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Sustainable Water ActioN - SWAN

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Bottom picture Horseshoe Bend, Arizona, USA
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PROLOGUE

SWAN (Sustainable Water Action) is a four-year International Cooperation Project, funded by the European Commission, which aims to promote scientific cooperation between the United States of America and European countries. It involves five European Union Member States (Bulgaria, France, the Netherlands, Spain and the United Kingdom) and the USA. The European teams belong to the Bulgarian Academy of Sciences - National Institute of Geophysics, Geodesy & Geography (BAS-NIGGG; Bulgaria), the Centre National de la Recherche Scientifique (CNRS, France), the UNESCO-IHE Institute for Water Education (IHE; the Netherlands), the Universidad de Sevilla (US; Spain), and the University of the West of England (UWE; United Kingdom). The American team is from the University of Arizona (UoA). The project builds upon the experiences of the International Research Center (UMI) iGLOBES (Interdisciplinary and Global Environmental Studies), established in 2008 by the French CNRS (Centre National de la Recherche Scientifique), and those of the Department of Hydrology and Water Resources at the UoA. The project is based at the UoA campus in Tucson, Arizona.

The scientific and institutional objectives of SWAN are to establish a common framework, for interdisciplinary research about water resources management, which can serve as the scientific basis for a permanent collaborative organization. A major step is to realize a '*Network for a Transatlantic Dialogue on Water*' (NTDW), supporting long-term international collaboration between scientists, students and stakeholder communities. From a scientific perspective, the NTDW will build upon an explicit recognition of uncertainty and complexity in water-related research, and encourage a commitment to trans-disciplinary research and comparative approaches. Accordingly, its purpose is to develop effective modes of collaboration with stakeholders and other partners in the field of water resources.

SWAN aims, over time, to extend the Network to incorporate partners from other countries in the Americas and Europe. Since the beginning of the project in March 2012 several scientific and institutional discussions have been carried out and considerable progress towards the scientific goals has been made. This document collects together several reports that describe the main scientific achievements, organized into five chapters corresponding to the Deliverables turned in to the European Commission.

Chapter 1

-Deliverable 1.1-

Relative Effect of Land Use - Land Cover Change and Climate Change on Extreme Precipitation Events In the Tucson-Phoenix Urban Corridor and Associated Watersheds

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1. INTRODUCTION

Humans have profoundly altered their environment. Nearly one-third of the global land cover has been modified (Lyon et al. 2008) while at the same time, the composition of the atmosphere has been dramatically altered by anthropogenic greenhouse gas emissions (IPCC, 2007). Changes in extreme events are expected to be one of the most dramatic consequences of our changing environment (NRC, 2011), and could pose huge pressures on the health, economy, and overall wellbeing of at-risk communities. In this work we will focus on the effects of climate and land cover change on urban environments, with a particular emphasis on extreme rainfall events. Urban regions compose only a small fraction of the land surface (roughly 3%) but the percent of the population living in cities has increased dramatically and is likely to increase in the coming decades (see Figure 1). Projections show that by 2030, 3 out of 5 people will live in urban regions (UN, 2007). As a result of the number of people in urban areas, as much as 35 percent of human induced CO_2 emissions originate from cities (Hutyra et al., 2011). At the same time, urban areas are characterized by high density of population and civil infrastructure, and serve as social, economic and political hubs. Consequently, urban areas are more vulnerable to extreme precipitation and flooding events (Rosenzweig et al., 2010). In fact, many of the major weather disasters in the last 30 years have been in urban areas, ranging from major ice and snow events, to floods, and hurricanes - these billion dollar weather events have had huge social and economic cost (NRC, 2012). Our area of study will be the Phoenix-Tucson area of the semiarid southwestern United States, as this region has experienced some of the most rapid urban development in the United States in the past six decades.

Climate change and land use/land cover change (LULCC) will affect the surface hydrologic response of urban regions and their associated watersheds. We will look at the changes in hydrologic response using the concept of “Ecosystem Services”. Ecosystem services are the contributions of ecosystem structure and function - in combination with other inputs - to human well being (Burkhard et al., 2012a). The additional note ‘in combination with other inputs’ refers to the ways human activities modify ecosystems for fulfilling the needs of the society. This definition has been promoted by the ’Salzau Message’ on Sustaining Ecosystem Services and Natural Capital (2010). Still according to the same document, ecosystems, ecosystem functioning, and ecosystem services are being threatened and degraded by human activities, and the situation will be exaggerated by climate change and biodiversity loss.

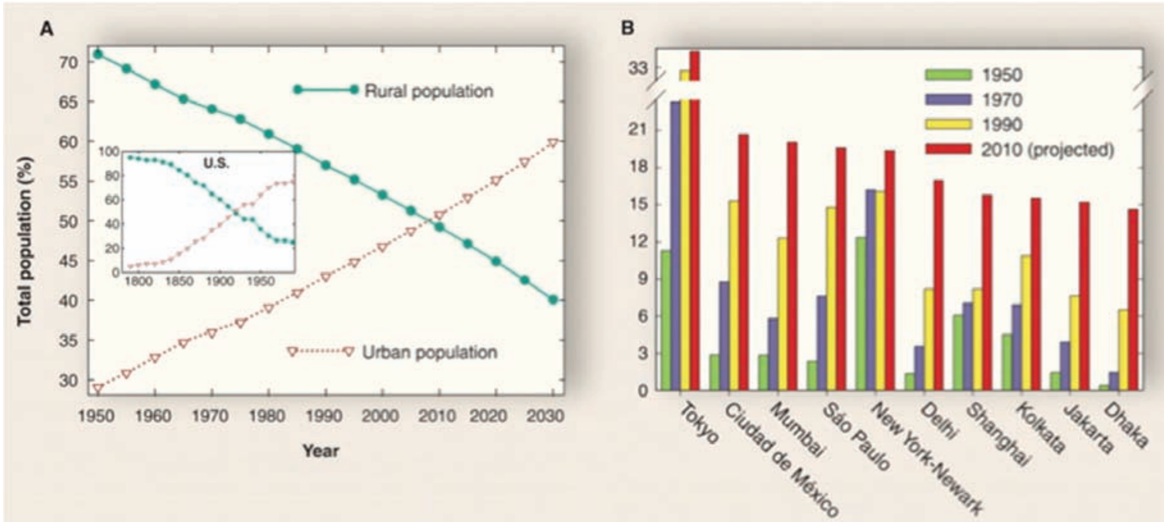

Figure 1. (A) Change in world urban and rural population (%) from 1950 to 2030 (projected). Inset shows comparable data for the United States from 1790 to 1990. (B) Change in population of the 10 largest urban agglomerations from 1950 to 2010 (projected), ranked from left (largest) to right by their projected population size in 2010: Tokyo, Japan; Ciudad de México, Mexico; Mumbai, India; Sáo Paulo, Brazil; New York–Newark, USA; Delhi, India; Shanghai, China; Kolkata, India;

The ecosystem services approach studies the human-environmental systems in a manner that provides qualitative and quantitative data that is crucial for the better understanding of the consequences of human activities on nature and society. Its analysis methods are developed in a way that provides more efficient and comprehensive data that helps to identify and quantify the ecological and socio-economic trade-offs and synergies on which decision-making should be based ('Salzau Message'). Climate change has the potential to substantially alter the provisioning of essential ecosystem services (MEA, 2005; Naidoo et al., 2008), with individual ecoregions and ecosystem services projected to exhibit different degrees of vulnerability (Gonzalez et al., 2010; Beaumont et al., 2011) (in Cheelkin et al., 2013). Climate change is expected to be one of the main factors affecting human health and well being over the coming decades (Thomas et al. 2004; ME Assessment 2005; Schröter et al. 2005; Pimm 2009). Ecosystem services can also be altered by land use change. A method for assessing the vulnerability of ecosystem services to land use change is presented by Metzger et al., 2006. 'Vulnerability' is defined as the degree to which a system is susceptible to, or unable to cope with, adverse natural or anthropogenic changes.

In this work we will investigate the combined effects of climate change and land use / cover change (LULCC) on extreme precipitation in the Tucson-Phoenix corridor and their associated watersheds. We will evaluate how the ecosystem services provided by the watersheds might be affected in the future. We address this question through the use of historical observations and numerical modeling. The work is divided in two objectives:

Objective 1) We will investigate the relative effect of projected LULCC and projected climate change on extreme precipitation events in the Tucson-Phoenix urban corridor using the Weather Research Forecast (WRF) regional climate model coupled to a state-of-the-art land surface model with detailed characterization of urban regions. Our hypothesis is that these two different anthropogenic forcings act synergistically to magnify extremes.

Objective 2) We will quantify how climate change and LULCC can result in changes in ecosystem services provided by the Verde Basin Watershed. We focus primarily on the flood mitigation role of the watershed.

2. BACKGROUND

2.1. Effects of Climate Change on the Hydrology of Arizona

Arizona is located in the subtropical latitudes of the Southwestern US and is characterized by hot summers and mild winters. The climate in the region is highly variable, as it is affected by the complex interplay between the mountains, proximity to the Gulf of California, Gulf of Mexico and Pacific Oceans. During the winter, the mid-latitude storm track brings moisture and precipitation to the region. Variability in winter precipitation is strongly controlled by El Nino Southern Oscillation (ENSO), which brings wetter than average and cooler than average conditions to the region (Dettinger et al. 1998). The North American Monsoon (NAM) is the primary driver of summer precipitation. However, the NAM exhibits strong interannual variability that has also been linked to the Pacific Ocean (Castro et al. 2007).

Global climate models (GCMs) are the primary tools used to understand how anthropogenic greenhouse gas emissions could affect future climate throughout the globe. Many studies have analyzed projected climate changes in the Southwestern US using ensembles of different GCMs with several different possible pathways of greenhouse gas emissions. Some common conclusions that emerge from these studies are summarized as part of the National Climate Assessment (Garfin et al. 2013). The broad conclusions of the studies are that mean temperature is projected to increase substantially, particularly in the summer and fall. Mean precipitation is projected to decrease in southern Arizona, while precipitation extremes are projected to increase. The average higher temperatures will likely bring less mountain snowpack accumulation and reductions in streamflow.

2.2. Possible Changes in Ecosystem Services associated to Climate Change and LULCC

The concept of ecosystem services is based on the assumption that the ecosystem's structure and functions provide goods and services, which contribute to human well being. This concept has become a very popular scientific topic during the last two decades as it provides an appropriate methodological framework for linking both physical and socio-economic sciences with decision making. Ecosystem services are usually classified into four major groups: provisioning, regulating, cultural and supporting (Costanza et al. 1997; de Groot et al. 2002; MA, 2005). However, the supporting services are omitted by some researchers (Burkhard et al.

2009) as they do not contribute directly to the human well-being. Various ecosystem functions contribute to hydrological processes; therefore they can be defined as water related ecosystem services. They include: 1) freshwater (provisioning) – use of water for drinking, domestic use, irrigation, industry etc.; 2) water flow regulation (regulating) – maintaining of water cycle features such as water storage and buffer, natural drainage, flood regulation etc.; 3) water purification (regulating) - the capacity of ecosystems to purify water from sediments pesticides, disease-causing microbes etc. (Kandziora et al. 2013). In this work we will focus on water flow regulation ecosystem service. Flood regulating services are based on the water flows regulation functions of ecosystems that reduce the amount of surface runoff and consequently the flood hazard. The flood regulating services can have preventive or mitigating functions. In the first case, the ecosystems (i.e. forests) redirect or absorb parts of the incoming water (from rainfall), reducing the surface runoff and consequently the amount of river discharge. The mitigation function is related to ecosystems (i.e. flood plains and wetlands) which provide retention space for the water surplus to spill, thus reducing the flood's destructive power. The water retention function can be quantified using watershed based hydrological models and GIS spatial analyses (Nedkov and Burkhard, 2012).

In 2008 the Committee on Ecological Impacts of Climate Change, National Research Council, published a report on 'Ecological Impact of Climate Change', making a profound analysis of the topic. Climate change can impact ecosystems in many ways. A few of many possible examples are discussed below.

