.

2.2 Participants

The group of participants in this project expanded over time, as we identified potential for new academic collaborations, as well as strategic alliances with Costa Rican Institutions. This group now includes more than 50 collaborators, from US and Costa Rican universities and Costa Rican organizations and institutions. A detailed table is presented in Appendix 1, indicating

participants' affiliation, role in project and field of expertise. Individual participation in the various workshops and meetings held during this past year are shown in Appendix 2.

3. Activities

3.1. Preparatory activities.

In preparation for the meetings and discussions, we established a communication platform, conducted a series of informational webinars, compiled all available literature, and developed a preliminary version of a QnD model.

3.1.1 Communication strategy

We established a communication mechanism that ensured quick and reliable exchange of information among collaborators. This involved the creation of a web-based exchange facility (CUAHSI web sharing site) and a webinar series. We also initiated an intense search for bibliography and data available on this region.

CUAHSI web sharing site

We created a site for the Tempisque Basin Planning Grant in CUAHSI (Consortium of Universities for the Advancement of Hydrologic Science, Inc) https://cuahsi.centraldesktop.com/tempisquebasinplanninggrant/ . This site is password protected and allows all collaborators to freely access any pertinent information regarding the project, as well as upload any contributions. It is managed by Kathleen McKee, the project coordinator from the UF Water Institute (WI).

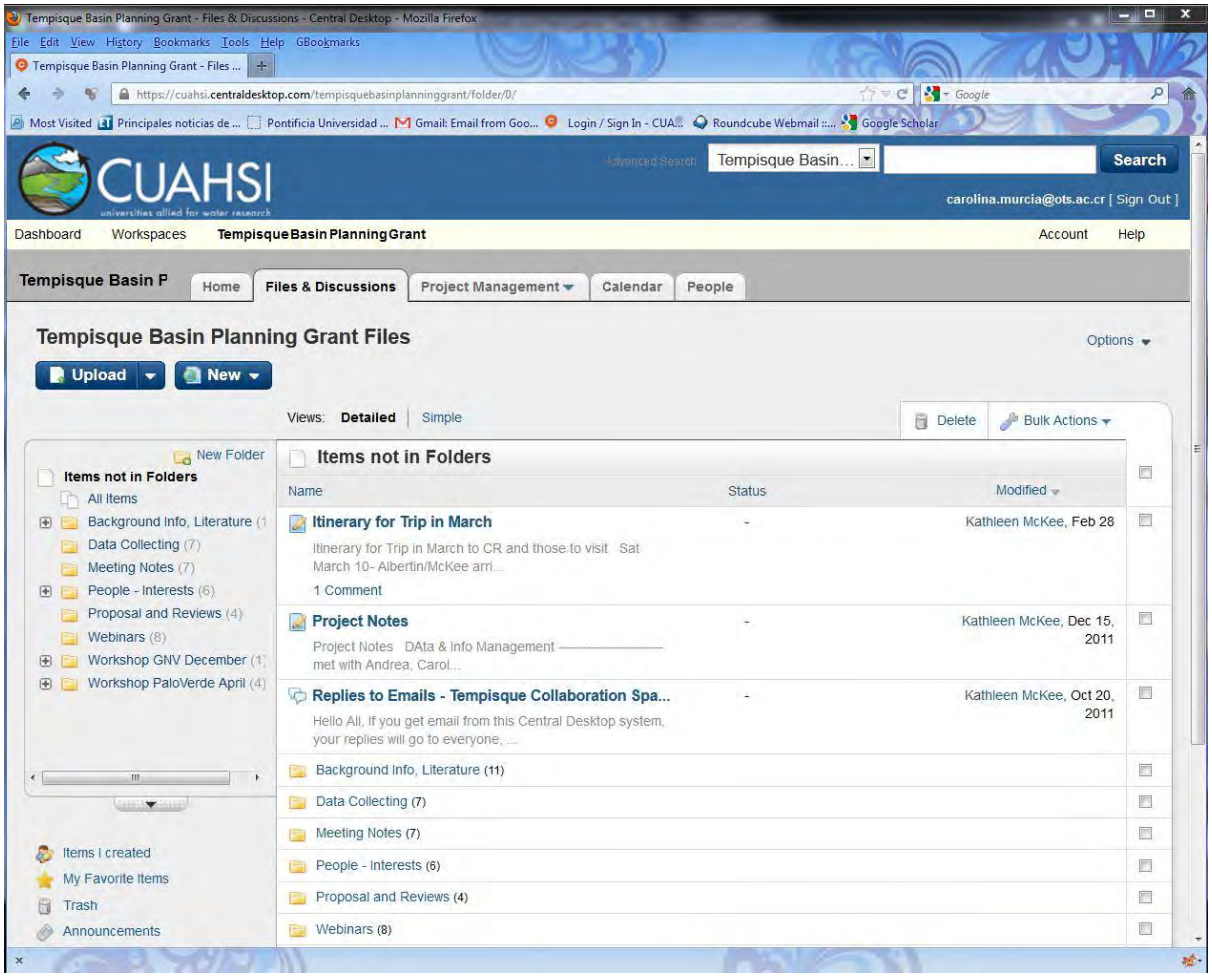


Figure 3. Screenshot of Tempisque Planning Grant collaborative workspace on CUAHSI

Webinars to establish common ground and introduce research teams

The WI project coordinator, organized a series of webinars (seven in total, four of which were broadcast before the December 1 workshop). The primary objectives of the webinars were to introduce the management challenges faced in Tempisque/Bebedero Basins to those not familiar with the region, and to provide researchers an opportunity to present aspects of their field of expertise to other team members. All webinars were recorded and archived in the CUAHSI web site and are available for public viewing. Anyone interested may submit a request to the WI. Webinars presented are summarized in Table 1.

Table 1. Webinars presented in 2011 and 2012.

Date	Webinar Title	Presenter
10/11/11	General introduction to the Tempisque and Bebedero watersheds: challenges and opportunities	Carolina Murcia (OTS)
10/18/11	Sustainability science research framework, and stakeholder mapping	Arnim Wiek, Dan Childers, Ben Warner and Chris Kuzdas (ASU)
11/04/11	Mean, extremes, and variability: Climate analysis and scenario generation for Central America at NASA GISS / Columbia University	Alex Ruane and Jonathan Winter (Columbia University, NASA)
11/17/11	QnD/GSA/UA modeling framework	Greg Kiker, Rafael Muñoz-Carpena and Oscar Perez-Ovilla (UF)
02/28/12	Public-Private Partnerships in Water Infrastructure Development: Response and Resistance in Sardinal, Costa Rica	Franklin Paniagua, Gaby Stocks (UF)
03/22/12	An overview of the Land Use Conflict Identification Strategy (LUCIS) model, and how it can be used to assist with land use planning in the Tempisque Basin, Costa Rica	Peggy Carr and Tom Hoctor (UF Urban and Regional Planning)
04/10/12	Institutional and Legal Framework for Water Management in the Tempisque River Watershed, Costa Rica	Franklin Paniagua & Joanna Reilly-Brown (UF SNRE and UF Law)

3.1.2 Data and bibliography compilation and archival

All scientific and grey literature written on the Tempisque/Bebedero Basin, as well as all available georeferenced data, including meteorological and hydrological data sets were compiled by the UF Post-Doctoral fellows and Kathleen McKee (UF WI). A description of the data compiled to date is summarized Table 2.

Literature was obtained from the OTS library which had a significant amount of material, including grey literature, contributions from all participants, on-line searches, and direct requests to Costa Rican institutions. A group was created in Mendeley Reference Manager (Tempisque Basin Project) to which collaborators were invited, giving full access to PDFs of all documents collected. Several datasets were obtained from OTS in Costa Rica, which has had a long-term presence in this region, as well as project from project collaborators. The majority of the data has been archived on an FTP website of the UF Water Institute. To obtain data (including GIS), requests have to be made directly to Kathleen McKee (WI).

Table 2. Literature and data collected to date for the project.

Data Type	Description	Location	Access
Literature	More than 130 journal articles, agency reports, theses and dissertations concerning the Tempisque/Bebedero River Basins & Gulf of Nicoya	Tempisque Basin Project Group in Mendeley Reference Manager	Private group for project members due to copyright restrictions
Meteorological Data Tempisque Basin	Monthly mean precipitation data from 86 stations in the Tempisque Basin and surrounding areas; data collected between 1966 and 1993 (varies by station). Obtained from IMN by Peter Waylen	UF Water Institute FTP site	Contact K. McKee (UF Water Institute)
Meteorological Data Palo Verde Biological Station (OTS)	Daily meteorological data for the Palo Verde Biological Station since 1997	OTS website and UF Water Institute FTP site	http://www.ots.ac.cr/meteoro/default.php?pestacion=1
Flow data ARCOSA Hydroelectric Complex	Daily flow data from 2002 to 2012 for the irrigation canals in the Arenal Tempisque irrigation district; flow depends on power generation in ARCOSA hydroelectric complex (ICE). Data provided by SENARA staff who obtained it from ICE.	UF Water Institute FTP site	Contact K. McKee (UF Water Institute)
Flow data Tempisque River	Daily hydrological data from 1980 to 1985 from the La Guardia gauging station (the only one on the Tempisque River). Data provided by Julio Calvo (ITCR), obtained from ICE.	UF Water Institute FTP site	Contact K. McKee (UF Water Institute)
Water use in crops and fish farms	Total amount of water used by crops and by fish farms in the Tempisque Basin by growing season, from 2002 - 2012. Data provided by SENARA and Alejandra Rojas (UCR)	UF Water Institute FTP site	Contact K. McKee (UF Water Institute)
GIS data	GIS/LULC data for the Tempisque River Basin from 2002; provided by OTS. Additionally, OTS gave our team access to the 2008 Digital Atlas of Costa Rica (ITCR), contains 74 data layers	UF Water Institute server	Contact K. McKee (UF Water Institute)
Socio-economic, agricultural and census data	INEC (*The National Statistics and Census Institute*) provides statistics for national and provincial data on: population and demographics, employment, social aspects (e.g. poversty, education, gender), economics and agriculture. It also conducts a national census every 10 years.	INEC website	http://www.inec.go.cr/Web/Home/GeneradorPagina.aspx

Data Type	Description	Location	Access
Legal information	Produraduría General de la República (the Attourney General's Office) provides information about all Costa Rican laws; CEDARENA (an apolitical nonprofit association) provides information concerning socio-environmental conflicts	Websites of the Procuraduría General and CEDARENA	www.pgr.go.cr; http://www.cedarena.org/003/?

3.1.3 Model and development - QnD

The QnD model (Questions and Decisions) (Kiker and Linkov, 2006; Kiker et al., 2006; Papajorgji et al., 2009) is being used as a base for modeling the Tempisque River Basin. QnD is an Integrated Exploratory Model that integrates all the information available into a user-friendly interface; allowing any user (academics, decision-makers or the general public) to interact with the model by changing parameters and observing the results of that action through a graphical interface. This model is spatially explicit and provides spatial and temporal detail of how environmental and socio-ecological features interplay and respond to management decisions (Figure 4). QND's core is implemented in Java, with object-oriented language, and all inputs are written in XML. Objects are dynamically instantiated, based on input specifications. QND is spatially distributed and is linked with GIS.

Because surface water is one of the main drivers of the system, the first task was to integrate a hydrologic module in QnD. The watershed was modeled as a node link system where the contributing water of each-sub-basin is transported to nodal points that are linked by different routing operations (Figure 5). Currently, the different stream routing processes involved between a pair of nodes are: Synthetic Unit Hydrograph, Flow-by structure (i.e. River/canal plus lateral seepage into reservoir), Flow-through structure (reservoir), pipe, and channel. This implementation is based on Hromadka *et al.* [1985] and Muñoz-Carpena and Parsons [2004].