Climate change is linked to a number of other changes that already can be seen around the world. These include earlier spring snowmelt and peak stream flow, melting mountain glaciers, a dramatic decrease in sea ice during the arctic summer, and increasing frequency of extreme weather events, including the most intense hurricanes (IPCC 2007b). Changes in average annual precipitation have varied from place to place in the United States.

Climate dynamics and the cycling of water between land, rivers and lakes, and clouds and oceans are closely connected. Climate change to date has produced complicated effects on water balances, supply, demand, and quality. When winter precipitation falls as rain instead of snow and as mountain snowpacks melt earlier, less water is "stored" in the form of snow for slow release throughout the summer (Mote 2003), when it is needed by the wildlife in and around streams and rivers and for agriculture and domestic uses. Even if the amount of precipitation does not change, warmer temperatures mean that moisture evaporates more quickly, so that the amount of moisture available to plants declines. The complex interaction between temperature and water demand and availability means that climate change can have many different kinds of effects on ecosystems.

The character of extreme weather and climate events is also changing on a global scale. The number of frost days in midlatitude regions is decreasing, while the number of days with extreme warm temperatures is increasing. Many land regions have experienced an increase in days with very heavy rain, but the recent CCSP report on climate extremes concluded that “there are recent regional tendencies toward more severe droughts in the southwestern U.S., parts of Canada and Alaska, and Mexico” (Kunkel et al. 2008, Dai et al. 2004; Seager et al., 2007).

These seemingly contradictory changes are consistent with a climate in which a greater input of heat energy is leading to a more active water cycle. In addition, warmer ocean temperatures are associated with the recent increase in the fraction of hurricanes that grow to the most destructive categories 4 and 5 (Emanuel 2005; Webster et al. 2005).

2.2.1. Changes in Extreme Precipitation

Our interest in extreme precipitation events stems in part from a previous study published by the group (Dominguez et al. 2012). In this study, we analyze an ensemble of dynamically downscaled climate model projections for the Western US. Dynamical downscaling is a method used to bring the coarse scale GCM projections (that are on the order of 200 km) to the regional scale using regional climate models. By analyzing this ensemble, we find a consistent and statistically significant increase in the intensity of future extreme winter precipitation events over the western United States (Figure 2). We define extreme precipitation as events that have a probability of occurring once every 20 or 50 years. All eight simulations analyzed in our work consistently show an increase in the intensity of extreme winter precipitation with the multi-model mean projecting an approximate 6% increase in 20-year return period and 7% increase in 50-year return period daily precipitation for the southwestern US. In contrast with extreme precipitation, the multi-model ensemble shows a decrease in mean winter precipitation of approximately 7.5% in the southwestern US.

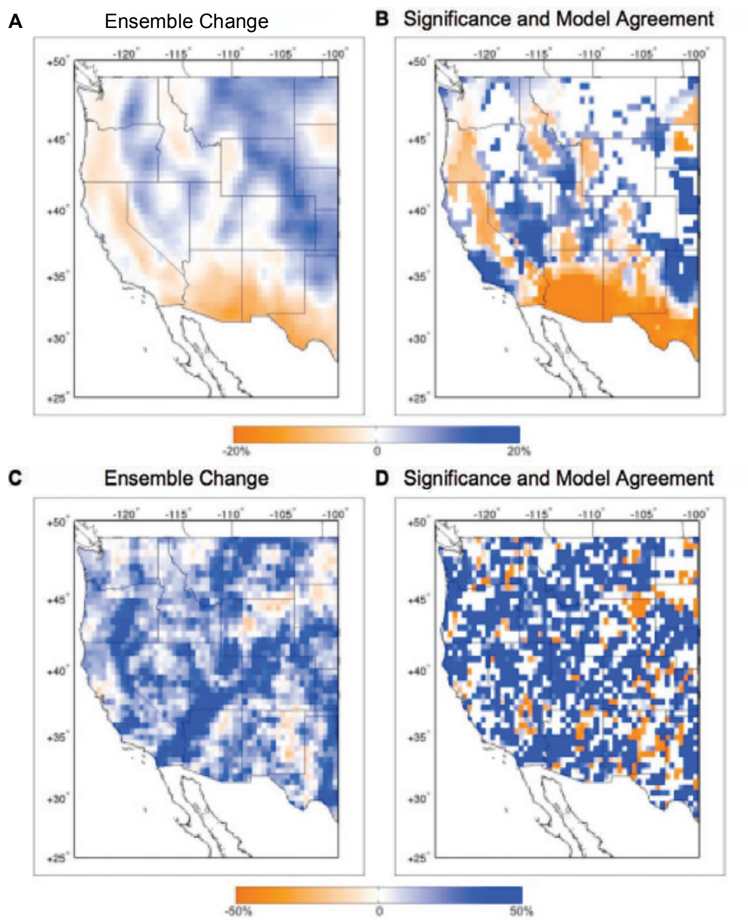

Figure 2. (A) Ensemble average percent change in mean winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (B) Ensemble average percent change in mean winter precipitation for only those models with statistically significant changes and only where more than 4 models agree on the sign of the change. (C) Ensemble average percent change in 50-year return period winter precipitation between the historical (1968–1999) and future (2038–2070) periods for all simulations. (D) Ensemble average percent change in 50-year return period winter precipitation for only those models with statistically significant changes and only where more than 4 models agree on the sign of the change.

2.2.2. Projected changes in Streamflow in the Verde Basin due to Climate Change

Our group has also explored how future climate change could potentially affect the hydrology of the Verde River Basin (Rajagopal et al., 2012, 2013). The Verde River Basin and the adjacent Salt Watershed are part of the larger Colorado River basin, and are the main source of water supply for approximately 4 million people living in the Phoenix metropolitan area.

In this study, we use the Variable Infiltration Capacity (VIC) model for the Salt and the Verde watersheds in central Arizona, drive the model with climate data from five statistically downscaled global climate models for the historical period and the future period. We then assess the physical hydrologic processes giving rise to changes in streamflow in the basin. While previous studies have covered the larger Colorado River basin, these studies are largely not beneficial in terms of actionable data for the management of these watersheds in the lower basin.

We find that declines may be expected in streamflow for both the Salt and the Verde River basins (Figure 3). Because snowmelt is currently 70% of total streamflow, the declines can be attributed primarily to increases in mean temperature, small decreases in mean winter precipitation and declines in snowmelt.

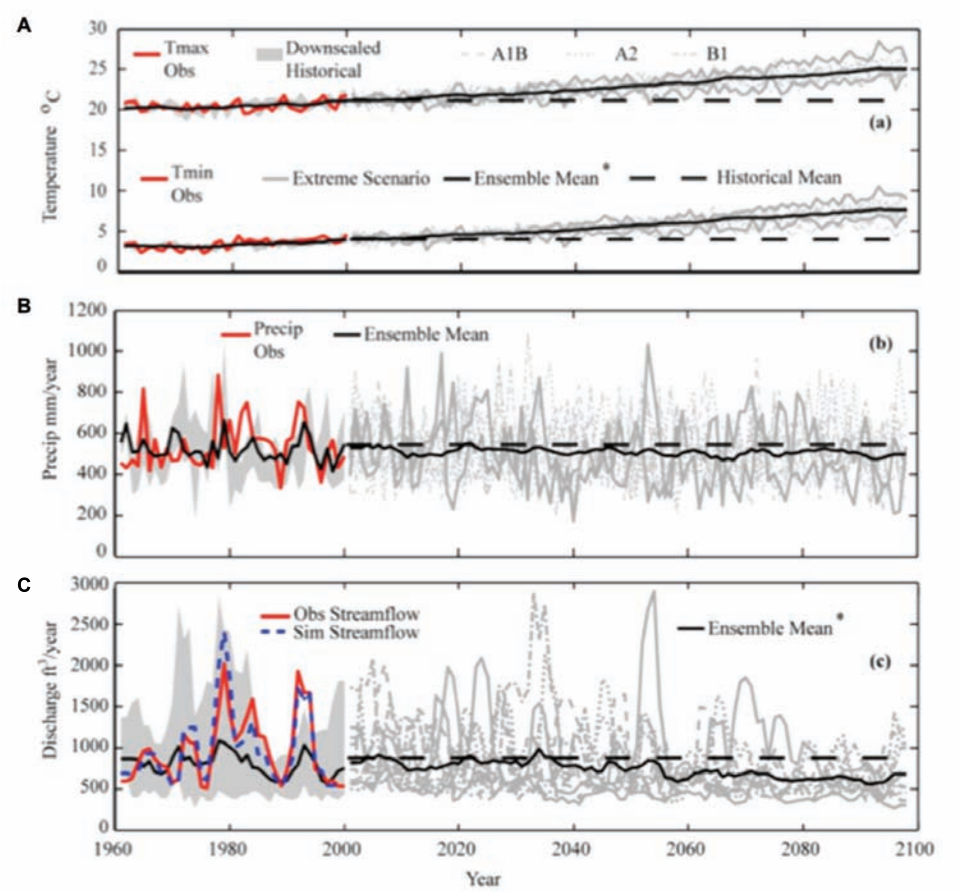

Figure 3: Historical and Future change to (A) temperature, (B) precipitation and (C) streamflow in the Salt River Basin. The * indicate that the ensemble mean had a significant trend using a non parametric test at the p-value 0.05. (Taken from Rajagopal et al., 2013)

2.2.3. Effects of Urbanization on the Hydrometeorology of Arizona

While a great deal of attention has been focused on the effects of changes in atmospheric composition on precipitation, less attention has been given to LULCC on precipitation patterns (Pielke et al., 2011). Urban regions in particular affect the overlying atmosphere in several ways. Perhaps the most well known mechanism is through the urban heat island (UHI). Changes in night-time temperatures associated with UHI have been found to be up to 10K in Phoenix (Grossman-Clarke et al., 2010). As natural surfaces are replaced by surfaces with different heat capacity, thermal inertia and albedo, urban regions tend to store more energy and convert it to sensible heat (Shepherd et al., 2005). In addition to the UHI, urban regions are can alter precipitation patterns through 1) changes in convergence patterns due to increased surface roughness; 2) destabilization of the boundary layer due to increased surface sensible heat flux, and in some cases due to irrigation; and 3) enhanced aerosols for cloud concentration nuclei (CCN) (Shepherd et al., 2005; Changnon et al., 1981; Shepherd et al., 2002; Diem and Brown, 2003).

Increased precipitation downwind of urban regions has been documented by Changnon et al. (1991) and Braham et al. (1981). Diem and Brown (2003) argue that increases in summer precipitation totals over the Lower Verde basin, located downwind of Phoenix AZ, could be due to urbanization and irrigation in the Phoenix area. The authors hypothesize that convergence and contribution of water vapor resulting from irrigation are the dominant mechanisms for this downwind effect (CCN concentration changes play a secondary role). Shepherd et al. (2006) used a 108-year precipitation historical record and found that the convective monsoon thunderstorms that form east of Phoenix propagate west, and interact with urban dynamic circulation to form precipitation over the metropolitan area. Changes in intensity and frequency of precipitation associated with urbanization have also been documented in the Phoenix area. The rapid growth of the city of Phoenix has been related to an increase in the frequency and intensity of late afternoon and evening monsoonal storms, with declines in events between midnight and noon (Balling and Brazel, 1987). The frequency of intense summer convective storms over Phoenix has also increased in recent decades (Selover, 1997). More recently, detailed regional climate model studies have evaluated the effect of LULCC on energy and precipitation in the Greater Phoenix area (Georgescu et al., 2009a; b). Using detailed land cover descriptions of the area for 1973, 1992 and 2001 as boundary conditions for the RAMS regional climate model, the authors find that mesoscale circulations were stronger for the 2001 than the 1973 period. They also found enhanced precipitation and argue that the physical mechanisms are a complex interplay of micro-meso and large-scale circulation during the monsoon season. However, precipitation recycling seems to play an important role in precipitation enhancement as well (Georgescu et al., 2009b).

3. METHODOLOGY

The primary tool we use to investigate the combined effects of climate change and LULCC on extreme precipitation in the Tucson-Phoenix corridor and their associated watersheds is numerical modeling. Numerical models will allow us to perform experiments and sensitivity analyses to test the relative effect of these different forcing mechanisms. Furthermore, numerical models allow us to incorporate future scenarios of land use and large-scale climate, and evaluate the regional response. The numerical model that we use to simulate the regional climate of the historical period 1990-2000 and the future period 2030-2040 is the WRF-Noah-UCM model This coupled land surface and urban modeling system for the community weather research and forecasting (WRF) regional climate model is an international collaborative research and development effort aim to addressing emerging issues arising in the urban areas (Chen et al., 2011). Our region of interest encompasses the Tucson-Phoenix corridor, which encompasses the urban regions, and the Salt, Verde, Santa Cruz and Gila River basins. The primary (highest resolution) domain of the WRF-Noah-UCM will cover approximately the entire state of Arizona.

3.1. Models

3.1.1. Weather Research Forecast (WRF) Model

Global Climate Models (GCM) usually fail to represent urban areas due to their coarse resolution (usually ~200 km) and the relative small size of urban areas. One of the most important advances in urban meteorological forecasting has been the development of urban canopy models (UCM) for Numerical Prediction Models (NWP, e.g. WRF) with increasing resolution to few kilometers. This allows a better representation of urban areas and also as major improvement compared to former tools. We intend to implement the single layer urban canopy model (UCM) coupled in WRF Version 3.4.1 to investigate the effect of LULCC (including urbanization) and climate change on regional climate, especially precipitation extremes which can potentially cause extensive damage and are important for urban flood infrastructure planning.

The regional climate model we use is the Advanced Research version of Weather Research and Forecasting Model (WRF) (Skamarock et al., 2005). It was collaborative effort principally among the National Center for Atmospheric Research, the National Center for Environmental

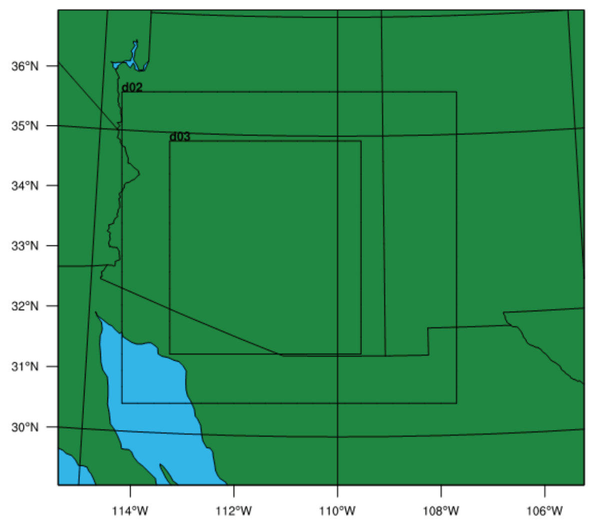

Figure 4. Domain configuration, outer domain resolution is 30km, intermediate 10km and inner domain 2.5 km.

Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), THE Naval Research Laboratory, the University of Oklahoma and the Federal Aviation Administration (FAA). The Advanced Research WRF (ARW) modeling system is designed to be flexible, portable and efficient on parallel computing platforms, and suitable for use in a broad range of applications across scales ranging from meter to kilometers. The WRF model features nonhydrostatic, compressible with a mass coordinate (Chen et al., 2011, Skamarock et al., 2005). The physical parameterizations that will be used in the initial runs includes: Morrison double-moment scheme for all nests, CAM scheme which allows for aerosols and trace gases for longwave and shortwave radiation, Eta similarity which based on Monin-Obukhov with Zilitinkevich thermal roughness length and standard similarity function for the surface layer parameterization and land surface use the unified NCEP/NCAR/AFWA scheme, Mellor-Yamada-Janjin scheme for the planetary boundary layer physics, for the outer two domains turn on the cumulous parameterization using Kain-Fritsch scheme. Twoway interaction is used to communicate information between model run and large scale observation data.

In our numerical experiments, the coupled WRF/Noah/UCM model is integrated over the southwestern United States, with latitude 28N to 36N, and longitude 115W to 105W. The domain mainly encompasses the state of Arizona. It has 3 nested domains with outer grid size 30 km, intermediate domain grid spacing 10 km and most inner domain grid spacing 2.5 km. The graphical representation is shown in Figure 4.

3.1.2. Urban Canopy Model

Chen et al, 2004 developed a coupled Noah/Urban-canopy model (UCM) based on Kusaka et al. 2001. The Noah-UCM is coupled to the regional climate model WRF Version 3.4.1. The Noah LSM has single vegetation canopy layer and the following prognostic variables: soil moisture and temperature in the soil layers, water stored on the canopy and snow stored on the ground (Chen et al., 2004). In our experiment, we use the Noah LSM as our land surface model (Chen et al., 1996) to provide surface energy fluxes and surface skin temperature which serve as the boundary conditions for the atmospheric model. The Noah LSM has a bulk parameterization for urban land use (Liu et al. 2004, Tewari et al. 2004). However, we are using a single layer urban canopy model (UCM) to better represent the energy and temperature fluxes in the urban region. This single-layer urban canopy model was first developed by Kusaka et al. 2001 and further modified by Kusaka and Kimura, 2004. It consists of 2-dimensional symmetrical street canyons with infinite length, and treats radiation in 3 dimensions - which consider the canyon orientation and the diurnal variation of azimuth angle (Tewari et al. 2007). The UCM model estimates temperature and sensible and latent heat fluxes at roof, wall, and roads - which later serve as lower boundary conditions for atmospheric model.

Chen et al, 2004 show the difference of urban temperature by comparing simulation result of traditional parameterization and the UCM models. The result show that traditional approach fails to capture the UHI effect over Houston area.

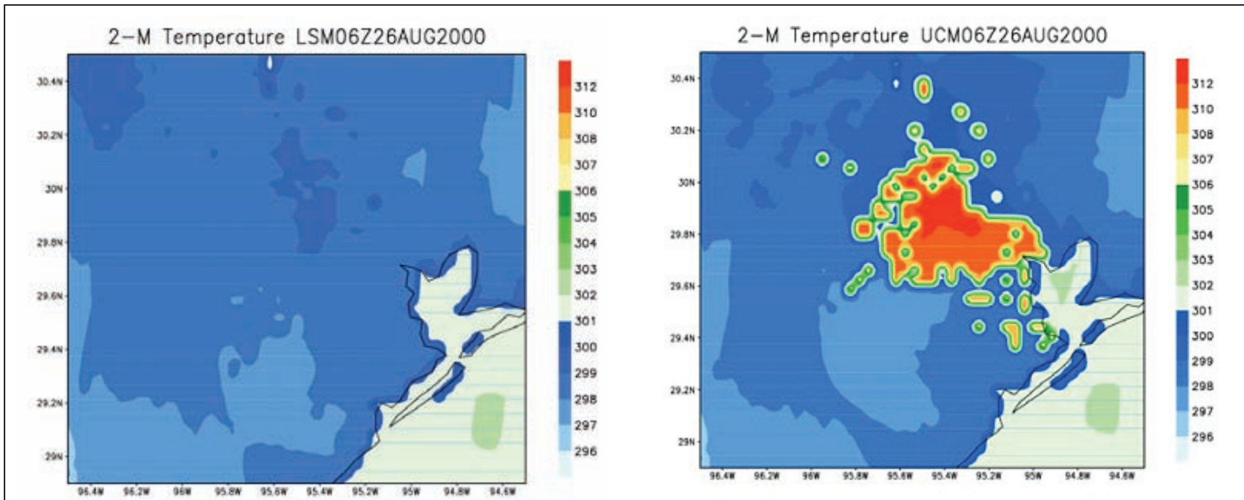

Figure 5. WRF simulation results of temperature without UCM (left figure) and with UCM (right figure) of Houston area

3.1.3. Projections of Future Land Use

The land use map we use to evaluate the effects past land use change on climate obtained through the North America Land Cover (NALC) data (year 2005, shown in Figure 6 below). The NALC dataset was produced by Canada Centre for Remote Sensing from observations acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS/Terra), at a 250-meter spatial and 10-day temporal resolution. In addition to the map of land use for the year 2005, we also have projections of land use for the future (year 2050, shown in Figure 6 below) to simulate future scenarios. The future land use projection is obtained by merging the North America Land Cover data (NALC, 2005) with projection data. For the most part of Arizona, we use the State of Arizona's land use projection that was generated by Maricopa Association of Governments (MAG) using the Red Dot Algorithm (RDA). The algorithm could be simply stated as follows: 1) dividing the land-use extent and pattern according to land ownership of Arizona, 2) exclude areas that are unlikely to develop or likely to develop relative slowly into urban areas, e.g., military base, natural parks, forests, native American lands, Bureau of Land Management (BLM) lands, flood plains and steep slopes, 3) the rest of which are State Trust lands and private lands that are places where future development would possibly occur. For the areas around and south of Tucson, an urban developing model named SLEUTH model was used to simulate future condition (Norman et al., 2012).

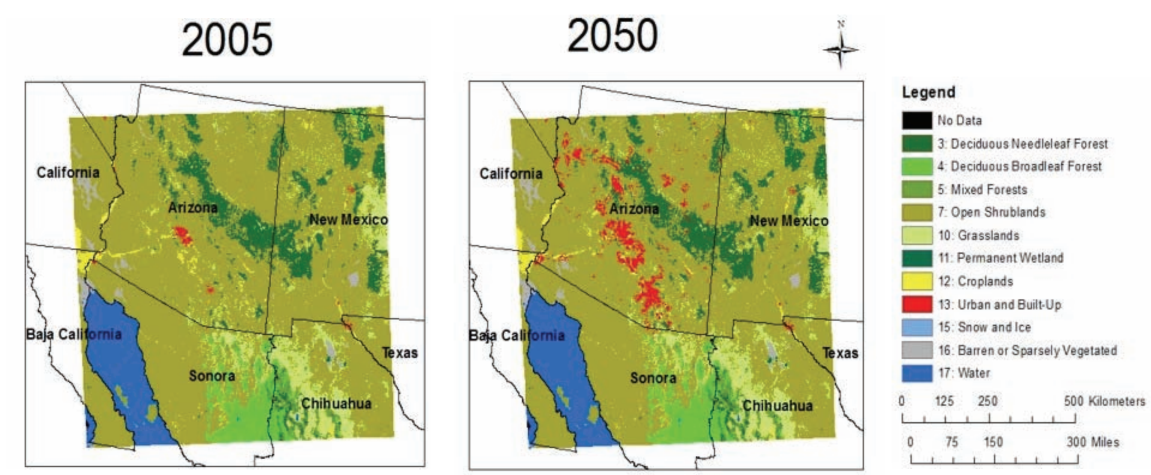

Figure 6. Land use map for year 2005 representing current condition and land use projection for year 2050 representing future scenario.

The model was initially developed by Clarke et al, 1997, later verified and validated by Clarke and Gaydos 1998. The name of the model is an acronym for its input layer names: slope, land use, exclusion, urban extent, transportation, and hill shade (Norman et al., 2012). The SLEUTH simulates four types of urban land-use changes: spontaneous growth, new spreading center growth, edge growth and road-influenced growth (Jantz et al., 2010).The SLEUTH model characterize with five parameters: dispersion, breed, spread, road gravity and slope to simulate the aforementioned land-use change types. All parameters have to be calibrated with historical land use data and are use to predict future land use and land cover scenarios. The aforementioned projected land cover data aggregated together and adapted to MODIS 20-level classification scheme to be consistent. Urban areas are assumed to be high intensity residential area in WRF, however, we modified the corresponding urban parameterization in WRF to make it more realistically reflect the urban condition in this experiment.