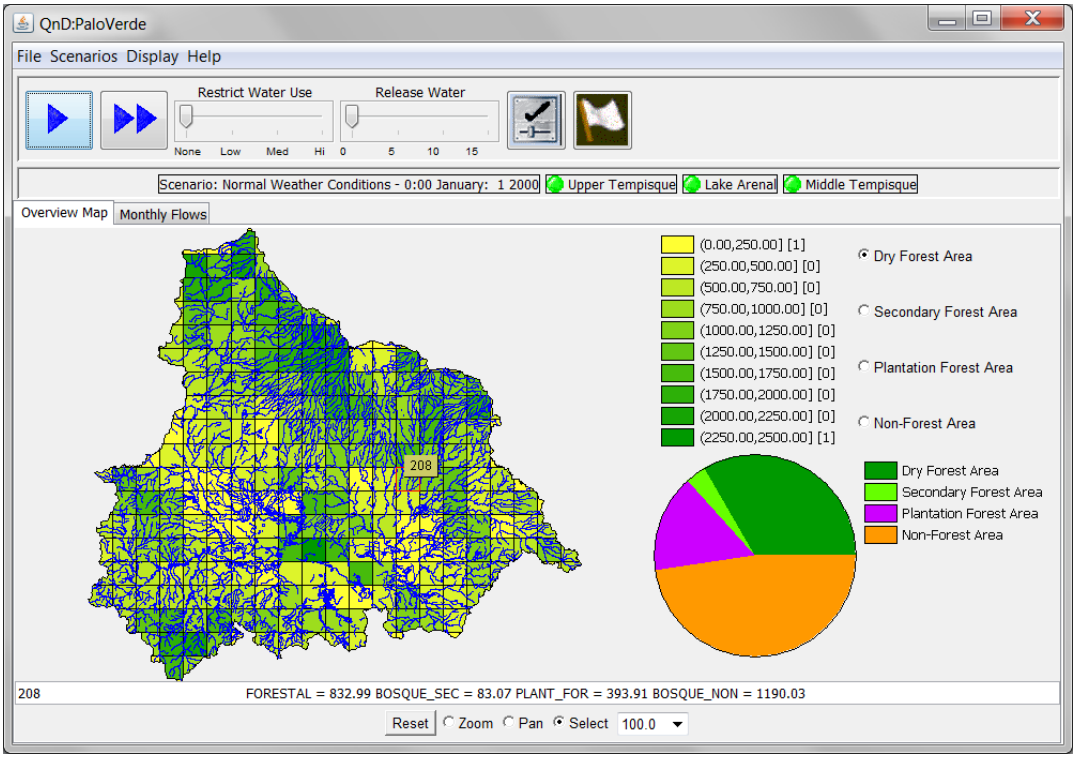


Figure 4. QnD interface

To complete the hydrologic component of this model, researchers from the University of Florida (Greg Kiker, Rafael Muñoz-Carpena and Miguel Campo-Bescos) are working closely with Julio Calvo, from the Technological Institute of Costa Rica. Dr. Calvo has provided daily hydrological data from 1980 to 1985 from the Guardia gauging station on the Tempisque River, and currently, the hydrologic module implemented on QnD is being calibrated for the Upper Tempisque Basin.

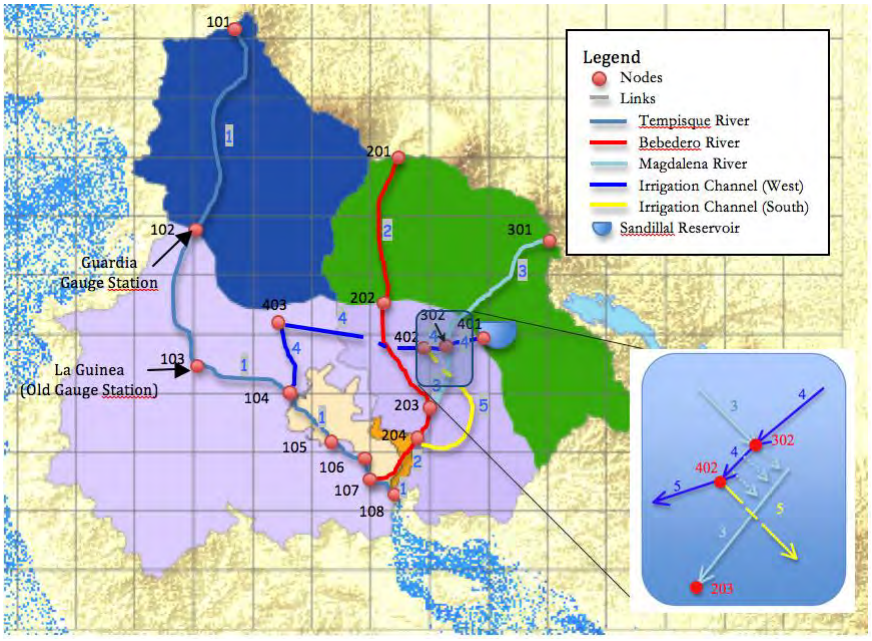


Figure 5. Draft link-node system for the Tempisque-Bebedero Watershed

3.2 Workshops and Meetings

3.2.1. Gainesville workshop, December 2011

Objectives

A one-day workshop was held on December 1, 2011 at the University of Florida in Gainesville, and facilitated by Carolina Murcia, Rafael Muñoz-Carpena, Kathleen McKee and Arnim Wiek. It was attended by 29 members of the Tempisque Working Group including five from Costa Rica (Appendix 2; see descriptions of each participant's role in the project and research expertise in Appendix 1).

The primary goals of the workshop were to: (1) get to know each other in person, (2) gain an overall perspective of the project goals and overall research framework, (3) explore preliminary research questions, methods, stakeholder engagement, and data needs, (4) identify gaps in expertise, (5) explore how proposal(s) will be written and how teams will work together, and (6) discuss the workshop in Costa Rica in April 2012.

Activities

Participants were welcomed to the workshop by Wendy Graham and Kathleen McKee from the UF Water Institute, and the project was introduced to the group by Carolina Murcia (OTS) and Rafael Muñoz Carpena (UF). There were two breakout sessions (see Appendix 3 for detailed

agenda), Session 1: Disciplinary Perspectives, and Session 2: Interdisciplinary Perspectives. These sessions were facilitated by Arnm Wiek (ASU).

During Breakout Session1: Disciplinary Perspectives, participants were placed in one of four groups, based on their research interests and field of expertise. These groups were: (1) Ecology and Land Use, (2) Climate and Water, (3) Economy and Resources, and (4) Institutions and Governance. Each group was asked to address the following three research modules for the Tempisque Bebedero River Basins, keeping in mind that the central unifying theme (within the group's particular discipline), was the sustainability of water resources:

1. Current state analysis and assessment
2. Future-oriented research
3. Strategy analysis and design

The guiding questions when discussing these modules were:

a. What are the research questions?
b. What are the research methods?
c. What is the stakeholder involvement?
d. What data/knowledge can we build on?
e. How do you expect the leadership team would support your research?

Each group had approximately 1.5 hrs to discuss these questions and report back to the entire group.

In the Interdisciplinary Perspectives breakout session, participants were divided into four groups, ensuring that people from different disciplines were placed together. Each group was asked to address the three research modules presented in the morning's breakout session, and they were asked to outline the following three products:

a. A conceptual model for the Tempisque region across all four disciplinary areas (the model needs to be functional: that it can be used for creating scenarios and for testing strategy options)
   Resource: Conceptual model from pre-proposal (Figure 2)
b. A small set of 2-4 future scenarios for the Tempisque region across all four disciplinary areas
c. A small set of 2-4 intervention strategies that are promising for transitioning the region to a sustainable state across all four disciplinary areas

Results

For brevity, we are not transcribing the results from all the groups, but showcasing one or two examples from each session.

Breakout 1: Two examples of responses are:

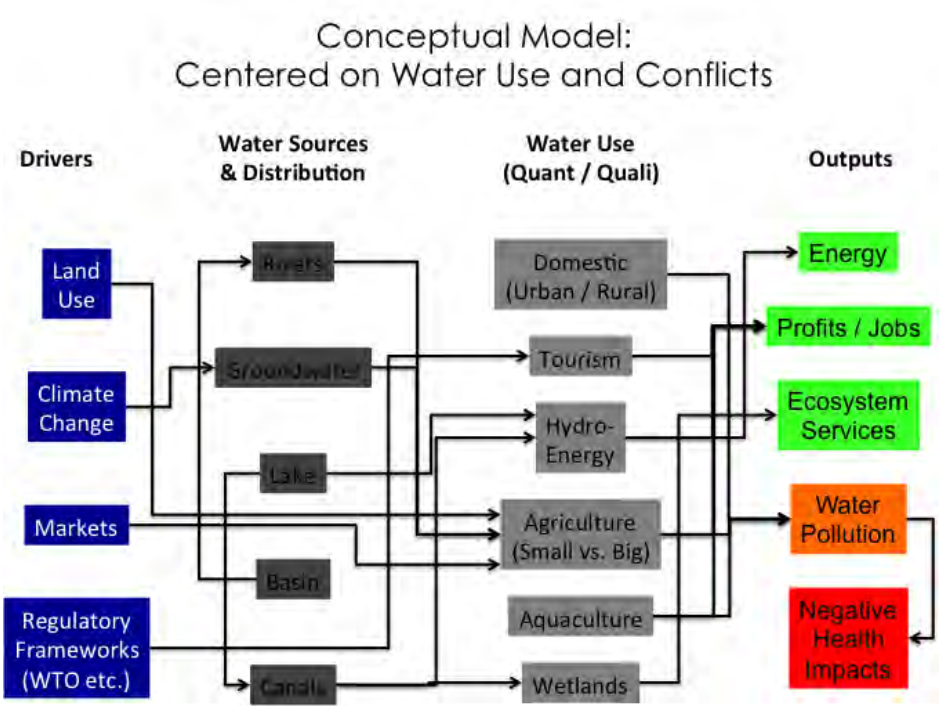
(1) The Ecology and Land Use group proposed these research questions to address all three research modules:

1. What are water and elemental budgets on system (spatio-temporal analyses)?
2. What are major land cover/land cover changes in the basin and how do they link with climate & hydrology?
3. How to develop Payment for Ecosystem Services that recognize spatiotemporal variables in ecosystem function (which are ultimately responsible for those ES)?
4. Under a water scarcity scenario, what would be an appropriate water allocation to maintain biodiversity and ecosystem services?
5. What would be the key design features that would maximize desirable ecosystem services and wetland & watershed scales?

(2) In response to the future- oriented research module, the Institutions and Governance group proposed the following:

1. We recommended constructing governance scenarios: Who will be doing what with water? In particular, we are interested in constructing three (families of) scenarios:
    - small-scale water governance (distributed)
    - large-scale water governance (AG business, large-scale tourism)
    - poly-centric water governance (hybrid).
2. We plan to conduct a comprehensive sustainability assessment of these scenarios, including in how far are the future regimes capable of adapting to droughts and other disruptive events?
3. How will the neoliberal model (that replaced the communal model) introduced through the free trade agreement DR-CAFTA in 2004/2007 continue to impact water extraction, allocation, use, treatment, etc.?
4. What will be the role of the central government in the future of water extraction, allocation, use, treatment, etc. in the Tempisque region?

Breakout 2: One group, facilitated by Arnim Wiek, proposed the following conceptual model for the Tempisque/Bebedero Basins:



Note: Missing elements that need to be added: actors, regulating policies/practices (related to stocks and flows) as well as conflicts are missing (related to uses that extract from the same source)!