3.1.4. Variable Infiltration Capacity (VIC) Model

The land surface model used to analyze the hydrologic impacts of climate change in the Verde River Basin is the Variable Infiltration Capacity (VIC) macroscale energy and water balance model (Liang et al., 1994; Cherkauer et al., 2003; and Andreadis et al., 2007). As compared to other land surface schemes, VIC's distinguishing hydrologic features are its representation of sub grid variability in soil storage capacity as a spatial probability distribution, to which surface runoff is related (Zhao et al., 1980), and its parameterization of base flow, which occurs from a lower soil moisture zone as a nonlinear recession (Dumenil and Todini, 1992). Sub grid-scale variability in soil properties is represented in VIC by a spatially varying infiltration capacity. Movement of moisture between the soil layers is modeled as gravity drainage, with the unsaturated hydraulic conductivity a function of the degree of saturation of the soil (Campbell, 1974). The deepest soil layer produces base flow according a nonlinear base flow formulation Liang et al (1994). In this way, the model separates subsurface flow from quick storm response. Horizontally, the land surface is described by a given number of tiled land cover classes. The subsurface is characterized vertically by an arbitrary number of soil layers. For most applications two or three soil layers have been used, with the top layer relatively thin (usually 5-10 cm). The land cover (vegetation) classes are specified by the fraction of the grid cell which they occupy, with their leaf area index (LAI), canopy resistance, and relative fraction of roots in each of the soil layers. The VIC model has been tested and applied at a range of scales, from large river basins to continental and global scales. These studies have been reported in Abdulla et al. (1996); Nijssen et al. (1997); Wood et al. (1997); Wood et al. (1998); Dubayah et al., (2000); O'Donnell et al , (1999); and Nijssen et al. (2001).

3.2. Data

We use the NCEP-II reanalysis as atmospheric forcing to run the model for the historical period. For diagnosis of the model performance, we will use the NARR reanalysis data with 32 km resolution. NCEP-II is an improved version of the NCEP-NCAR reanalysis. In 1998, the Reanalysis II project was started at the National Energy Research Supercomputing Center of the Department of Energy. The improvements include an updated model, better physical parameterizations and assorted error fixes (Kanamitsu et al., 2002). The NCEP-II covers the period from 1979-present. The NARR project is an extension of the NCEP Global Reanalysis, which is run over the North American Region. It was suggested by the NECP-NCAR Advisory Committee and completed in 2004 after 6 years of development and production effort. The NARR model uses the high resolution NCEP Eta Model (32km/45 layer) together with the Regional Data Assimilation System (RDAS) (Mesinger et al., 2006). The NARR assimilates precipitation, temperature, winds with more accuracy as compared to NCEP-II. Current output includes 8 times daily temperature, precipitation and other variables.

State of the art future climate projections rely on Global Climate Models (GCMs) driven by different greenhouse gas emission scenarios. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) collects GCM output contributed by leading modeling centers around the world in response to proposed activity of the World Climate Research Program's (WCRPs) Working Group on Coupled Modeling (WGCM). These GCM simulations which included past, present and future climate were archived in 2006 and are the primary data for the phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Covey et al., 2003). Unfortunately, GCMs generally do not realistically represent precipitation or other climate variables that are spatially heterogeneous due to their coarse spatial resolution and physical parameterizations, especially in complex terrain. Consequently, the models must be downscaled using either statistical or dynamical downscaling (see Fowler et al., 2007, for details on the two methods). In this work we present results based on both statistical and dynamical downscaling.

Dynamical downscaling is a physically based method to bring the global scale projections to the regional scale using RCMs. We will use this method to test the sensitivity of LULCC and climate change in the Tucson-Phoenix corridor because the use of RCMs allows us to change the land cover (while this would be impossible when using statistical downscaling). Dynamical downscaling is significantly more computationally expensive than statistical downscaling, and far fewer scenarios can be modeled. However, regional models can simulate changes that have never been observed in the historical period, addressing the issue of non-stationarity (Fowler et al. 2007). In addition, dynamical downscaling generally better captures mean and extreme precipitation at the regional scale as stated by Leung and Quian (2009). We will use two different downscaled datasets to evaluate climate model performance for the historical period, provide an envelope of possible future climate projections, and address the issue of model uncertainty in future climate. The two downscaled simulations were generated at the University of Arizona using the WRF model driven by two different AR4-generation GCMs: 1) the Hadley Centre coupled model, version 3 (HadCM3), and 2) the Max-Planck-Institute for Meteorology coupled model (ECHAM5_MPI-OM, MPI hereafter). The HadCM3 and MPI GCMs have been found to perform well for the historical period compared to observations for both the US Southwest (Dominguez et al., 2009) and the Northern Hemisphere (Gleckler et al., 2008). The simulations encompass the conterminous US and northern Mexico at a spatial resolution of 35km, and a temporal resolution of 6 hours.

As stated before, statistical downscaling is less computationally expensive than dynamical downscaling. While it can't simulate the bi-directional feedbacks between changes in land use and the atmosphere, statistical downscaling can provide many scenarios of possible future changes in climate due to increased greenhouse gas forcing. We will use statistical downscaled scenarios to evaluate possible future changes in ecosystem services in the Verde River Basin caused by increased GHG forcing. We use different emission scenarios from the IPCC Fourth Assessment Report (B1, A1B and A2) from three GCM's: HADCM3, MPI and CCSM3. Two additional GCM simulations viz. MIROC and PCM were added to represent the simulated driest and wettest extreme respectively for the 21st century in comparison to historical observed precipitation. A total of 11 different GCM scenarios will be used. Bias correction and spatial downscaling for the models from the WCRP CMIP3 dataset has been performed and archived at the Santa Clara University and the Lawrence Livermore National Laboratory website (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html).

This is the source of the GCM data used in this study. The methodology for bias correction and spatial downscaling follows Wood et al., (2002, 2004) and Maurer et al., (2007). Bias correction removes biases in the GCM when its simulations of historical climate conditions tend to be too wet/dry/warm/cold relative to the observations. To correct for such biases a quantile mapping technique was used.

4. RESULTS

We have been working in parallel on the WRF simulations with modified land cover, and on the analysis of the VIC results with statistically downscaled data. The goal is to write two separate manuscripts likely to be submitted to the Journal of Hydrometeorology and to Water Resources Research (respectively). Our results are summarized below.

4.1. Relative effect of LULCC and climate change on extreme precipitation events in the Tucson-Phoenix urban corridor

The first months of this project were dedicated to the analysis of the land use data for the 2005 and 2050 periods. Ingesting this data into WRF involved changing the geographical projections and identifying and modifying land use categories to be consistent with WRF. As and example, all land use classified as urban region were set to “high intensity” urban in the Noah-UCM, we will test the sensitivity of this assumption in the coming months.

We selected the year 2004 to calibrate the WRF model. NCEP/DOE Reanalysis II data for the period of July-August of 2004 is used to run the model at a 30km resolution, and we compare the WRF-generated temperature and precipitation to that of NARR (used as a proxy for observations) (Figure 7). We see that temperature is realistically simulated, with a slight hot bias in the southwestern part of the domain. Precipitation on the other had is significantly overestimated in the eastern part of the domain. Summer season precipitation in the Southwestern United States is particularly difficult to simulate. Summer events are usually strong convective events with a small spatial and temporal resolution (a few kilometers, and one to two hours duration). In previous studies we have found that several factors contribute to the overestimation, including excessive precipitable water, excessive CAPE, and deficiencies in the convective parameterization scheme (Tripathi and Dominguez, Accepted in Journal of Geophysical Research). We test the sensitivity of our simulation to the lateral boundary conditions by using different forcing datasets and find that the lateral boundary conditions significantly affect our representation of precipitation in the region (Figure 7). Forcing the model at its lateral boundaries with the NCEP-NCAR reanalysis results in significant overestimation of precipitation in the eastern part of the domain, while using NARR results in a more realistic representation of the local meteorological variables. For this reason we decided to use NARR as our lateral boundary forcing.

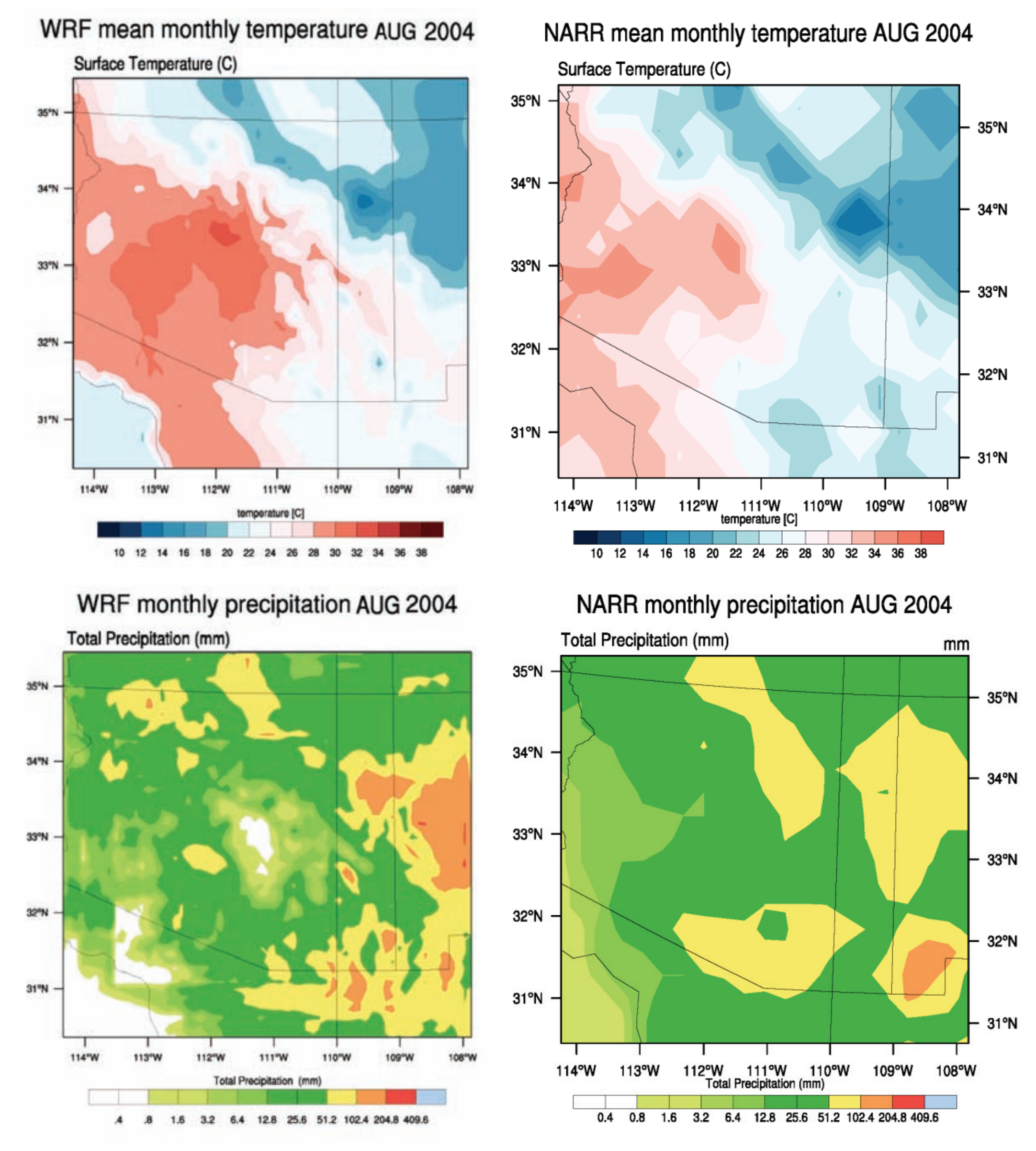

Figure 7. WRF simulations (left) compared to NARR (right) for temperature (top) and precipitation (bottom).