In both the morning and afternoon breakout sessions, participants greatly benefitted from the local knowledge of the Costa Ricans in order to gain a deeper understanding of this region. To take further advantage of this knowledge, an impromptu hydrology seminar was scheduled for the following morning, during which Dr. Julio Calvo gave a presentation on the water budget of the Tempisque River Basin, and later, along with Dr. Jorge Jimenez answered questions about the hydrology of this region.

3.2.2. Preparatory visit to Costa Rica in March 2012

Objectives and Activities

Kathleen McKee, Rafael Muñoz-Carpena, and Andrea Albertin travelled to Costa Rica from March 10 to 17, 2012 to strengthen ties with Costa Rican collaborators, in both academic and stakeholder institutions. They met with those Costa Rican researchers that were not able to attend the December workshop in Gainesville, and presented the project to potential new collaborators (research scientists and institutional stakeholders). Mahmood Sasa (OTS/UCR) coordinated a series of meetings with these researchers and stakeholders, the majority of which were held at the OTS headquarters in San José. See Appendix 4 for the agenda, and Appendix 1 and 2 for detailed information of names, institutional affiliations and field of expertise of attendants to these meetings.

During the meetings, the team from UF briefly explained the Tempisque workgroup initiatives and project vision and Costa Rican researchers in turn spoke about their expertise, research experience, and interests in the Tempisque/Bebedero Basins. Dr. Rafael Muñoz-Carpena presented an invited seminar at the main campus of the University of Costa Rica in San José where he gave the vision for the project and details on some of the modeling tools for integration and analysis of complex systems for this project. Kathleen McKee and Andrea Albertin spent three days prior to the meetings in San José at the OTS Palo Verde Biological Station in preparation for the workshop to be held there in April.

Results

Several important outcomes resulted from the week in Costa Rica. First, Dr. Julio Calvo recommended that in addition to the workshop in Palo Verde held in April, a one-day meeting should be scheduled just prior to the workshop with key stakeholders in water management in the region (largely from water management institutions) as well as with interested researchers that could not participate in a multi-day workshop. The meeting was held on April 23 in San Jose (see Section 3.2.3. for details). Second, many of the people that we met with during the week attended either the April 23 meeting or the workshop in Palo Verde and showed interest in collaboration. Third, William Murillo from SENARA gave approval for us to obtain a large data set of water flows and water use in the Tempisque –Arenal Irrigation District. Finally, staff at the OTS headquarters further facilitated bibliographic, meteorological data and GIS data collected for the basin.

3.2.3 Meeting with key stakeholders in San José April 23, 2012

Objectives and participants

This meeting was held in the main offices of OTS in San José. Its main purpose was to meet with key stakeholders in water management in the Tempisque/Bebedero region (and nationally) as well as to meet with Costa Rican research scientists who could not attend the multi-day workshop in Palo Verde. The specific objectives of the meeting were to 1) gain a better understanding of the challenges these institutions face to manage water resources in the region, 2) identify further research gaps based on their information needs, and 3) create an additional opportunity for personal interaction among CR and US participants.

A total of 26 people attended the meeting, with 15 Costa Rican participants from two institutions, two universities and three organizations (Appendix 2), and all of those Spanish speaking collaborators from the US. Key stakeholders in the meeting included José Miguel Zeledón and Álvaro Porras, the Director and Assistant Director of MINAET's Dirección de Aguas (*Water Directive*) and Sadí Laporte, a lead engineer from ICE. The Dirección de Aguas manages

water resources in Costa Rica, while ICE manages hydroelectric power generation from Lake Arenal.

Activities

Following the round of introductions, there was a brief overview of the project's goals and vision, and a description of the dynamics of the workshop. Participants were asked to join one of five break-out thematic groups: (1) hydroelectric power generation, (2) agriculture and fish farms, (3) biodiversity and conservation, (4) Gulf of Nicoya and fisheries, and (5) tourism and urban areas. Each group was asked to discuss the following questions:

1. What is the value/importance of your group's component within the Tempisque/Bebedero Basins?
2. What are the current knowledge gaps related to sustainable water use in this component?
3. What is the future vision/scenario this component in 50 to 100 years?
4. What do we need to know in order to address this future vision/ scenario?

At the end of the breakout session, each group presented their results to the plenary, generating a lively and informative discussion. As a wrap-up, participants were asked if and how they would like to remain engaged in the project and what they thought we could contribute to the work currently undertaken in these basins.

Results

The detailed results of each group's responses to the questions addressed in the breakout session are listed in Appendix 6. These were the key recommendations:

- Hydroelectric power generation: This is a pivotal element in the system´s dynamics because the amount of water flowing through the Tempisque-Arenal Irrigation District depends on the amount of power generated on a particular day. In the future, more water will need to be diverted to the basin from the Atlantic versant to supply the increasing needs of the Pacific side.
- Agriculture/fish farms: The biggest need is to find ways for more efficient use of water in irrigation and more effective ways to charge for water use
- Tourism and urban areas: Tourism will grow in the basin and along the coast in an uncontrolled manner, ultimately becoming limited by a lack of water. There is need for planning that matches the potential growth to the actual hydrological capacity of the region.
- Biodiversity and conservation: There water needs of wetland and terrestrial natural ecosystems required to maintain their integrity must be quantified and incorporated

into the whole basin hydrological model. Likewise, environmental services of these ecosystems need to be quantified and internalized.

- Gulf of Nicoya, Fisheries: This is an area of increasing importance due to potential for tourism and food security. There is need to quantify population status and habitat needs and availability of key fish species.
- All groups identified a primary knowledge gap in the lack of information of groundwater resources and interactions between ground and surface water.

3.2.4 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, (2) define the teams that will prepare these proposals, (3) identify the funding sources for which these proposals will be prepared, (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: Yamileth Astorga, Julio Calvo, Jorge Jiménez, Eugenio González and Rafael Celis, respectively (Appendices 1 and 2). Two researchers from UNA scheduled to attend (Elba de la Cruz and Viria Bravo) cancelled at the last minute for health reasons.

Activities

Field Trip

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.

Sessions

From Wednesday to Friday (April 26 to 28), 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 (detailed agenda shown in Appendix 7). 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.

Results

- **Goals and project framework established/revised**

Long term goal:

Understand components and pathways to water sustainability in the face of stationary, non-stationary, and chaotic climate, land use, economic and social stressors.

Research Goals:

1. Identify and analyze patterns of response of hydrologic, ecologic and human systems to stationary and non-stationary climate, land use, economic, and social stressors in the Tempisque Basin. Develop quantitative measures of the seven ASU water sustainability criteria[1] (see below) that can be measured and/or modeled.

[1] ASU Sustainability Criteria:

1. Socio-ecological system integrity: aquifer viability; minimum flows for natural system functioning; water quality; plan using appropriate system boundaries.
2. Livelihoods & opportunities: ensure all individuals and communities pursuing a) livelihoods and b) economic activities have sufficient access to water.
3. Equity: ensure all residents have access to safe water; ensure sufficient water access beyond basic needs; ensure fair distribution of costs & benefits among all stakeholders; ensure access to safe water for future generations.
4. Resource efficiency & maintenance: ensure efficient use of water through a variety of techniques and approaches; ensure groundwater recharge exceeds withdrawl.
5. Governance: involve all affected groups in open & fair decision-making; ensure continued collaboration in future decision-making.
6. Precaution & adaptation: anticipate, mitigate, and adapt to water shortages and problems.
7. Scale: reduce/eliminate negative impacts on other regions; integrate management across geographic & political scales.

2. Identify and analyze pathways to sustainability in the Tempisque Basin under the ASU sustainability assessment and implementation framework. Incorporate biophysical and agent-based models developed using knowledge gained in 1 (above) as part of the process.
3. Identify and analyze legal and institutional capacity to implement policy solutions required transition to more sustainable trajectories. Can existing institutions achieve desired goals, or are new institutions or legislation required.

Framework: Use two Tempisque Basin case Studies

1. Basin-wide sustainability analysis of the existing engineered system. Use high-level (bureaucratic) stakeholders to look at sustainability trajectories from a top-down governance perspective.
2. Local-scale sustainability analysis of proposed new reservoir/irrigation system. Use community level stakeholders to look at sustainability trajectories from a bottom-up governance perspective.

- **Working groups formed**

The group was divided into four thematic groups:

1. Net Primary production/Evapotranspiration/Land use-Land cover
2. Water and Climate
3. Wetlands Linkage
4. Socio-ecological Interactions
5. Institutions and Governance

Each group has a leader and continues to meet after the workshop to move forward their particular component either as part of a larger proposal or as a smaller proposal in itself (depending on funding sources).

- **Research questions submitted by each team member**

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 (Appendix 8). 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.

- **Potential funding sources identified**
  - NSF - Coupled Natural and Human Systems - Interdisciplinary Team Exploratory Project. Approx. $200K, due Nov 20, 2012. Hydrologic Sciences opportunity at NSF (general call June/Dec)
  - NSF supplemental funding, after you already have a project funded
  - NSF-PIRE and IGERT training grants (only US citizens)
  - Costa Rican FEES grants: Money from 4 public universities to promote inter-institutional collaborations
  - World Bank and International Development Bank; they are currently funding MarViva
  - Fish and Wildlife Service / Ducks Unlimited; for research in the wetland
  - NASA LULC
  - Tinker Foundation; capacity building, stakeholder´s engagement. LOI due August 2012; proposal due Sept 15th 2012.
  - Gates foundation. Social issues, equity.

4. Quantitative inference of research needs and their interactions

In this section we provide a *post-hoc* preliminary analysis and synthesis of the research questions formulated at the Palo Verde researcher workshop. The participating researchers belong to two kinds of institutions; academic and non-profit private organizations (NGOs). By analyzing the research questions and their institutional origin we expected to: (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 in a more sophisticated modeling effort. For instance, research questions can be used to build a utility function that weights the important factors composing the objective function of the problem, and mental models can be used to evaluate policy relevant to the Tempisque problem. Hence, ultimately the analysis and quantification of the research questions information is useful for environmental management and for research related to individual response and collective organization and change as a function of the problem at hand (Morgan et al., 2002; Linkov et al., 2011; Sparrevik et al, 2011; Wood et al., 2012).

The analysis performed in this section makes use of various techniques to analyze the set of research questions formulated in the Palo Verde workshop (Appendix 8). Further analysis and more structured elicitation of social information will be desirable in future research efforts.

4.1 Analysis of research questions conditional to topic and time

Research questions were analyzed as a function of two categories: topic and time scale (Table 1 and 2). These categories were assigned to the research questions workshop *a-posteriori* by a third party. Using this classification, we assessed the frequency distributions of selected topic and time classes for questions formulated by the two types of researchers: academics and NGOs. It should be mentioned that the number of researchers differs between the two types of institutions, with academics being the largest group.

Table 1: Topics and time classes assigned by stakeholders to the formulated questions

Topic class	Topic
1	Climate behavior
2	Climate on vegetation
3	Governance
4	Human impacts on Nat systems
5	Impacts of Nat Systems on climate/production
6	Impacts on water system behavior
7	Nat system behavior
8	Use/decision process
9	Water system behavior
10	Nat System sustainability
11	Water sustainability
12	Incentive mechanisms
13	Governance structure
14	Institutions
15	Law & Policy
16	Stakeholders
17	Water Use

Time Class	Time frame
1	Historic trends
2	Current status
3	Expected behavior

Questions formulated by academics had a different focus from those formulated by members of NGOs (Figure 6). The former load toward: climate behavior (topic 1), human impacts on natural systems (4), impact on water system behavior (6), water sustainability (11), and institutions (14). Questions formulated by members of NGOs have a very different focus;

namely use/decision processes (8), law and policy (15), and water use (17). Both groups generated questions on topics 4, 10, 11, 13 and 16.

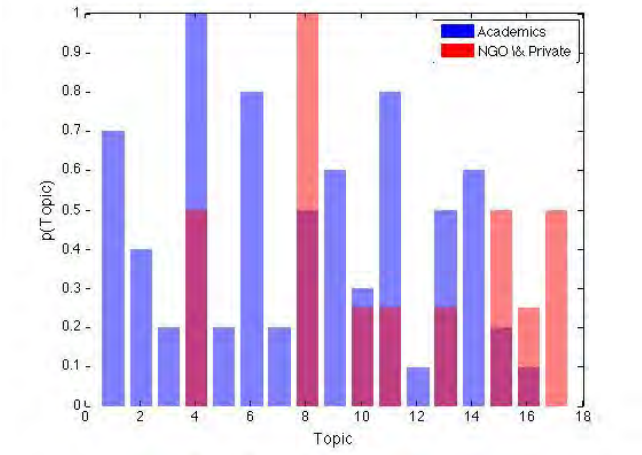


Figure 6: Frequency distribution of the selected topics by the stakeholders independently of the questions formulated during the workshop. The normalization is performed by dividing the number of choices for a topic of a stakeholder group (considered independent to the others) by the maximum number of choices for the stakeholder group considered.

Likewise, questions formulated by academics leaned towards historic trends (time class 1) and current status (time class 2) of systems, whereas the NGO members formulated question that were more focused on future scenarios (time class 3)(Figure 7). This suggests that academics rely more strongly on the analysis of trends to predict the future, while those affiliated with NGOs are keener on exploring at once the future scenarios.

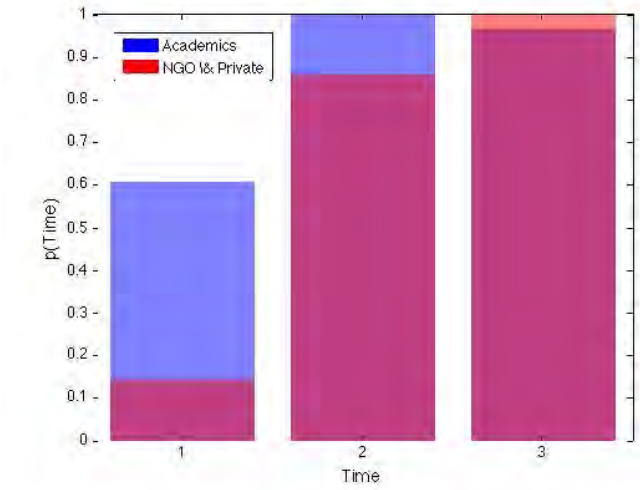


Figure 7: Frequency distribution of the time classes associated with responses form researchers from academia *vs.* researchers from NGOs. Normalization is performed by dividing the number of choices for a topic of a researcher group (considered independent to the others) by the maximum number of choices for the researcher group considered.

These preferences about the future of the basin can prioritize research and development activities, and increase importance toward solutions with different time horizons in terms of their potential effects. Overall, from these data it seems there is an agreement toward a strategic planning for the future.

4.2 Elicitation of research needs interactions

4.2.1 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 for the evaluation of policy options through the integrations of data, decisions, and model predictions. Here, we used an analogous textual analysis for all questions formulated in the Palo Verde workshop. Thus, the analysis is considering all questions for all the goals together.

The text mining functionality of the model provides support for creating term maps based on a corpus of a text. 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.

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, Waltman, Noyons, & Buter, 2010). 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,* 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, Waltman, Dekker, & Van den Berg, (2010), and in Waltman, Van Eck, & Noyons, (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 to be 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 has zoom, scroll, and term search functionality to support a detailed examination of a term map. Other relevant network variables can be calculated and represented.

4.2.2 Graphical interpretation of the elicited semantic network and further analysis

The total unique terms from the research questions analyzed were 317 and after applying the minimum threshold for the occurrences (equal to 3) the final number was reduced to 29. Table 3 shows the occurrence of the 29 terms in the text analyzed (all questions together) and their relevance.

Table 3: Mapping of all the questions formulated in the workshop. The terms are reported together with their occurrence and their relevance.

Term	Occurrences	Relevance
basin level	3	2.13
prediction	4	2.08
current pattern	3	1.81

Term	Occurrences	Relevance
institution	7	1.60
local scale	3	1.56
sustainanility solution	3	1.56
approach	4	1.47
Enso (El Niño Southern Oscilation)	4	1.44
large scale atmospheric driver	4	1.44
water use	6	1.34
phase	6	1.26
local precipitation	6	1.14
sustainability	5	1.02
future climate scenario	4	1.01
statistical relationship	4	0.94
Asadas (acronym)	3	0.82
watershed	4	0.79
tempisque basin	6	0.60
component	3	0.59
Pvw (Palo Verde Wetland)	7	0.55
wetland	4	0.55
water sustainability	5	0.52
water	8	0.50
hydrology	3	0.47
impact	6	0.46
groundwater	3	0.40
basin	10	0.35
climate change	8	0.31
change	15	0.28

Low relevance is for the terms with general meaning and vice-versa. 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.

Figures 6, 7, 8 and 9 report a preliminary analysis for the elicitation of the mental model researchers involved in the Palo Verde workshop. A brief explanation of each figure is reported in the captions. 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.

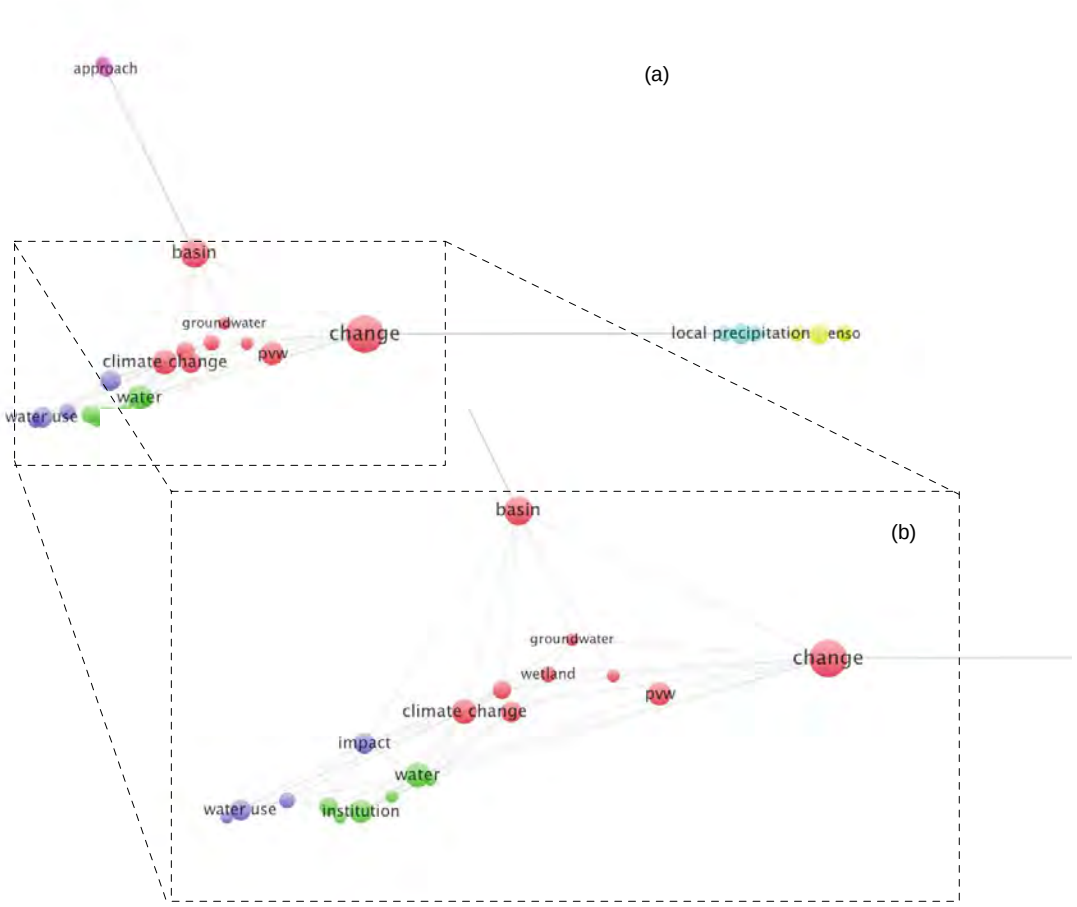


Figure 8: (a) Semantic network of all the workshop's questions after the ``clustering and mapping'' model. Clusters are nodes with the same color (from blue to red in order of importance). The distance between two terms can be interpreted as an indication of the relatedness of the terms. The diameter of nodes is proportional to the occurrence of each term. One node is associated to one term. (b) The area around the most important cluster is zoomed in.

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.

In general the maps show that *basin* and *change* (any change, from climate change to land-use change) are the most important factors of the Tempisque problem. Further analyses are required to disentangle which change is connected to other term.

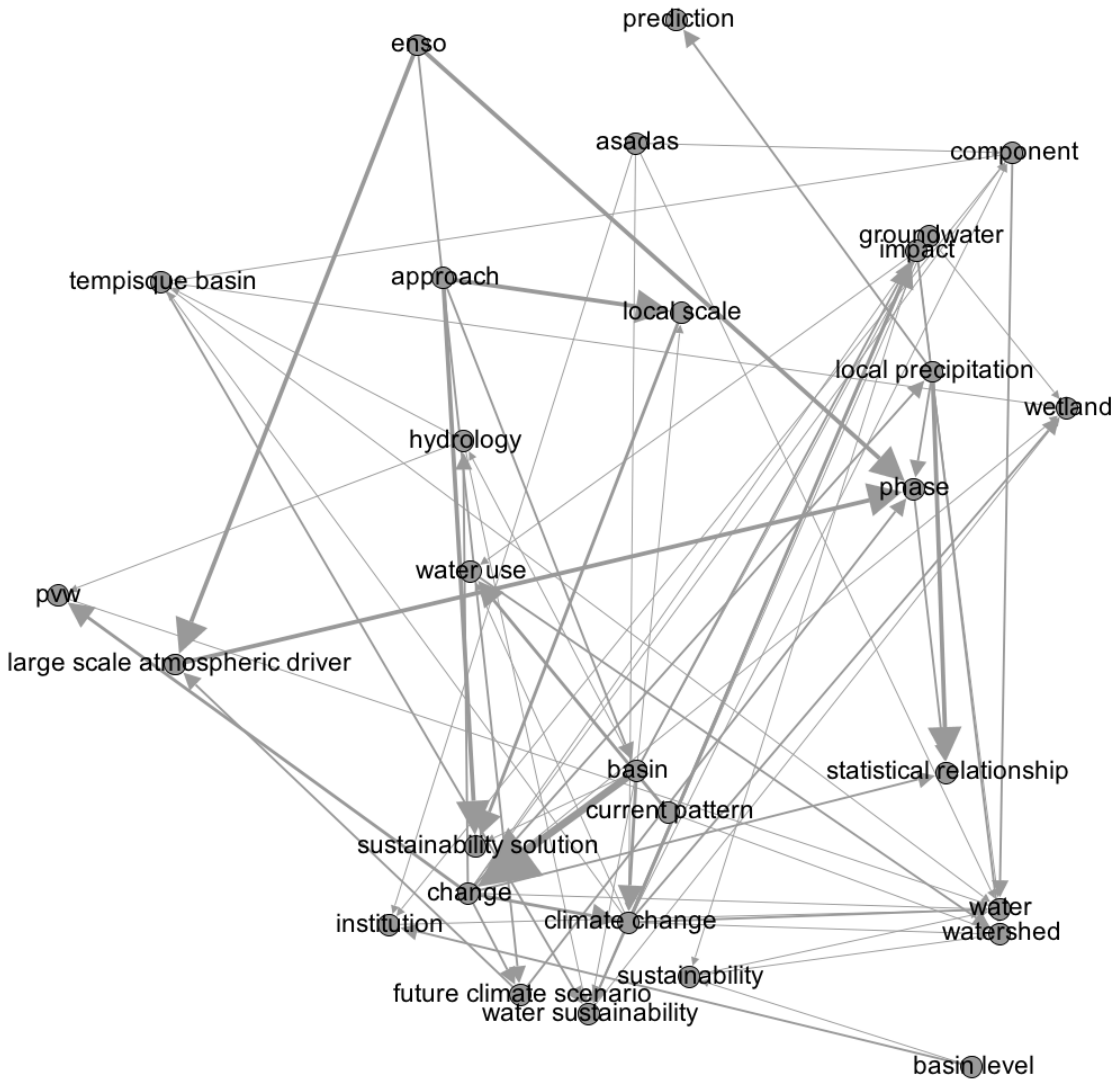


Figure 9: Potential influence diagram among the terms/factors of the Tempisque problem.