4.2. Effect of climate change on ecosystem services provided by the Verde Basin Watershed

Our group has historical (1949-1985) and future (2010-2100) 3-hourly simulations of the hydrology in the Verde River basin using the VIC hydrologic model (Rajagopal et al. 2012, 2013). We are using this data to evaluate possible future changes in ecosystem services due to climate change. For the purposes of this paper, we focus only on extreme flooding events. As a first step, we select historical flooding events and analyze the response of the basin to these extreme events. We divide annual cycle into two phases: cold season and warm season, in order to differentiate the effect of snow melting and summer monsoon on extreme streamflow. We define cold season as starting from December 1st to May 31st, warm season as starting from June 1st to November 30th. We evaluate VIC performance by comparing to USGS observation data. In Figure 8 below, blue and red color represents the USGS observation data and VIC model data respectively. Upper three plots are streamflow data for cold season, and

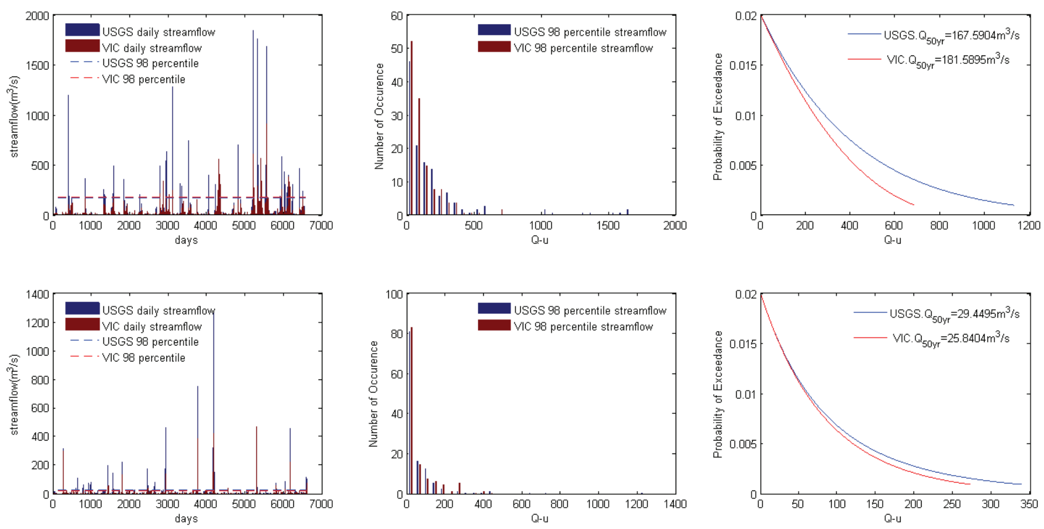

Figure 8. Comparison of streamflow simulated by the VIC hydrologic model and measured at the USGS gauge

lower plots are data for warm season.

We define streamflow events that exceed 98 percentile as extreme events, and we analyze the occurrence and magnitude of such events. Panels a) and d) in Figure 8, show daily streamflow along with the 98 percentile streamflow level represented in dash line. The 98 percentile level in both figures lies relatively close in magnitude. On the other hand, USGS data might suggest more extreme streamflow data in this historical period. In other words, VIC model seems to be underestimating the magnitude of extreme events. Panels b) and e) show histogram for extreme streamflow in cold and warm season where x axis represents the magnitude that streamflow exceeds the threshold value (98 percentile), y axis is the number of occurrence of certain streamflow events. It shows that the VIC model captures the pattern of extreme flow events relatively well. The number of occurrence for each bin is similar to the USGS data. Although the VIC model simulates more low-level extreme streamflow as compared to USGS observation data. This phenomenon is more obvious in figure c) and f) which give probability of exceedance.

Based on the comparison of the VIC streamflow and USGS measurements, we will focus our attention on two flooding events that were realistically captured in the simulation: March 1-6 of 1978 and February 15-24 of 1980.

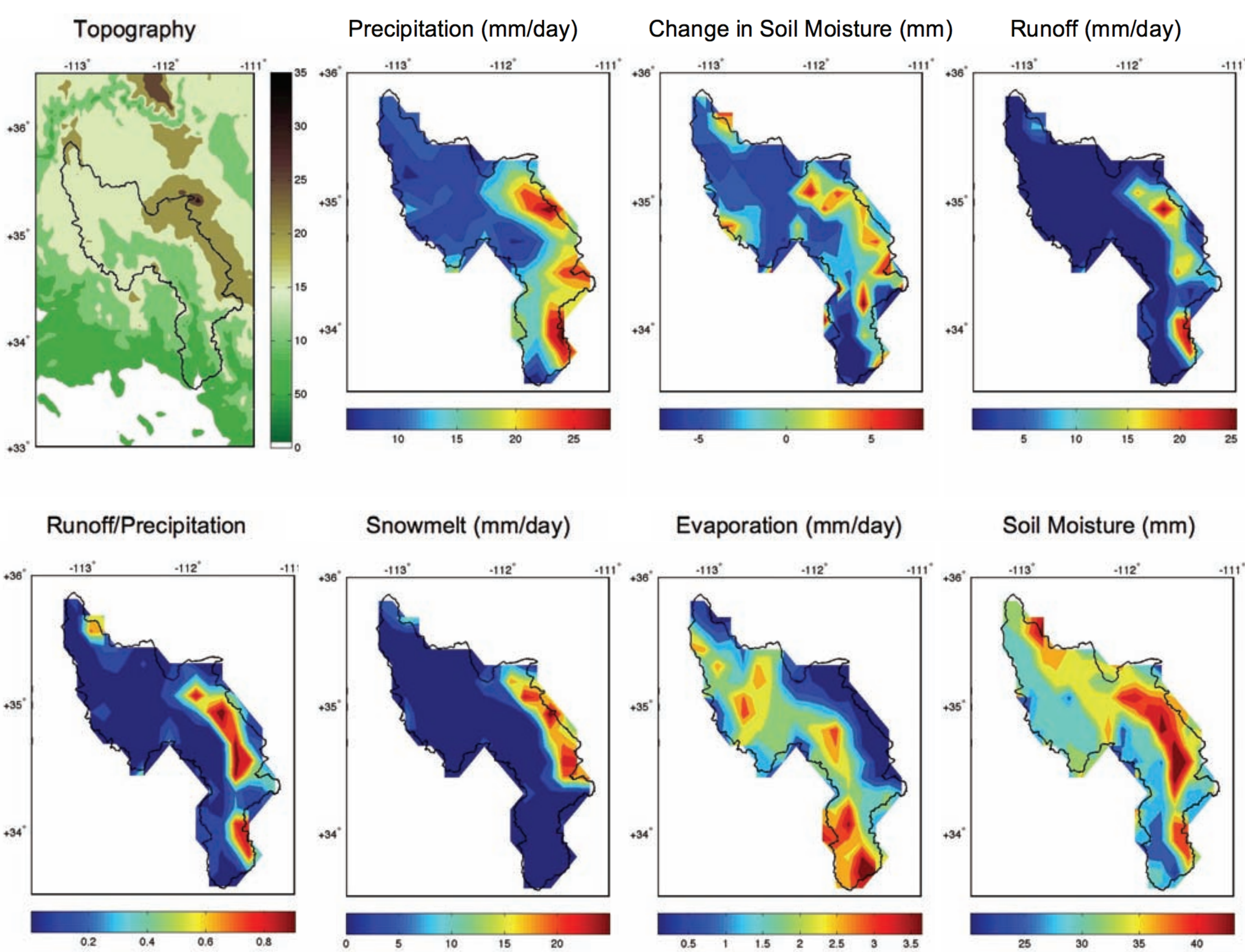

Figure 9. Topography and average hydrologic response of the Verde Basin to the extreme flooding event on March 1-6 of 1978 as simulated by the VIC hydrologic model.

Figure 9 shows different hydrologic variables over the Verde River Basin averaged in time for the March 1-6, 1978 period of intense flooding. We can see that the precipitation focused on the mountainous eastern part of the basin. This part of the basin also experiences significant changes in soil moisture and runoff – while evapotranspiration is concentrated in the warmer lower elevations. Soil moisture changes (March 6 – March 1) are positive in the higher elevations and negative in the valley. From this preliminary analysis it is clear that different locations within the watershed serve a different hydrologic function.

5. CONCLUSIONS AND FUTURE WORK

Understanding how the combined effect of climate change and LULCC could affect climate in the Tucson-Phoenix urban corridor and watersheds is of critical importance in this rapidly developing semiarid region. We address this question through the use of historical observations and numerical modeling. The work is divided in two objectives:

5.1. Relative effect of LULCC and climate change on extreme precipitation events in the Tucson-Phoenix urban corridor

Using the Weather Research Forecast (WRF) regional climate model coupled to a state-of-the-art land surface model with detailed characterization of urban regions, we have begun the process of ingesting modified land cover data into the WRF model and calibrating the model for the year 2004. We find that there is an overestimation of precipitation in the eastern side of the domain, and we are evaluating the effect of anomalous lateral boundary conditions.

When the calibration of the model is finished, we will begin our experiments (see Figure 10 for the experimental design.

	No Climate Change	Climate Change
No LU/LC change	Experiment 1	Experiment 2
LU/LC change	Experiment 3	Experiment 4

Figure 10. Experimental design for WRF-Noah-UCM simulations.

Task 1: Run model for 3 dry and 3 wet historical summer seasons using historical land cover, with NCEP/DOE -RII atmospheric forcing (Experiment 1). We will then modify land cover data to 2050 projected conditions, using the same atmospheric forcing (Experiment 3). These two experiments will show the sensitivity of climate to different land cover conditions.

Task 2: With historical land cover data we will run model using future climate projections 2031 – 2040, and historical climate 1991 – 2000 with UKMO-Hadcm3 forcing (Experiment 2). We will do the same with projected land cover (Experiment 4). These experiments will allow us to quantify relative importance of land cover change with respect to climate change on regional climate.

Task 3: repeat Task 2 with MPI-Echam5 forcing data.

5.2. Effect of climate change on ecosystem services provided by the Verde Basin Watershed

We focus on the flood mitigation role of the Verde watershed, based on previous simulations performed by Rajagopal et al. (2012, 2013). We have compared extreme flooding events, defined as those above the 98th percentile, in both the historical VIC simulations and the USGS data. Based on this analysis we have selected two winter periods and performed a preliminary evaluation of the hydrologic response of the watershed to extreme precipitation.

We will now perform an evaluation of the ecosystem services of the watershed based on an approach that uses hydrologic modeling results to quantify flood regulation functions of different land cover classes which enables the assignment of ecosystem service supply capacities for each of them. The method is based on the assumption that land cover classes presented in areas with high water regulation capacities (as calculated by the hydrologic modeling and the soil type assessment) have high flood regulating capacities. Thus, the results of the capacity assessments performed in the case study areas can be used for ecosystem service mapping in all areas where respective land cover and soil data are available

6. REFERENCES

Balling, R., and S. Brazel, 1987: Recent changes in Phoenix summertime diurnal precipitation patterns. Theor. Appl. Climatol., 38, 50–54.

Braham, R. R., R. G. Semonin, A. H. Auer, S. A. Changnon Jr., and J. M. Hales, 1981: Summary of urban effects on clouds and rain.METROMEX: A Review and Summary, Meteor. Monogr., No. 40, Amer. Meteor. Soc., 141–152.

Burkhard, B., de Groot, R.,Costanza, R., Seppelt, S. E., Potschin, M., 2012a. Solutions for sustaining natural capital and ecosystem services. Ecological Indicators 21, 1-6.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012b. Mapping of ecosystem service supply, demand and budgets. Ecological Indicators 21, 17-29.

Burkhard, B., Kroll, F., Müller, F., Windhorst, W., 2009. Landscapes capacities to provide ecosystem services – a concept for land-cover based assessments. Landscape Online 15, 1–22.

Castro, C.L., R.A. Pielke, Sr., J.O. Adegoke, S.D Schubert, and P.J. Pegion, 2007. Investigation of the Summer Climate of the Contiguous U.S. and Mexico Using the Regional Atmospheric Modeling System (RAMS). Part II: Model Climate Variability. J. Climate, 20, 3866-3887.

Changnon, S.A., R.G. Semonin, A.H. Auer, R.R. Braham, and J. Hales, 1981. METROMEX: A review and summary. Meteor. Monogr. No. 40, Amer. Meteor. Soc., 81 pp.