Of great importance is the potential influence diagram shown in Figure 9. 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 3). For example the word ``change'' is after basin in the text (all questions together) very frequently. Thus the arrow is drawn from basin to change. In this way potential causal

relationship can be assessed. In this case, these causal relationships are related to all the researchers because we investigated the text composed by all the questions formulated without regard to its institutional origin. Hence, the semantic network in Figure 9 can be used as an influence diagram of the Tempisque sustainability problem.

5. Additional outcomes

The following describes activities not proposed in this grant but that have resulted from further activities conducted by sub-teams of this group.

5.1. Proposals and funding sources

The Tempisque workgroup at large is continuing to look for potential funding sources and preparing and submitting proposals. This is a list of activities and outcomes on several fronts:

In May, Arnim Wiek and Christopher Kuzdas (ASU) were awarded an **NSF Doctoral Dissertation Improvement Grant** in the Decision, Risk, and Management Sciences Program to integrate water conflict research into my dissertation. The CNIC in-person workshop in Gainesville (Dec 2011) and the webinar series helped clarify the key issues in the region prior to the DDIG submittal in January. The competitiveness of the DDIG proposal also likely increased due to the broader team that the results of the DDIG research could potentially disseminate through. The collaborative support network that formed through the CNIC was an outstanding resource for crafting the successful DDIG proposal and will continue to be beneficial as research funded by the DDIG in completed.

Costa Rican researchers (Mahmood Sasa, Yamileth Astorga, Eugenio Gonzalez, Jorge Jimenez, Julio Calvo, Elba de la Cruz, Ingo Wehrtman, Gerardo Umaña, Elba de la Cruz, and Lola Campos) have met three times at the OTS headquarters in San Pedro to move forward with a proposal for the Tempisque Basin. One funding source identified during the workshop in Palo Verde was FEES (**Special Fund for the Financing of Higher Public Education**). These funds (up to $80,000) are to promote collaborations among researchers from all four of Costa Rica's major public universities (UCR, UNA, ITCR and UNED). The group is currently preparing a proposal for the Tempisque Basin for submission by October 1, 2012.

A team from UF led by Rafael Muñoz-Carpena, Mark Brown, Peter Waylen and Tom Ankersen (with 17 other researchers across 11 UF departments), submitted the proposal "UF Consortium for Complex Social Ecological Systems (CSES)" to **University of Florida´s Office of the Vice President for Research**. This is a planning grant for Collaborative Research Projects, with the primary aim of developing a unique nexus of shared expertise at UF to prepare suites of large proposals for basic trans-disciplinary research, NSF Centers and Networks, and education and training grants. The Tempisque River Basin will be a primary focus of the proposed consortium.

The team is now preparing a proposal entitled “Water as an Integrator of Complex Socio-Ecological Systems: Responding to Disturbance, Change, and Uncertainty" for submission to the UF 2013 **Water Institute Graduate Fellows Program**. The UF Water Institute is soliciting proposals that will fund the second interdisciplinary faculty-graduate fellow team to conduct integrative research in an emerging area of water science, broadly interpreted to include the social, natural, and engineering sciences. Six Ph.D. students will be funded for four years.

Carolina Murcia, Science Director of the Organization for Tropical Studies submitted in mid-September a proposal to the **Tinker Foundation** entitled: “Tempisque Basin Water Management and Sustainability: The policy dimension”. The request for $181,000 will secure funds to: (a) Involve stakeholders and decision-makers throughout all stages of the Tempisque Water Management and Sustainability Project, including the translation of the technical aspects of the project, (b) Provide general coordination, integration and synthesis of this large international interdisciplinary and inter-institutional project to ensure that it appropriately incorporates the necessary scientific knowledge to address societal concerns, and (c) Fill the most critical gaps in our knowledge of the water usage by key stakeholders in order to refine the project´s work plan and a decision-making tool.

5.2. Training

Water Institute Fellows/UF-UCR Law Clinic Practicum in Tempisque Basin

Water Institute Graduate Fellows and Law students from UF and the University of Costa Rica spent part of their summer in Costa Rica participating in the combined UF Law School Conservation Clinic and the International Environmental Law Skills Lab. This gave all Program participants experience in providing short-term development assistance (consultancies) and working in interdisciplinary teams. Students worked on a variety of projects, each of which focused on water management issues pertinent to the Tempisque-Bebedero Basin, one of Costa Rica’s largest and most water-limited watersheds. The Tempisque-Bebedero Basin and the Pacific Coast of Central America has been characterized as a “climate change hot-spot” due to predicted impacts on water resources, principally drought. Teams of students worked on projects that included an investigation of the legal, socioeconomic, and environmental issues associated with rice production in the buffer zone of Palo Verde National Park; an assessment of the legal and scientific tools available for improving the health of the impaired wetland at Palo Verde National Park, an internationally recognized wetland; and an analysis of the institutional and legal framework for drought management in the Tempisque Basin. Participants also evaluated new recommendations for establishing minimum environmental flows in the Basin, investigated the environmental and social impacts of a proposed water storage dam in the Basin, and reviewed and critiqued current regulations for nutrient pollution in the Tempisque River. The reports and associated powerpoint can be found at:

http://www.law.ufl.edu/academics/academic-programs/study-abroad/summer-abroad/costa-rica/project-spotlight

5.3. Publications and reports

Arnim Wiek and Chris Kuzdas (ASU) submitted a report to the Costa Rican Nicoya Watershed Commission. Many of the issues that are faced in the Nicoya Peninsula of Costa Rica are similar to those in the broader Tempisque region. This report was greatly facilitated by CNIC efforts that helped clarify key issues in the region, lending credibility to the report. Working with professionals in Costa Rica through the CNIC grant encouraged the ASU team to remain diligent about producing usable products for our local partners.

5.4 Awards

Global Water Forum Emerging Scholar Award Finalist. In Mid-September, ASU´s initial qualitative work on water conflict was selected as a finalist in the Global Water Forum Emerging Scholar Contest, with a very short article being published on their website in October. This award for a 1,000 word research article submitted by Arnim Wiek and Chris Kuzdas was based on a series of interviews with experts or involved persons in three water conflict cases in Guanacaste. About half of the persons interviewed were involved to some degree with CNIC efforts, which allowed initial contacts and development of working relationships with individuals that we interviewed.

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7. Appendices

Appendix 1. Collaborators of the Tempisque Basin Project, roles and field of expertise.

We have listed all Senior Personnel (named in the proposal) and those researchers that joined the project after the award was granted under a single category (researcher).

Institution/ Organization	Team Member	Role in project and Field of expertise	
US Organizations and Universities			
OTS	Losos, Elizabeth	Co-PI	President and CEO of OTS. She has primary administrative responsibility for all grants and contracts submitted on behalf of the organization by Duke University.
OTS	Murcia, Carolina	Researcher	Tropical conservation ecologist, and Science Director for OTS. She serves as the coordinator of the grant, and conceptual leader of the project, along with Dr. Muñoz Carpena.
OTS	Sasa, Mahmood	Researcher	Director of OTS Palo Verde Biological Station, and researcher at the Clodomiro Picado Institute, University of Costa Rica. He is the main liaison with the Costa Rican scientists and institutions. He contributes his expertise on animal populations, particularly impacts on amphibian and reptile populations.
UF	Muñoz-Carpena, Rafael	PI	Engineer specialized in modeling of environmental systems. He focuses on the use of global sensitivity and uncertainty techniques as an essential tool for the objective evaluation of computer models in a wide variety of applications and in particular the analysis of integrated systems.
UF	Graham, Wendy	Co-PI	Director of the UF Water Institute, is an engineer with expertise on coupled hydrologic-water quality- ecosystem modeling. She leads the evaluation of impacts of agricultural production on surface and groundwater quality.
UF	Huffaker, Ray	Co-PI	Natural resources economist. He leads the bio-economic component of the project, with particular focus on the economic dynamics of natural resource law.
UF	Kiker, Greg	Co-PI	Engineer specialized in object-oriented modeling and is developer of QnD. In collaboration with Dr. Muñoz-Carpena, he is developing the models for the global uncertainty and sensitivity analyses.
UF	Waylen, Peter	Co-PI	physical geographer specializing in hydrology, and particularly on interannual and interseasonal variability of hydrometeorological variables. He is

Institution/ Organization	Team Member	Role in project and Field of expertise	
			responsible for the climatological models on precipitation.
UF	Ankersen, Tom	Researcher	Lawyer of the UF Conservation Clinic with expertise on international environmental law and policy and water law. He leads the legal and policy analyses of the project, along with Richard Haman
UF	Bohlman, Stephanie	Researcher	Expertise in forestry, land use change and species/functional group composition and forest structure response to climate change. Has worked extensively in the Azuero Peninsula of Panama.
UF	Brown, Mark	Researcher	Systems ecologist with expertise on evaluation of restoration of altered landscapes, particularly wetlands, and on quantitative evaluation of natural capital and environmental services. He leads these two aspects of the project.
UF	Cohen, Matt	Researcher	Ecohydrologist who specializes in Forest Water Resources and Watershed Systems. His primary area of research is watershed hydrology and biogeochemistry, with an emphasis on wetland processes.
UF	Hamann, Richard	Researcher	Lawyer of the UF Conservation Clinic with expertise on international environmental law and policy and water law. He leads the legal and policy analyses of the project, along with Tom Ankersen
UF	Keys, Eric	Researcher	Geographer specialized in cultural and political ecology. He leads the analyses on land use and land cover change driven by climate change.
UF	Southworth, Jane	Researcher	Physical geographer specializing in remote sensing and climate change modeling. She handles satellite image analysis of deforestation and forest fragmentation.
UF	McKee, Kathleen	Project Coordinator	Research Coordinator for the UF Water Institute and a wetland soil scientist. Additionally, she has experience with database management, project management, group facilitation and communication. She is assisting Carolina Murcia and Rafael Muñoz-Carpena in coordinating activities for the Tempisque project.
UF	Asseng, Senthold	Researcher	Focuses in systems analysis to understand, compare and improve the productivity and sustainability of atmosphere-crop-soil systems changing over time and space and at different scales. He specializes in impact and adaptation of climate variability and climate change on cropping systems.
UF	Frederick, Peter	Researcher	Wildlife ecologist interested in the ecology and conservation of wetlands, and particularly of wetland vertebrates.

Institution/ Organization	Team Member	Role in project and Field of expertise	
UF	Albertin, Andrea	PostDoc	Aquatic biogeo-chemist; er role in the project is Data collection and fostering relationships and inter-institutional cooperation with our Costa Rican counterparts. She previously worked for OTS in Palo Verde.
UF	Campo Bescos, Miguel	PostDoc	Engineer specialized in modeling landscape evolution. His role in the project is the Integration of a hydrologic model in QnD.
UF	Perez-Ovilla, Oscar	PostDoc	Expert in modeling hydrologic systems. Worked in the integration of a hydrologic model in QnD.
UF	Laing, Joelle	PhD Student	Water Institute Fellow studying nutrient cycling in Florida Springs
UF	Nelson, Natalie	PhD Student	She studies land-use change and coastal systems modeling.
UF	Paniagua, Franklin	PhD Student	Costa Rican environmental lawyer. He contributes to knowledge base of Environmental Law in Costa Rica and local knowledge of communities and institutions
UF	Stocks, Gaby	PhD Student	Anthropologist, Local knowledge of communities and institutions
ASU	Childers, Dan	Researcher	Professor in the School of Sustainability and Director of the Central Arizona-Phoenix Long-Term Ecological Research Program (CAP LTER). He is a systems ecologist who specializes in wetland and aquatic ecosystems, a sustainability scientist, and an urban ecologist. He Leads sustainability component of the project.
ASU	Wiek, Arnim	Researcher	Assistant professor in the School of Sustainability where he works on emerging technologies, regional development, land use conflicts and resource governance.
ASU	Kuzdas, Chris	PhD Student	Sustainability Scientist. He studies governance strategies that could mitigate detrimental resource conflicts and accelerate regional progress towards sustainability
ASU	Warner, Ben	PhD Student	Sustainability Scientist. He studies how climate-adaptation projects affect the adaptive capacity of different water users across the Tempisque Basin
Columbia/ NASA	Winter, Jonathan	Researcher	Associate Research Scientist at the Center for Climate Systems Research, where he studies the effects of climate variability and climate change on water resources and agricultural productivity.
NASA/Columbia	Ruane, Alex	Researcher	Research Physical Scientist at NASA GISS, where he works on climate prediction and climate change impacts assessments.
Costa Rican Universities and Organizations			
ITCR	Calvo, Julio	Researcher	Rector of this institution and a Hydrologist. He has worked extensively on hydrologic processes and water budgets in the Tempisque Basin, and he

Institution/ Organization	Team Member	Role in project and Field of expertise	
			currently has a project in the Upper Tempisque Watershed.
UCR	Springer, Monika	Researcher	Aquatic entomologist. She specializes in biological monitoring using macroinvertebrates.
UCR	Aguilar Pereira, José Francisco	Researcher	Chair of the School of Agricultural Engineering, UCR.
UCR	Arias, Mario	Researcher	Hydrogeologist, faculty in the Geology Department of UCR. He has conducted studies on aquifers in the Guanacaste coastal region.
UCR	Astorga, Yamileth	Researcher	Coordinator of the Institutional Program for Integrated Environmental Management (ProGAI) at UCR. She is a hydrologist interested in water budgets and sustainable water resource development, and works extensively in the Tempisque/Bebedero Basins.
UCR	Campos, Lola	Researcher	Professor in the Central American School of Geology. She is a sedimentary geologist and expert in hydrogeology.
UCR	Hernández, Cinthya	Researcher	Team member of ProGAI, along with Yamileth Astorga. She Co-coordinates CIDECAT, in the Tempisque Basin.
UCR	Losilla, Marcelino	Researcher	Hydrogeologist retired from UCR, with extensive experience throughout the country.
UCR	Pujol, Rosendo	Researcher	Director of ProDUS, a program which focuses ion the analysis and understanding of the interaction between human settlements and natural systems. He is an expert in regional and environmental planning, transportation and ecotourism.
UCR	Quesada, Marvin	Researcher	Expert in the complexities of climate variability in Costa Rica.
UCR	Rojas González, Alejandra	Researcher	Professor in the School of Agricultural Engineering, UCR. She specializes in hydrologic modeling and is currently working on modeling water use in the Arenal-Tempisque Irrigation District.
UCR	Umaña, Gerardo	Researcher	Limnologist and one of the few people in Costa Rica currently working on lakes. He has been sampling physical-chemical and phytoplankton/zooplankton in Lago Cote (near Lake Arenal) for the past 10 years.
UCR	Wehrtmann, Ingo	Researcher	Professor in CIMAR and coordinator of the Fishing and Aquaculture Research Unit. Expert in crustaceans and migrations of larvae and adults from freshwater to estuaries and vice versa. He is interested in the effects that rivers dams could have on migrating populations.
UNA	de la Cruz, IRET	Researcher	Coordinator of the Environmental Area of the Regional Institute of Studies on Toxic Substances (IRET). She has been monitoring the levels of

Institution/ Organization	Team Member	Role in project and Field of expertise	
			pollutants reaching the PV wetland and its impact on small vertebrates.
UNA	Baldi, Mario	Researcher	Veterinary Doctor specialized in emergent wildlife disease, and researcher in the Research Program on Tropical Disease. He is currently directing a project on avian flu and other insect-borne disease in the lower Tempisque region.
UNA	Bravo, Viria	Researcher	Spatial analyst and forester (by training) working in IRET, a group which conducts ecotoxicological studies on the effects of pesticides on water quality and aquatic fauna. She is
UNA	Pinnock, Margaret	Researcher	Ecotoxicologiist working in IRET, a group which conducts ecotoxicological studies on the effects of pesticides on water quality and aquatic fauna.
Texas A&M	Gonzalez, Eugenio	Researcher	Director of this facility and former Director of OTS Palo Verde Biological Station. Currently, he is also member of the PV National Park Scientific Committee for Research and has been involved in monitoring and control of cattails in the Palo Verde wetland for over a decade. He has a comprehensive understanding of the factors that affect the PaloVerde wetland.
MARVIVA	Jimenez, Jorge	Researcher	CEO of MarViva; He is a marine biologist and former director of OTS in Costa Rica. In this capacity, he led the effort to have an integrated management of the basin with the goal of protecting the PV wetland. As a member of Marviva, he has a vision of the potential impacts on watershed management on fisheries in the Gulf.
ProDesarrollo Internacional	Celis, Rafael	Researcher	Natural resources economist and director of ProDesarrollo Internacional, a consulting firm based in Costa Rica. He is a natural resources economist with extensive experience in the Tempisque Basin.
Costa Rica Por Siempre	Espinoza, Edgar	Researcher	Conservation officer for Forever Costa Rica (Costa Rica por Siempre) a non-profit association that manages the public-private conservation initiative developed by the Costa Rican government and The Nature Conservancy, the Linden Trust for Conservation, the Gordon & Betty Moore Foundation, and the Walton Family Foundation.
Costa Rican Institutions			
ICE	Laporte, Sadí	Institutional collaborator	Engineer; ICE manages hydroelectric power generation from Lake Arenal and the residual water is then used for irrigation and tilapia farms in the Tempisque/Bebedero Basins.
MINAET	Porras, Alvaro	Institutional collaborator	Assistant Director of the Water Directive, the entity which coordinates the administration of water

Institution/ Organization	Team Member	Role in project and Field of expertise	
			resources in Costa Rica.
MINAET	Zeledón, José Miguel	Institutional collaborator	Director of the Water Directive, the entity which coordinates the administration of water resources in Costa Rica.
SENARA	Murillo Montero, William	Institutional collaborator	Civil engineer in charge of the large AGUAnacaste initiative for effective water resource management in the Arenal Tempisque Irrigation District

Appendix 2. Collaborator participation in workshops and other meetings

Institution/ Organization	Team Member	Role in Project	December Workshop Gainesville, FL	March Meetings Costa Rica	Stakeholder Meeting April 23 Costa Rica	Palo Verde Researchers Workshop Costa Rica	Small group discussions, written participation
US Organizations and Universities							
OTS	Losos, Elizabeth	Co-PI					
OTS	Murcia, Carolina	Researcher	X		X	X	X
OTS	Sasa, Mahmood	Researcher	X	X	X	X	X
UF	Muñoz-Carpena, Rafael	PI	X	X	X	X	X
UF	Graham, Wendy	Co-PI	X			X	X
UF	Huffaker, Ray	Co-PI	X			X	X
UF	Kiker, Greg	Co-PI	X			X	X
UF	Waylen, Peter	Co-PI	X			X	X
UF	Ankersen, Tom	Researcher	X		X	X	X
UF	Bohlman, Stephanie	Researcher	X				X
UF	Brown, Mark	Researcher	X			X	X
UF	Cohen, Matt	Researcher	X				X
UF	Hamann, Richard	Researcher	X			X	X
UF	Keys, Eric	Researcher	X				X
UF	Southworth, Jane	Researcher	X			X	X
UF	McKee, Kathleen	Project Coordinator	X	X	X	X	X
UF	Asseng, Senthold	Researcher	X			X	X
UF	Frederick, Peter	Researcher				X	X
UF	Albertin, Andrea	PostDoc	X	X	X	X	X
UF	Campo Bescos, Miguel	PostDoc			X	X	X
UF	Perez-Ovilla, Oscar	PostDoc	X				X
UF	Laing, Joelle	PhD Student			X	X	X
UF	Nelson, Natalie	PhD Student	X				X
UF	Paniagua, Franklin	PhD Student	X				X
UF	Stocks, Gaby	PhD Student	X		X	X	X
ASU	Childers, Dan	Researcher	X		X	X	X

Institution/ Organization	Team Member	Role in Project	December Workshop Gainesville, FL	March Meetings Costa Rica	Stakeholder Meeting April 23 Costa Rica	Palo Verde Researchers Workshop Costa Rica	Small group discussions, written participation
ASU	Wiek, Arnim	Researcher	X				X
ASU	Kuzdas, Chris	PhD Student	X			X	X
ASU	Warner, Ben	PhD Student	X			X	X
Columbia /NASA	Winter, Jonathan	Researcher	X			X	X
NASA/Columbia	Ruane, Alex	Researcher					X
Costa Rican Universities and Organizations							
ITCR	Calvo, Julio	Researcher	X	X	X	X	X
UCR	Springer, Monika	Researcher		X	X		
UCR	Aguilar, José Francisco	Researcher			X		
UCR	Arias, Mario	Researcher			X		
UCR	Astorga, Yamileth	Researcher		X		X	X
UCR	Campos, Lola	Researcher		X			
UCR	Hernández, Cinthya	Researcher		X	X		
UCR	Losilla, Marcelino	Researcher			X		
UCR	Pujol, Rosendo	Researcher		X	X		X
UCR	Quesada, Marvin	Researcher					X
UCR	Rojas González, Alejandra	Researcher		X	X		
UCR	Umaña, Gerardo	Researcher		X			
UCR	Wehrtmann, Ingo	Researcher		X			
UCR	Barrantes, Karla	Potential collab		X			
UCR	Pérez Molina, Eduardo	Potential collab		X			
UCR	Sánchez Hernández, Leonardo	Potential collab		X			
UNA	de la Cruz, Elba	Researcher		X			
UNA	Baldi, Mario	Researcher		X			
UNA	Bravo, Viria	Researcher		X			
UNA	Pinnock, Margaret	Researcher		X			
UNA	Spinola, Manuel	Potential collab		X			