Changnon, S. A., 1992: Inadvertent weather modification in urban areas: Lessons for global climate change. Bull. Amer. Meteor. Soc., 73, 619–627.

Chèelkin, Gutièrrez, A. G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann, H, 2013. A 2 °C warmer world is not safe for ecosystem services in the European Alps. Global Change Biology 19, 1827–1840.

Chen, F., K. Mitchell, J. Schaake, Y. Xue, H. Pan, V. Koren, Y. Duan, M. Ek, and A. Betts, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. J. Geophys. Res., 101, 7251-7268.

Chen F, Kusaka H, Tewari M, Bao J-W, Hirakuchi H (2004) Utilizing the coupled WRF/LSM/Urban Modeling System with detailed urban classification to simulate the urban heat island phenomena over the Greater Houston Area. 5th Conference on Urban Environment, Vancouver, BC, Canada, 23–27 August 2004

Chen, F., and Coauthors, 2011: The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. International Journal of Climatology, 31, 273-288.

Clarke, K. C., Hoppen, S., & Gaydos, L. (1997). A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. Environment and Planning B: Planning and Design, 24(2), 247–261. http://dx.doi.org/10.1068/b240247

Clarke, K. C., & Gaydos, L. J. (1998). Loose-coupling a cellular automaton model and GIS: Long-term urban growth prediction for San Francisco and Washington/Baltimore. International Journal of Geographical Information Science, 12(7),699–714.

Commitee on Ecological Impacts of Climate Change, National Research Council, 2008. Ecological Impacts of Climate Change. ISBN: 0-309-12711-4, 70 pages, 8 1/2 x 11. http://www.nap.edu/catalog/12491.html

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.

Covey, C., K. M. AchutaRao, U. Cubasch, P. Jones, S. J. Lambert, M. E. Mann, T. J. Phillips, and K. E. Taylor (2003), An overview of results from the Coupled Model Intercomparison Project, Global and Planetary Change, 37(1-2), 103-133.

De Groot, R., Wilson, M., Boumas, R. 2002. A typology for the Classification, description and valuation of Ecosystem Functions, Goods and Servises. Ecological Economics 41, 393-408, Elsevier.

Dettinger, M. D., D. R. Cayan, H. F. Diaz, and D. M. Meko. 1998. North–south precipitation patterns in western North America on interannual-to-decadal timescales. Journal of Climate 11:3095–3111

Diem, J. E., and D.P. Brown, 2003. Anthropogenic impacts on summer precipitation in central Arizona, U.S.A., Prof. Geogr. 55, 343–355.

Dominguez, F. and J. Cañon and J. Valdes, 2009. IPCC-AR4 Climate Simulations For The Southwestern US: The Importance Of Future ENSO Projections. Climatic Change DOI: 10.1007/s10584-009-9672-5

Dominguez, F., E. Rivera, D. P. Lettenmaier, and C. L. Castro (2012), Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models, Geophys. Res. Lett., 39, L05803, doi:10.1029/2011GL050762.

Fowler, H. J.; Blenkinsop, S.; Tebaldi, C., 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling

International Journal Of Climatology Volume: 27 Issue: 12 Pages: 1547-1578 DOI: 10.1002/joc.1556

Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy, eds. 2013. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. A report by the Southwest Climate Alliance. Washington, DC: Island Press

Georgescu, M., G. Miguez-Macho, L.T. Steyaert, and C.P. Weaver, 2009a. Climatic effects of 30 years of landscape change over the greater Phoenix, Arizona, region: 1. surface energy budget changes, J Geophys Res 114, doi:10.1029/2008JD010745.

Georgescu, M., G. Miguez-Macho, L.T. Steyaert, and C.P. Weaver, 2009b. Climatic effects of 30 years of landscape change over the greater Phoenix, Arizona, region: 2. dynamical and thermodynamical response. J Geophys Res. 114, doi:10.1029/2008JD010762.

Gleckler, P. J.; Taylor, K. E.; Doutriaux, C., 2008. Performance metrics for climate models. Journal Of Geophysical Research-Atmospheres V: 113 I: D6 Article Number: D06104 DOI: 10.1029/2007JD008972

Grossman-Clarke, Susanne; Zehnder, Joseph A.; Loridan, Thomas; et al., 2010; Contribution of Land Use Changes to Near-Surface Air Temperatures during Recent Summer Extreme Heat

Events in the Phoenix Metropolitan Area. Journal Of Applied Meteorology And Climatology V: 49 I: 8 Pages: 1649-1664 DOI: 10.1175/2010JAMC2362.1

Hutyra, L.R., B. Yoon, J. Hepinstall-Cymerman, M. Alberti, 2011. Carbon consequences of land cover changes in the Seattle metropolitan region: An examination of spatio-temporal patterns and carbon consequences, Landscape and Urban Planning 103, 83-93.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jantz, C. A., Goetz, S. J., Donato, D., & Claggett, P. (2010). Designing and implementing a regional urban modeling system using the SLEUTH cellular urban model. Computers, Environment and Urban Systems, 34(1), 1–16, doi:16/j.compenvurbsys.2009.08.003

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S-K Yang, J.J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP-DEO AMIP-II Reanalysis (R-2). Bulletin of the American Meteorological Society, 1631-1643.

Kandziora, M., Burkhard, B., Müller, F., 2013. Interaction of ecosystem properties, ecosystem integrity and ecosystem service indicators – A theoretical matrix exercise. Ecological Indicators 38, 54-78.

Kusaka H, Kimura F. 2004. Coupling a single-layer urban canopy model with a simple atmospheric model: impact on urban heat island simulation for an idealized case. Journal of the Meteorological Society of Japan 82: 67–80.

Kusaka, H., H. Kondo, Y. Kikegawa, and F. Kimura, 2001: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound.-Layer Meteorol., 101, 329-358.

Leung, L. R., and Y. Qian (2009), Atmospheric rivers induced heavy precipitation and flooding in the western US simulated by the WRF regional climate model, Geophys. Res. Lett., 36, L03820, doi:10.1029/2008GL036445.

Liu, Y., F. Chen, T. Warner, S. Swerdlin, J. Bowers, and S. Halvorson, 2004: Improvements to surface flux computations in a non-local-mixing PBL scheme, and refinements on urban rocesses in the Noah land-surface model with the NCAR/ATEC real-time FDDA and forecast system. 20th conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction. 11-15 January, 2004, Seattle, Washington.

Lyon, S., F. Dominguez, D. Gochis et al., 2008. Coupling Terrestrial And Atmospheric Water Dynamics To Improve Prediction In A Changing Environment, Bulletin American Meteorological Society. V. 89, No. 9, 1275–1279.

MA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, D.C (World Resources Institute).

Maurer, E. P., H. G. Hidalgo, T. Das, M. D. Dettinger and D. R. Cayan (2010). "The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California." Hydrology and Earth System Sciences 14(6): 1125-1138.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. Bull. Amer. Meteorol. Soc., 87, 343-360.

Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. Agriculture, Ecosystems and Environment 114, 69–85.

Montoya, J. M., Raffaeli, D., 2010. Climate change, biotic interactions and ecosystem services. Philosophical Transactions of the Royal Society B 365, 2013-2018.

Nedkov, S., Burkhard, B., 2012. Flood regulating ecosystem services – mapping supply and demand, in the Etropole municipality, Bulgaria. Ecological Indicators 21, 67–79.

Norman, Laura M., Mark Feller, and Miguel L. Villarreal. 2012. “Developing Spatially Explicit Footprints of Plausible Land-use Scenarios in the Santa Cruz Watershed, Arizona and Sonora.” Landscape and Urban Planning 107 (3) (September 15): 225–235. doi:10.1016/j.landurbplan.2012.06.015.

NRC (National Research Council), 2011. Climate stabilization targets, Washington, DC: The National Academies Press, 286 p.

NRC (National Research Council), 2012. NRC Report on Urban Meteorology: Forecasting, Monitoring, and Meeting Users' Needs. National Academies Press. Authors: Snow, J.T., X. Zeng, P. Klein, S.E. Sarnat, J.M. Shepherd, and E.M. Stanley, Washington, D.C., 190 pp.

Pielke, R.A. Sr., A. Pitman, D. Niyogi, R. Mahmood, C. McAlpine, F. Hossain, K.K. Goldewijk, U. Nair, R. Betts, S. Fall, M. Reichstein, P. Kabat, and N. de Noblet, 2011. Land use/land cover changes and climate: Modeling analysis and observational evidence, WIREs Climate Change Advanced Review, doi: 10.1002/wcc.144.

Rajagopal S, F Dominguez, HV Gupta, PA Troch, CL Castro, 2013 (in review). On physical mechanisms related to climate-induced drying of two semi-arid watersheds in the southwest US, Journal of Hydrometeorology

Rajagopal S, HV Gupta, F Dominguez, PA Troch, CL Castro, 2012. Assessing Impacts of Climate Change in a semi arid Watershed using statistically downscaled IPCC Climate Output, submitted to Proceedings of the Arizona Hydrological Society 2011 Annual Symposium: "Watersheds Near and Far", September 18-20, 2011, High Country Conference Center, Flagstaff, Arizona.

Rosenzweig C., W. Solecki, S.A. Hammer, S. Mehrota, 2010. Cities lead the way in climate change action, Nature 467, 909-911.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG. 2005. A description of the Advanced Research WRF version 2. NCAR Technical Note TN-468 + STR, 88 [Available from NCAR, P. O. Box 3000, Boulder, CO 80307].

Selover, N., 1997: Precipitation patterns around an urban desert environ ment topographic or urban influences? Proc. Association of American Geographers Convention, Fort Worth, TX, Association of American Geographers.

Shepherd, J. M., 2005. A review of current investigations of urban-induced rainfall and recommendations for the future, Earth Interactions 9.

Shepherd, J. M., 2006: Evidence of urban-induced precipitation variability in arid climate regimes. J. Arid. Environ., 67, 607-628.

Shepherd, J., H. Pierce, and A. Negri, 2002. Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. J Appl Meteorol. 41, 689–701.

Tewari., M., F. Chen, W. Wang, J. Dudhia, M. LeMone, K. Mitchell, M. Ek, G. Gayno, J. Wegiel, and R. Cuenca, 2004: Implementation and verification of the unified Noah land surface model in the WRF model . 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction. 11-15 January, 2004, Seattle, Washington.

Tewari., M., F. Chen, H. Kusaka, S. Miao, 2007: Coupled WRF/Unified Noah/Urban-Canopy Modeling System.

United Nations. 2007. World Urbanization Prospects: The 2007 Revision [Available online at http://esa.un.org/unup].

Wood, A. W., E. P. Maurer, A. Kumar, and D. P. Lettenmaier (2002), Long-range experimental hydrologic forecasting for the eastern United States, Journal of Geophysical Research-Atmospheres, 107(D20).

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier (2004), Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic Change, 62(1-3), 189-216.

Chapter 2

-Deliverable 3.1-

Key Data And Information Requirements In The Context Of Current Debates On Water Management

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1. EXECUTIVE SUMMARY

This Deliverable builds on the five main themes that structure the work of SWAN project with respect to the issues of key data and information requirements for water management:

1.1. Current paradigms in the management of water resources and hydrologic risks

Water management goals, methodologies, conceptual approaches and institutional frameworks have evolved significantly over the past 30 years. These transformations have been stimulated by the promotion of the Integrated Water Resources Management (IWRM) paradigm by experts, academics, managers and international institutions. However, the application of IWRM faces resistance from defendants of the previously dominating infrastructural and resource-oriented *hydraulic paradigm*. It is also challenged by the contradictions and limitations that emerge from the practical experiences in its implementation at different scales. From a general perspective, criticism against the *hydraulic paradigm* and the emergence and consolidation of IWRM can be understood as being a part, in the water policy arena, of the historical shift from the post-war Keynesian regulation model to the current neo-liberal globalization system or, in more specific terms, from the “administrative rationalism” stage to the current “neo-privatization” trend.