Institution/ Organization	Team Member	Role in Project	December Workshop Gainesville, FL	March Meetings Costa Rica	Stakeholder Meeting April 23 Costa Rica	Palo Verde Researchers Workshop Costa Rica	Small group discussions, written participation
Soltis Center, Texas A&M	Gonzalez, Eugenio	Researcher	X	X	X	X	X
MARVIVA	Jimenez, Jorge	Researcher	X	X	X	X	X
ProDesarrollo Internacional	Celis, Rafael	Researcher		X	X	X	X
Costa Rica Por Siempre	Espinoza, Edgar	Researcher			X		
Costa Rican Institutions							
ICE	Sadí Laporte	Institutional collab			X		
MINAET	Alvaro Porras	Institutional collab			X		
MINAET	José Miguel Zeledón	Institutional collab			X		
SENARA	William Murillo Montero	Institutional collab		X			

Appendix 3. Agenda for December workshop in Gainesville, Florida

Time	Friday December 1st		Saturday December 2nd
		Facilitator	
08:00-08:30	Coffee and pastries, pick up nametags and materials, mingle		Presentations by Jorge Jiménez (MarViva) and Julio Calvo (ITCR) on the hydrology of the Tempisque Basin, discussion session ensued
08:30-8: 35	Welcome	*K. McKee & W. Graham, UF Water Institute*	
8:35-9:10	Self-introductions		
9:10-9:35	Introduction to the Project	*R. Muñoz Carpena & C. Murcia, UF and OTS*	
9:35-9:45	Survey synthesis: Expertise Matrix	*Arnim Wiek, ASU*	
9:45-9:55	Introduction to breakout group SESSION 1 – Disciplinary Perspectives	*Arnim Wiek, ASU*	
9:55-10:10	**COFFEE BREAK**		
10:10-11:25	Breakout Group SESSION 1		
11:25-12:15	Group reports		
12:15-13:00	**LUNCH** (Catered)		Participants travel home
13:00-13:30	Integration: Rethinking through QnD and GSA	*R. Muñoz Carpena & G. Kiker, UF*	
13:30-13:40	Introduction to Breakout group SESSION 2 – Interdisciplinary Perspectives	*Arnim Wiek, ASU*	
13:40-15:00	Breakout Group SESSION 1		
15:00-15:15	**COFFEE BREAK**		
15:15-16:00	Group Reports		
16:00-17:15	Wrap-Up: Where do we go from here?	*C. Murcia, K. McKee & R. Muñoz Carpena, OTS & UF*	
19:00 onward	**DINNER - BBQ** R. Muñoz-Carpena's home		

Appendix 4. Agenda for March trip to Costa Rica

<table>
<tr><th>Time</th><th>Sat & Sun
March 10-12</th><th>Monday
March 13</th><th>Tuesday
March 14</th><th>Wednesday
March 15</th><th>Thursday
March 16</th><th>Friday
March 17</th></tr>
<tr><td>09:00-10:00</td><td rowspan="8">K. McKee & A. Albertin visit Palo Verde Biological Station</td><td rowspan="8">Travel to San José</td><td rowspan="2">Mario Baldí</td><td rowspan="2">Monika Springer, Ingo Wehrtmann, Gerardo Umaña</td><td rowspan="2">Rafael Celis</td><td rowspan="2">Elba de La Cruz, Margaret Pinnock, Viria Bravo, Lola Campos</td></tr>
<tr><td>10:00-11:00</td></tr>
<tr><td>11:00-12:00</td><td>Meet with OTS staff to obtain GIS data</td><td>Meet with OTS staff to obtain meteorological data</td><td></td><td>Rafael Muñoz Carpena gives talk at UCR</td></tr>
<tr><td>12:00-13:00</td><td colspan="4">LUNCH</td></tr>
<tr><td>13:00-14:00</td><td rowspan="3">Yamileth Astorga, Cinthya Hernández, Jorge Jiménez, Manuel Spinola</td><td></td><td></td><td rowspan="2">Meeting at SENARA: William Murillo</td></tr>
<tr><td>14:00-15:00</td><td rowspan="2">Julio Calvo (ITCR)</td><td rowspan="2">Meeting at ProDUS-UCR: R. Pujol, K. Barrantes, L. Sánchez, E. Pérez</td></tr>
<tr><td>15:00-16:00</td><td rowspan="2">Meeting at UCR: Alejandra Rojas</td></tr>
<tr><td>16:00-17:00</td><td></td><td></td><td></td></tr>
</table>

Appendix 5. Agenda for April 23 stakeholder meeting

TIME	ACTIVITY
02:00-02:15	Agenda and introductions
02:15-02:30	Introduction to theTempisque project
02:30-02:40	Introduction to functions of key components, values, and vision.
02:40-03:15	Breakout group discussions
03:15-04:00	Group presentations, 10 min each
04:00-5:00	Wrap-up. Mechanisms for engaging their institutions

Appendix 6. Break-out group results from meeting with stakeholders

Group	Hydropower	Agriculture & Fish Farms
Members	Jose Miguel Zeledón, Sadí Laporte, Julio Calvo & Rafael Muñoz-Carpena	Jose Francisco Aguilar, Rafael Celis, Alejandra Rojas G, Marcelino Losilla & Mahmood Sasa
Reporter	Julio Calvo	Jose Francisco Aguilar
Current value or function	% of National Electric Generation	Generation of food
	Conflicts with timing of water release, esp for tilapia farms, and flooding irrigation	Agriculture is subordinated to energy production
	No immediate future plans for growth	Underground water used in irrigation is contaminated with pesticides and excess nutrients
	Information generated by ICE is considered an assest and source of revenue	
	No current regulation of the system	
Knowledge needs today	How to improve water delivery to better serve other uses	Alternative products with high nutritional value
	Alternative ways of regulation that do not compromise energy generation	Mechanisms for improving watering efficiency (drip vs. flooding), 60% of water goes to irrigation
	Potential for geothermic energy	Effects of differential water use between two Tempisque river sides
		Better mechanisms for decision-making to resolve conflicts
		Role of underground water on water balance
		Better mechanisms for charging water use, now it is charged by area irrigated, should be by water volume
		Impact of fish farms (11m3) on water budgets and quality, need for regulation mechanisms
		Assessment of water quality after irrigation - agricultural outputs
Future value or function (50/100 years)	Will require further input from Atlantic versant	Higher food demand due to increase in population size
	Potential projects involving drinking and irrigation water (Proy Rio Piedras, dw & Irr, Corobici -dw, Cuevas-irr), not yet funded	
Knowledge needs to understand behavior or assign its value/function in the future	Visioning needs to be presented in 20-30 year scenarios to be relevant for planning	Impacts of climatic events on food production and impact of global context on locl agriculture
	Better certainty on climate scenarios, 2 conflicting scenarios in IMN, observed high variability, projected longer mid-year dry season	Elimination of perverse incentives that force people to use technological packages with high environmental impact in order to qualify for subsidies
	Projections in changes in water flow with climate change	Mechanisms to increase value added for new products or for alternative productive or commercialization systems (e.g., cooperatives)
	Improve hydrometeorological station network	Estimates of water quanity and quality necessary to secure product quality
	Improve knowledge of underground water and incorporate in water balance	Future underground water availability
		Mechanisms to force conversion to more water-efficient crops
		Mechanisms to regulate quality of water output from agriculture
		Alternative crops that require less pesticides, fertilizers
		Alternative fish farming techniques that reduce use of antibiotics & hormones

Appendix 6. Continued

Group	Biodiversity & Conservation	Gulf of Nicoya, Fisheries
Members	Mario Arias, Monika Springer, Eugenio González, Edgar Espinoza, Tom Ankersen & Carolina Murcia	Jorge Jiménez & Miguel Campo Besco
Reporter	**Eugenio González**	**Jorge Jiménez**
Current value or function	Eco-systemic services to society	Upper gulf fisheries support 3000 fishermen, in 8 fishing communities. It has the highest productivity in the Pacific
	Unique remnant areas in this biogeographic region, of national and international importance (Ramsar sites)	Contains several species of high commercial value, e.g. snapper, some species have migratory behavior
	Dry forest is highly threatened at global level	Little knowledge of its dynamics or the dynamics of fish populations
		Contains 45,00 ha of mangroves
		It´s a zone of *social escape*
Knowledge needs today	How much water do wetland and dry forest ecosystems need in order to maintain its integrity	Type and amount of contamination reaching the Gulf of Nicoya from the Tempisque
	How have the forest and wetland changed so far, as a result of the regional use of water	Population status for key fish species
	How do the wetland and the undergaround water interact	Habitat needs at landscape-level (migrations)
		Optimal area to create an artisanal fishing zone
Future value or function (50/100 years)	Environmental services	Value increase by sea water fisheries (mariculture) of fish and bivalves (e.g., oysters, clams, etc.)
		Potential for tourism expanding from the Pacific coast
	Increased value due to continued ecosystem loss globally and regionally	Potential impact of sea level rise
Knowledge needs to understand behavior or assign its value/function in the future	Change in ecosystems' water demand with change in temperature and precipitation	Shape and size of the sea water level rise up the tempisque's mouth
	Change in ecosystems if water becomes limiting	Intrusion of sea water on coastal aquifers
	How will sea level rise affect current fresh-water dependent ecosystems	Changes in discharge patterns with climate change and demand for fresh water
	How will the socio-economical systems relate to the environment.	Changes in water quality output from agriculture and other uses on land
	How will changes in actors and their interaction affect the interaction human-environment.	Predited impacts of shift in land tenure on islansds, from public to private
	What is the potential for establishing corridors with other protected areas, especially in the lower zones that are most likely to be affected by sea-level rise.	Potential impact f increased tourism development on fisheries
		Techniques for cultivating fish, oysters and other bivalves
		Impact of climate change and contamination on fish population size and dynamics
		Regulatory plan for the coast and the hydrological resource.

Appendix 6. Continued

Group	Tourism and urban areas
Members	Rosendo Pujol, Cinthya Hernández, Alvaro Porras, Dan Childers, Gaby Stocks, Joelle Lange & Andrea Albertin
Reporter	**Cinthya Hernández**
Current value or function	Most economically dynamic sector, above agriculture & cattle raising
	It was difficult to put a value on a basic need: water for the population - it is simply essential Currently, meeting that demand is not a problem.
	Insufficient utility services (water and sewage)
Knowledge needs today	Planning processes are lacking; there is little regulation and no planning
	Zoning plans were just finished for the coastal areas (through a project financed by the IDB). However, the results haven't been made public.
	Although this isn't necessarily a knowledge need, the group identified the lack of clear definition of roles between intitutions as a major problem in this component.
	Instrumentation and monitoring of water quality
	More research on aquifers
	Better understanding of the resources.
Future value or function (50/100 years)	Tourism is going to grow in an uncontrolled manner. It will reach a reach a plateau, a breaking point where growth cannot continue due to lack of water
	City of Liberia is growing in population, and will likely continue to do so in the future. Population in rural areas will likely decrease.
Knowledge needs to understand behavior or assign its value/function in the future	Institutional definition of roles - and coordination of roles as well as monitoring and research relating to aquifers
	Territorial planning that indicates what is legally owned.
	Estimate from the US of what the population of retirees who settle in Costa Rica will be.
	Better data networks, more information, more accessible