Increasing attention is being paid to the potential interconnections between the encouragement of *water governance*, a central focus of the IWRM approach, with wider global socio-economic processes that challenge existing democratic institutions. The wider hegemonic economic thought in which IWRM prescriptions are integrated, particularly the *commodification* processes and monetary reductionism of natural resources and the preeminence of the river basin as the *natural* scale for water resources management, is also coming under scrutiny.

From an epistemological perspective, the traditional separation of social and natural sciences has ignored the overlap of both fields of knowledge, which results in the limited theoretical and methodological development for their joint analysis, as well as the paucity of available data for management. The consideration of water as a socio-ecological patrimony requires linking biophysical and socioeconomic variables, a significant challenge given the current knowledge and modeling capabilities. There is a strong need for information on the complexity of *socio-hydrological systems*, which are reflexive, adaptive, non-linear and complex, and have feedback loops, emerging properties and non-predictable responses to management interventions. In the context of the evolving paradigm for water management the recognition these knowledge limitations are of vital importance.

1.2. Economic considerations in evolving water management debates

The paradigm of IWRM incorporates two basic economic principles: cost recovery and the polluter-pays principle. Nevertheless, under current ecosystem-based approaches to water resources management, the goal has become to protect and enhance the services provided to society by the good functioning of aquatic ecosystems. It would therefore be appropriate to substitute the term of polluter pays for the more ambitious concept of payment for the deterioration of ecological function of water ecosystems or, more broadly, for loss of ecosystem services.

The persistence of the traditional hydraulic paradigm and standard economic perspectives limit our ability to rigorously and comprehensively calculate costs that are outside their standard analytical and accounting frameworks. Under standard economic practice, environmental considerations are externalities outside the system, impacts that result from the use and consumption of water but are not compensated through the water pricing system. The main obstacle to overcome this scenario is the difficulty of precisely quantifying or valuing the degradation of complex natural ecosystems that result from human actions. It is difficult to translate that degradation into replacement costs and determine the price to pay by those that have caused it.

The difficulty of identifying and valuing ecosystem services derives from the diversity of dimensions that are encompassed by the concept (productive, ecological, cultural, etc.). Furthermore, ecosystem services often result from interrelations between different ecosystem components, thus adding complexity to any systematization and evaluation attempt. Even the classification of ecosystem services in non-overlapping categories is problematic. Many of these knowledge limitations are to some extent insurmountable, inherent to the complexity of socio-natural systems. Institutional arrangements are necessary to deal with these uncertainties (in the sense of ignorance) and the need to manage water resources and associated ecosystems in this uncertain and partially understood context. It may therefore be necessary to shift the emphasis from the quantification and deterministic approach to valuating trade-offs and management alternatives, toward a more deliberative approach, where interested actors can jointly discuss values, preferences, risks and alternatives.

1.3. New information technologies and water resources management

The proliferation of information and communication technologies (ICT) has caused profound changes in the availability of information about our planet, in its storage and processing capabilities, its distribution and dissemination. These processes also pertain to water-related information, so that the availability of key data for sustainable water management is evolving in relation with the development of the ICTs. That is particularly relevant in a context of a growing social and political support for open government and open data standards. However, there remain significant challenges to take full advantage of the opportunities offered by the ICTs, challenges that derive from the inertias of existing models of information generation and management.

In the European Union there have been several initiatives that attempt to harmonize existing public information systems, limit duplicities and redundancies and improve public access to information. However, public administrations are still reluctant to accept the public right to access environmental information and, to a large extent, have not reorganized their information management procedures and systems in order to facilitate knowledge generation and information integration. The pending issue for water policy in the field of information is to ensure that information gives rise to knowledge truly useful for participatory planning and management. This implies the need to facilitate the conditions in which knowledge is produced through collaborative methods and is disseminated and shared in an open, free and easy way, in accordance with the characteristics and potentialities of the new networked society. The collaborative generation of information has, surely, institutional implications concerning changes in the geometries of power, that is, potential changes in the identity of the agents that control information and, as a result, the decision-making processes.

1.4. Modeling hydro-social systems: reflections about key information and data requirements

Adapting water management to current challenges requires taking systemic approach to water resources, overcoming the simple, reductionist and static perspectives that still persist. The development and use of dynamic modeling techniques to develop hydro-social models can help us move in the right direction. Building dynamic models is a laborious process since it requires going beyond the requirements of traditional hydrologic model building. Dynamic models incorporate the views and perspectives of managers, decision makers and stakeholders in the characterization and diagnostic phases, as well as in the definition of objectives and management alternatives. This approach enables the combination of the analyst's technical expertise with the range of incommensurable perspectives that affect socio-ecological systems.

The combination within the same model of natural and social parameters—the essence of hydro-social models—, implies such level of complexity that the models can only hope to represent specific geographic and hydro-social realities. It requires a new institutional and technical framework to overcome current limitations to the involvement of the public and stakeholders in the definition of water management alternatives.

The lack of good quality information is the most significant limiting factor for a successful modeling exercise of complex hydro-social realities. Scale aspects of knowledge bases are also important, particularly in order to better understand how to consolidate information gathered at different spatial levels. Bridging scales enables better integration of local knowledge into global models and data sets, that is, integration of scientific and indigenous knowledge, which may strengthen the accuracy and contribute to its translation into effective policy strategies addressing global environmental changes.

1.5. Transparency and public participation as key components of the new water governance

Traditional transparency and public participation efforts have focused on the need to disseminate information to the public rather than on collaborative generation of information for water planning and management. This has been the dominant *rational comprehensive planning* approach, where public participation is not *inherent* to the planning process, but rather *instrumental* to improve knowledge in the diagnostic phase.

The emphasis on public participation mechanisms to legitimize public policy decision-making processes found its theoretical grounding in the deliberative democracy theoretical framework. However, after more than two decades of general acceptance and widespread implementation of this approach, there is a growing body of work that is critically questioning the limits of the *participatory governance* perspective to natural resources management and its true impact on final decisions. This critical work is framed within the debates of *post-politics* or *post-democracy* in the context of the global neoliberal globalization processes.

Too often, in the final stages of decision making processes there is a *political externalization* of key final operational decisions. Water managers (or politics) impose decisions that are not coherent with scientific, integrated and participatory processes that precisely aim to understand, anticipate and direct sustainable management decisions. There is a lack of understanding about these informal decision making processes. Research about the links between science and politics must incorporate information about the factors that drive and help explain these fundamental mechanisms.

2. INTRODUCTION AND BACKGROUND

The SWAN project (FP7-INCO-2011-7) aims to promote trans-disciplinary scientific cooperation between the US and the EU through collaborative work of project partners along three transverse themes: 1) Climate change and uncertainty; 2) Risks and vulnerabilities; and 3) Water demand and sustainability. The collaboration builds on the experience of the International Research Center (UMI) "*Water, Environment and Public Policy*", established in 2008 by the French CNRS (Centre National de la Recherche Scientifique) in collaboration with the University of Arizona, at the latter's campus in Tucson. SWAN has interrelated scientific and institutional objectives: defining a common framework for interdisciplinary research on water resources management that can serve as a scientific basis for a permanent collaborative institution, the Sustainable Water Center (as originally conceived) or a Network for Transatlantic Water Dialogue, as currently envisioned.

The debates on emerging scientific and water management paradigms, new and collaborative ways of generating information and meeting growing information requirements, and integrative modeling and scientific approaches are all fundamental components of SWAN's research work. These debates are part of Task 3.2, which is the responsibility of the University of Seville (SWAN Partner 4), in close collaboration with the University of Arizona (SWAN Partner 1) and the Bulgarian Academy of Sciences, BAS-NIGG (SWAN Partner 5). This working paper presents a first approach to these debates. It identifies key themes that will be further developed in the remaining years of the SWAN project.

This Deliverable draws on the results of a workshop organized around the theme of *New paradigms for water resources and risk management: Data and information requirements for sustainable water management,* organized by the University of Seville SWAN team in January 2013. Preliminary conclusions were discussed and enriched with contributions from seminar participants and other SWAN team members and are being published in the Spanish Geographer Association Bulletin (Pita *et al.*, 2014).

The Deliverable builds on the five main themes that were discussed in the January 2013 Workshop and that structure the work of SWAN with respect to the issues of key data and information requirements for water management:

- Current paradigms in the management of water resources and hydrologic risks. Resulting information needs
- Economic considerations in evolving water management debates.
- New information technologies for the management of water resources. Resulting opportunities and requirements.
- Hydro-social systems modeling. Information needs and key data.
- Transparency and public participation as key components of the new water governance. Resulting information needs.

A follow up International Conference organized by the SWAN University of Seville team on the same theme is scheduled for June 2014 and will build on the contents of this Deliverable. The output of this conference will serve to further refine the conclusions presented in this report and inform the goals and scientific contents of the Network for Transatlantic Water Dialogue that will be the main scientific and institutional output of SWAN.

3. CURRENT PARADIGMS IN THE MANAGEMENT OF WATER RESOURCES AND HYDROLOGIC RISKS: RESULTING INFORMATION NEEDS

Water management goals, methodologies, conceptual approaches and institutional frameworks (actors involved, legal contexts) have evolved significantly over the past 30 years. These transformations have been stimulated by the promotion of the Integrated Water Resources Management (IWRM) paradigm by experts, academics, managers and international lending institutions, since the approval of the Dublin Statement on Water and Sustainable Development (Dublin Principles) at the 1992 International Conference on Water and Environment. This long lasting process of paradigm change and consolidation is the manifestation, in the water resources field, of a wider and deeply contentious transformation in the way we currently understand society-nature interactions and the management of natural resources.

In practice, the application of IWRM has met significant resistance both from the dominant values and interests of previous management approaches as well as growing criticisms from new theoretical and applied perspectives. The current water management landscape is dynamic and heterogeneous and its evolution cannot be described in a linear way. There is a distinctive hegemony of IWRM principles in programmatic and discursive terms, even in countries like Spain where the hydraulic paradigm has been dominant until very recently. But this hegemonic position of IWRM is challenged by pervasive reminiscences of traditional, infrastructural and resource oriented tendencies, on the one hand, and emergent criticism from new perspectives, rooted in current visions of complexity, risk and insecurity, on the other. In general, the diverse water management institutional frameworks that exist in practice reflect to different degrees elements of these different origins.

In this context of change and transformation it becomes relevant to reflect upon the new information and knowledge requirements for natural resources management in general and water management in particular. These requirements are conditioned by the growing opportunities provided by polycentric and changing loci of data generation; the different avenues for dissemination of existing information in an era of rapidly evolving information technologies; the promotion of public policies and legislation that enhance the dissemination, harmonization and reutilization of publicly produced information; and the growing demands for transparency and knowledge in natural resources management from increasingly demanding and critical social actors.

3.1. A new paradigm for water resources management?

The hegemonic water management paradigm during most of the twentieth century in much of the western world emphasized resource development in order to expand supply to meet (while also encouraging) increasing demand, through the public planning and funding of hydraulic infrastructures. This approach, known as the *hydraulic paradigm* or *hydraulic mission* has been well described in different contexts, mainly in bio-geographical regions affected by aridity (see Allan, 1999 and 2006; Faggi, 1996; Feitelson, 1996; Moral and Sauri, 1999; Reisner, 1986; Swyngedouw, 1999; Hutchinson, Varady, and Drake, 2010). It entailed a project for the transformation of arid landscapes, characterised by drought and barrenness, and the resulting socioeconomic under-development and lack of growth. The privileged instrument behind this project for physical and social transformation would be hydraulic works funded with public money, in the all too frequent case that private initiative were not in a position to take on the risks of investment. Under this paradigm, scientific and technical expertise typically supported dominating socio-political structures and cultural values to identify existing problems and propose solutions through rigid management plans with little room for adaptation, uncertainty or public participation. Two basic certainties encompassed in this vision are that Nature can be controlled and that the State, its development agencies, irrigators, power generators, etc., were engaged in essential and appropriate activities of public interest. The uni-functional ('build') and uni-disciplinary ('engineering') bureaucracy adopted a command-and-control philosophy, seeing users as subjects (and the State the provider) rather than active agents. This project seized both liberal western economies as well as the centrally planned economies of the Soviet Union. The hydraulic mission proved to be readily exportable to the global South in the second half of the 20th century.