Appendix 7. Agenda for Palo Verde workshop

Time	Tuesday April 24th	Wednesday April 25th		Thursday April 26th		Friday April 27th	
05:00-08:00		Walk down to wetland		early walk, bird watch			
07:00-08:00	**BREAKFAST**					River field trip, Breakfast to go	
08:00-08:30	Field Trip	Welcome and intro to wed/fri agenda	MS/CM	Analysis of current conditions - Continued -	WG		
08:30-09:00		WSC proposal and the project	RM/CM				
09:00-09:30		J Winter/J Southworth/P Waylan	KMcK			Definition of communication and coordination mechanisms	KMK
09:30-10:00		Rafael Celis. Economics, markets	KMcK				
10:00-10:30						**COFFEE BREAK**	
10:30-11:00		**COFFEE BREAK**		**COFFEE BREAK**		Funding opportunities	
11:00-11:45		Chris Kuzdas. Ben Warner	KMcK	Sustainability and visioning	DC		
11:45-12:45		Mahmood Sasa. the wetland and the park	KMcK				
12:45-13:30		**LUNCH**		**LUNCH**		**LUNCH**	
13:30- 14:00		Yamileth Astorga. Water allocation and use	KMcK	Definition of the long-term goal for the project-	CM	Next steps beyond WSC	
14:00-14:45		Jorge Jimenez. Nicoya Gulf and impacts on fisheries	KMcK				CM/RMC
14:45-15:00		General discussion	KMcK	**COFFEE BREAK**			
15:00-15:30		**COFFEE BREAK**		Formulation of specific aims	**WG**	**COFFEE BREAK**	
15:30-16:00		**Analysis of current conditions -** Domain of interest, stakeholder id, institutions, phyical dimension, drivers, to feed figure 1, and others developed on Dec wkshp	KMcK			Groups - Research questions	
16:00-16:30							
16:30-17:00				Stakeholder engagement strategies, how are we going to coordinate with them	GS		
17:00-17:30							
17:30-18:00							
18:00-18:30							
18:30-19:00	**DINNER**						
19:00-19:30							
19:30-ETC	HAPPY HOUR!!!	After dinner informal meetings					

Key to color-coding in agenda by thematic groups:

Introduction to Tempisque
Overall,System BIG picture
Project definition
WSC proposal development
Communication and integration

Appendix 8. Research questions submitted by collaborators during the April researcher´s workshop

Questions are organized by goals, topics, and temporal framework (from historic trends, to current status, to future scenarios)

GOAL ONE: Identify, quantify and analyze patterns of response of hydrological, ecological and human systems to stationary and non-stationary stressors (using the 7 criteria of sustainability adapted to this project)

Climate behavior:

- Can phases of El Niño Southern Oscillation (ENSO) and large-scale atmospheric drivers of precipitation be identified in Global Climate Models (GCM) for the observed time period?
- Can statistical relationships between Caribbean Low Level Jet (CLLJ) and Inter-Tropical Convergence Zone (ITCZ) be used to predict local precipitation for the cold phase, neutral, and warm phase El Nino?
- What changes in monthly mean local precipitation can be inferred from these changes using the derived statistical relationships?
- How do these predictions of precipitation compare to a simple addition of the mean climate change signal to the seasonal cycle to the observed record?
- How do the phases of ENSO and large-scale atmospheric drivers change under future climate scenarios?
- Can dynamical downscaling (regional climate models) improve predictions of local precipitation using the above methodologies?
- Does the spatial variability in precipitation change under future climate scenarios?

Impacts of climate on vegetation:

- Can phases of ENSO and large-scale atmospheric drivers of precipitation be identified in GCMs for the observed time period?
- Can statistical relationships between CLLJ and ITCZ be used to predict local precipitation for the cold phase, neutral, and warm phase El Nino?
- What changes in monthly mean local precipitation can be inferred from these changes using the derived statistical relationships?
- How do these predictions of precipitation compare to a simple addition of the mean climate change signal to the seasonal cycle to the observed record?
- How do the phases of ENSO and large-scale atmospheric drivers change under future climate scenarios?
- Can dynamical downscaling (regional climate models) improve predictions of local precipitation using the above methodologies?
- Does the spatial variability in precipitation change under future climate scenarios?

Impacts of natural ecosystems on climate/production

- What are the impacts of past, present and future forest cover on hydrologic cycling (including near-shore ocean effects) and regional climate?
- Can NPP estimates across a 12 year time serve as a proxy for estimating crop production in the basin?

Natural ecosystems behavior

- What role did/does river pulse flooding events play in the Palo Verde marsh?
- What is the appropriate percent cover of open water and emergent vegetation in the PVW to maximize faunal use? (Also addresses goal 2)

Impacts of human activities on natural systems

- What is the water budget of the PVW and to what extent is the degradation of the PVW a consequence of changes in water management and allocation over the past 40 yrs?
- What are the effects of and interactions between nutrients, hydrology, fire, sedimentation on wetland plant density and composition in the PVW?
- How do social, political and economic changes affect forest cover and land use change in the basin, and in turn affect hydrology.
- What effect do contaminants (pesticides, herbicides, hormones, heavy metals) have on populations of fishes, birds, reptiles, herpetofauna and other aquatic animals in the Larger Tempique-Bebedero Region (LTBR)?
- What are the causes of changes in species composition in the PVW?
- What is the impact of large-scale and intensive agriculture on natural ecosystems?
- How are the fisheries in the estuary being impacted/regulated by the variations in water flow and quality from the Tempisque?
- Are estuarine wildlife populations restricted in their distribution and movements as a result of changes in floodplain conditions and flow characteristics?
- Is the wetland flood pulse hydrologically connected to factors outside the wetland and not just wetland-local precipitation/conditions?
- How much and which type of pollution are the agricultural, aquacultural and urban centers, adding to the hydrological system of the Tempisque Basin and the Nicoya Gulf?
- How much is the contribution of the nutrients runoff from the Tempisque basin, affected bloom algae of the Nicoya Gulf?
- Are the soils and sediments polluted with heavy metals, as residues from the pesticides application?

Water system behavior

- Does the *relevance* of the water system model, which combines the optimum level of complexity with the minimum uncertainty, allow the understanding of the Tempisque water system behavior?
- Can an innovative exploratory mechanistic (stochastic-deterministic) approach yield a useful proxy of the complex water system?
- Does the visioning of future states of the water system (as a step-wise complexity model building with concurrent global sensitivity and uncertainty exploration) allow identifying

the important system drivers that control desirable sustainable outcomes that include human and ecological values and services?

- What is the role of groundwater in the Tempisque basin water budget?
- What are the sources and flow paths of groundwater to the Tempisque and Bebedero rivers, wetlands and the Gulf of Nicoya?
- Do the main water catchments managed by the ASADAS have enough water to sustain the increasing demand of population, economical activities, and climate change?

Impacts on water system behavior

- Are there critical hydrological/social features in the catchment (either as a spatial/temporal pattern or a specific socio-ecological process) that act as buffers for resilience?
- Are there social features that serve to destabilize or encourage the transition from one state to another?
- What level of inputs is required to create and/or sustain a change from the current state in watershed and ecosystem service configuration?
- How do the water-using components of the Tempisque Basin depend and affect each other?
- How do the relations among the water-using components of the Tempisque Basin change under climate change?
- How will climate variability, climate change, land cover change and extraction for human uses affect the stores, fluxes and flow paths of groundwater in the basin?
- How will climate variability, climate change, land cover change and extraction for human, agriculture, aquaculture use affect fate and transport of solutes (nutrients, pesticides, antibiotics, hormones) to water supply wells, rivers, wetlands, and the gulf?
- What is the risk of increased pollution and reduced water volume at catchments managed by ASADAS and Municipalities?

Use/decision process

- How does the political economy shape farmer decisions
- What socio-economic changes in the coastal communities are associated with changes in the socio-economic dynamics of the basin and the biophysical of the basin?
- What drives land user decisions in the Tempisque Basin?
- How do water users make decisions about water use in the face of scarcity?
- Is the distribution of water equitable in the Tempisque River Basin?
- How do different actors understand equity and what obstacles to they identify for its enactment?
- What is the system of incentives, disincentives and distortions that drive the use of water in the watershed?
- Who are the winners and losers under the current pattern of water use in the watershed (externalities)?

- What are the qualitative and quantitative welfare and equity consequences of the current pattern of water use in the watershed?

Governance

- What are the technology, stakeholder arrangements, and adaptive governance schemes?
- What are the natural resource use conflicts (paradigmatic legal cases) and collaboration efforts among stakeholder and institutions?

GOAL TWO: Identify, quantify and analyze pathways to sustainability, using ASU stakeholder engagement model.

Nat System sustainability

- What are appropriate local-scale management responses to reverse the declines and restore properties and functions of PVW and aquatic fauna?
- What are appropriate basin scale interventions necessary to enhance long-term resilience of the PVW?
- Are there financial mechanisms available by which estuarine economic sectors (fish, tourism) can support conservation measures within the basin level?
- What ecosystem response times are required to transition from one undesired to state to a more desired watershed and ecosystem service configuration?

Water Sustainability

- How similar or different are the sustainability solutions produced by the basin-wide (top-down) approach vs. the local-scale (bottom-up) approach?
- Are there unanticipated differences in the approaches used to generate sustainability solutions at the basin-wide scale (top-down) vs. the local scale (bottom-up)?
- How similar or different are the sustainability solutions produced by the sustainability science approach (basin-scale or local-scale) compared with solutions generated by only "expert opinion"?
- Is the current pattern of water use in the watershed sustainable?
- How can sustainability be retrofitted into large scale engineered water systems that were built to last but were not designed around principles of water sustainability?
- Can sustainability indices be combined with hydrology and land use-multi-agent based modeling to study current water sustainability in the Tempisque Basin?
- Can a multi-agent based model be used to investigate the impact of future climate change and alternative pathways and their impacts on water sustainability of the basin?
- Are there win-win situations in managing water sustainability in the Tempisque Basin, including the regional society, agriculture, wetlands, and fisheries? How would that change under climate change?
- What are the most appropriate basin specific measures of sustainability that characterize the integrity and irreplaceable functions of the groundwater system

Water use

- What will be the impact of climate change on the pattern of water use in the watershed under current conditions?
- What will be the impact of an ambitious bio-fuel production program (mostly sugar cane alcohol) on the use of water and on the biophysical and socioeconomic sustainability of the watershed?

GOAL THREE: Identify and analyze the legal framework and institutional capacity to address sustainability changes

Stakeholders

- Which are the key stakeholders that should participate in an organization structure for sustainability?
- How can stakeholders be seated at the negotiating table to understand the trade-offs they face and negotiate water use arrangements that result in an efficient and sustainable use of watershed resources?

Institutions

- What kind of temporal scales are at play in defining institutional responses to basin-wide ecological and economic stressors?
- Using a coupled socio-ecological model, what institutional reaction times (and network patterns) are required to comprehend adversely trending indicators, formulate a workable and comprehensive plan, and execute a course correction?
- Can small scale infrastructure and institutions (such as ASADAS) efficiently provide sustainable water management and delivery services as a component of national development policy?
- What institutional structures are required to establish water sustainability under current variable climatic conditions?
- How do institutional structures need to be changed to prepare the basin for climate change?
- How will institutions allocate water to users as scarcity becomes a reality?

Governance structure

- What alternative – and opposition – water governance regimes exist or have existed in the Tempisque-Bebedero basin?
- Why have some alternative water governance regimes successfully opposed prevailing institutions while others have not?
- Are the existing institutional systems/structures capable of implementing the necessary sustainable solutions or are new institutions or governance structures needed?
- How to link important institutions at the estuarine level (like INCOPESCA) with the institutions working at the basin level?
- Under what conditions might alternative water governance regimes accelerate regional progress toward sustainability or, conversely, de-rail socio–ecological system stability?

- What organization structure is the one that is most likely to generate waters sustainability at the basin level?

Incentive mechanisms

- Can payments for environmental services serve as the basis for capturing the externalities that result from the unintended consequences of large scale engineered water projects designed to manage water for multiple uses?

Law and policy

- How has 1941-based water policy and water governance in Costa Rica been able to adapt and evolve to meet 21st century demands?
- How have new policies (e.g. environmental flows) been integrated in the water governance framework in Costa Rica despite reliance on a 1941 water law?
- How to implement the environmental flows concept in the regulatory framework?
- What legal and policy reforms are required to make water use more sustainable under different production, conservation, and climate change scenarios?