As a reaction to this, over the past three decades there has been a substantial shift in the conceptual framework for water resources management, albeit with significant inertias from the past, and strong contradictions and substantial geographical differences in its implementation. The *post-hydraulic paradigm* has at its core the promotion of *demand management* approaches, the introduction of *economic incentives* for rationalization of water management and use, the conservation and restoration of *aquatic ecosystems*, and the *incorporation of stakeholders and the wider public in decision-making processes*.

These are common characteristics of a management approach that is widely known as Integrated Water Resources Management (IWRM), and has received significant attention from academics, managers and international funding institutions. As some of its recent critics argue, IWRM has been promoted as the "panacea" to resolve water management problems worldwide, and inspired national water resources legislation in different parts of the world—the South African National Water Act (NWA) of 1998, the 2000 Water Framework Directive (WFD) in the European Union or the 2004 Australian Intergovernmental Agreement on a National Water Initiative (NWI), to name just a few. From a general perspective, criticism against the hydraulic paradigm and the emergence and consolidation of IWRM can be understood as being a part, inside the particular water policy arena, of a whole historical shift from the post-war Keynesian regulation model to the current neo-liberal globalization system (Raco, 2013) or, in more specific terms, from the “administrative rationalism” stage to the current “neo-privatization” trend (Castro, 2011, Swyngedouw, 2007).

In the US, the concept of IWRM is strongly established and even gaining considerable traction. The United States Army Corps of Engineers (USACE) launched in February 2013 an on-line Federal Support Toolbox to provide Integrated Water Resources Management information (www.watertoolbox.us). The toolbox responds in part to the publication in 2010 of a National Report entitled *Responding to National Water Resources Challenges*, the result of a nationwide assessment process of water resources issues in the US facilitated by the USACE which established as a goal the need to "Promulgate policies, concepts, and clear and consistent definitions that support IWRM" (USACE, 2010). Additionally, the American Water Resources Association (AWRA), a leading association for water managers and researchers in North America, adopted a Policy Statement in 2011 recommending that "water management goals, policies, programs and plans be organized around the concept of IWRM" and has organized two Summer Specialty conferences on this topic (Snowbird, 2011 and Reno, June 2014).

IWRM is also the reference used by the SWAN project as the starting point and initial framework for its scientific endeavors. However, building on concrete experiences in different parts of the world, over the past few years a growing debate has emerged questioning the limitations, contradictions and conflicts that the integrated management paradigm finds in its practical implementation. In its 2011 policy statement, the American Water Resources Association (AWRA) recognized these limitations by stating that: "IWRM suffers from a lack of clear definition, the lack of standard measures to track the success of IWRM plans and projects, and the absence of guidance for those involved in planning and project development". From an applied perspective, for instance, Giordano and Shah (2013) discuss several examples in Asia and Africa where international lending institutions pushed for the approval of water policies aligned with IWRM, with mixed results. From a more theoretical standpoint, Molle (2009) is critical with the status of "nirvana" concept of the IWRM prescriptions, while Pahl-Wostl *et al.* (2011 and 2012) question the possibility of existing "panaceas" and argue that water management requires a further evolution along different axis:

- From central control to poly-centric governance, where the definition of the problems, the alternatives and the solutions are the result of a *cooperative* process between different actors and management centers;

- From prescriptive solutions to adaptive management approaches that facilitate learning and *adaptation* to a changing reality and to evolving understandings of the problem;

- From separate approaches to discrete environmental problems toward an *integrated* approach that transcends disciplines, geographical and professional boundaries, and areas of expertise.

Some advanced formulations of IWRM, as the European Water Framework Directive (Directive 2000/60/EC), advocate for the incorporation of a wide range of areas of expertise and opinions through the entire decision-making process: from problem identification and development of alternatives, to the implementation of solutions (WFD, 1st consideration). However, from a critical perspective increasing attention is paid to the potential interconnection between the encouragement of *water governance* approaches with wider global socio-economic processes that question current democratic institutions and *devolve* power toward higher (EU, WTO, IMF, etc.) or lower institutional levels (NGOs, municipalities, etc.) (Heynen *et al*., 2007, Swyngendow, 2011).

The preeminence of the river basin as the *natural* scale for water resources management (Mostert *et al.,* 2008), a central focus of the IWRM approach, is also coming under scrutiny. In the context of the complexity of socio-hydrological systems, the debate about *spatial fit* or the definition of adequate physical and institutional boundaries becomes particularly relevant. The delimitation of management boundaries exclusively in physical terms does not sufficiently recognize the existence of the multiple geographies—political, socioeconomic, cultural—of socio-ecological systems (van Meerkeert *et al.,* 2013). Critics acknowledge the undeniable and significant physiographic characteristics of the watershed, but also argue that there is no *natural* hydrologic scale that cannot be technically challenged. Authors such as Budds & Hinojosa (2012); Cohen & Davidson (2011); Del Moral & D'O (2014); Molle (2009), or Moss (2012), point to the diversity, ambiguity and lack of commonality of the different phenomenon that are used to define the watershed: micro and macro-watersheds or river basins, sub-basins, administrative boundaries, overlapping surface and groundwater boundaries, etc. Additionally, their lack of coincidence with existing institutional and socio-cultural boundaries, further complicate the traditional challenges of operational coordination with key sectoral policies such as agriculture, environmental and natural resources policy, or regional and urban land use planning, to name just a few. .

In this context, new and complementary management approaches are being proposed that aim to reinforce existing management prescriptions and more explicitly incorporate the concepts of hybridity between the social and the natural (*waterscapes*), complexity and uncertainty that underlie the new water management paradigm. Socio-ecosystem based management, polycentric governance (Ostrom, 2010), eco-adaptive management (Huitema *et al*., 2009), or the emerging concept of water security (Cook and Bakker, 2012; Staddon and James, 2012; Martinez Cortina *et al.,* 2010) are only some of the new or revised concepts that are gaining traction.

3.2. The emergence of the water security concept

In the context of these debates, it is unavoidable to make a specific reference to the notion of water security. As Cook and Bakker (2012) point out, over the last decade the water security concept has emerged from its original niche in studies of international security and hydropolitics to become much more widely used. To some extent it seems even to be supplanting the hegemonic position hitherto occupied by the “sustainable water” concept (Staddon and James, 2012). According to UNESCO (2008), “Water security involves protection of vulnerable water systems, protection against water related hazards such as floods and droughts, sustainable development of water resources and safeguarding access to water functions and services." The above definition subsumes key ideas of the "sustainable water management" paradigm as constitutive definitional elements whilst also importing the ideas of ecosystem functions and services, the risk of climate-related hydrological hazards, and water as an object of geopolitical security discourse. The idea of water security assumes that people's fundamental interests are in satisfying demands for water-related services such as food, fiber, waste disposal and sanitation. Thus, society's focus is not on the use of water per se but on the services and benefits provided per unit of water used (Martínez Cortina *et al.,* 2011).

Staddon and James (2012) point out that the gradual shift from 'sustainability' to 'security' implies continuing a course of action understood to be working (i.e. towards sustainable water use), but also incorporating a recognition of a widening and deepening urgency. Water security is counterposed to the implied (and undesirable) outcome of water ***in***security: a state of unreliable supplies of water of acceptable quality. Water security is centrally concerned with the potential risks both in terms of rights to water and threats that exist from external factors (which may be human or non-human) over water. While the sustainability discourse recognizes the possibility of "running out", it nevertheless tends to constitute itself in terms of the achievement of an ecological balance. The security discourse, by contrast, is based more on threats than opportunities and therefore tends to define the policy options negatively; policies that will prevent sub-optimal outcomes as much as those that will broker optimal ones.

More than a decade ago Ulrich Beck, although from another perspective, had envisioned the general context in which *water security* can be framed. Developing his notion of *global risk society* long before the credit crunch of 2008 and the austerity agendas that have followed, he stated that "collective life patterns, progress and control capacity, full employment and exploitation of nature typical of the *first modernity*, have been undermined by five interrelated processes: globalization, individualization, gender revolution, underemployment and global risks (such as the ecological crisis and the collapse of global financial markets). The real political and theoretical challenge of the *second modernity* is the fact that society must simultaneously meet all these challenges" (Beck, 2002 (1999): 2).

3.3. What are the new information requirements in the evolving water management paradigm

Traditional water management focused on the procurement of new water resources to meet demand. Data requirements were therefore limited and focused primarily on quantitative estimates of available resources and consumption, as well as chemical water quality parameters insofar as chemical pollution may affect existing uses. Furthermore, economic information was limited to basic budgetary estimations for planned investments since cost recovery, when it existed, was limited to fairly narrowly defined water use levies and fees.

The increasingly dominating water management paradigm recognizes the complex and multifaceted nature of water and therefore has additional information requirements that can be summarized as follows:

- *Environmental information* and, more specifically, information on biological as well as chemical quality of water resources and associated aquatic ecosystems, in order to respond to new ecosystem-based management goals.

- *Socioeconomic information*, which becomes essential in the transition from a technocratic management approach with centralized and hierarchical decision making processes, where social actors are recipients of management decisions, toward more participative decision processes, a part of a new management culture that incorporates institutional learning and adaptation.

- *Economic information* on the costs of water services and associated prices, but accounting for the multifunctional characteristics of water from which multiple ecosystem services derive. That is, the economic information must take into account not only the financial costs of service provision, but also the ecosystemic implications of these services and the associated costs (environmental and resource costs, in the language of the WFD).

- Development of *synthetic and sustainability indicators*: the wealth of data available makes it necessary to develop indicators that present this information in a manner that is concise, agreed upon and easily understood, in order to facilitate continuous monitoring and evaluation of these complex socio-ecological systems. However, as Garnåsjordet et. al (2012) point out, these indicators comprise not only a selection of facts in some technical sense. The choices involved in the development of the indicators are subjective and respond to underlying "narratives" that are conditioned by societal interests and implicit values embedded in the data-generating processes. Therefore, the development of the data and assessments needs to be deliberated in a political process reaching agreements for political action

3.4. In the context of the new requirements, what are the main deficiencies of currently available information for water resources management?

The primary limitations of currently available data and information are those that derive from the need to overcome the *nature-society dualism* that still is at the core of the hydraulic management paradigm. There is a strong need for information on the complexity of *socio-hydrological systems*, which are reflexive, adaptive, non-linear and complex, and have feed-back loops, emerging properties and non-predictable responses to management interventions.

The consideration of water as a socio-ecological patrimony requires linking biophysical and socioeconomic variables, a significant challenge given current knowledge and modeling capabilities. The traditional separation of social and natural sciences has ignored the overlap of both fields of knowledge, which results in the limited theoretical and methodological development for their joint analysis, as well as the paucity of available data for management.

There are significant gaps in knowledge in what refers to the efficacy of the measures implemented to improve the health of aquatic ecosystems. Current research in integrative analysis and inter-disciplinary modeling is producing increasingly robust information and knowledge, but the diversity and complexity of natural ecosystems impose significant restrictions on the transferability of the results from one spatially defined case to another.

These limitations in the understanding of the functioning of biophysical systems and their responses to management interventions also apply to the social dimension of socio-hydrological systems. As a result, attempts to precisely value the components of these systems, their functioning and interrelations do not seem feasible. Information and data need to be presented in a transparent manner, specifying their origin and the limitations and uncertainties they necessarily incorporate.

Nevertheless, scientists work on the development of models that target those gaps. Examples are the so called stress-response models, which are used for the development of indicators for analysis of human-environmental systems. According to Regions for Sustainable Change (RSC) partnership's Low-Carbon Indicators Toolkit, they are four[1]:

- Pressure – State – Response (PSR) model, developed by the Canadian scientist Anthony Fried in the 1970s and adopted by Organization for Economic Co-operation and Development's (OECD) State of the Environment (SOE) group[2].
- Driving force – State - Response (DSR) model is a variation of the PSR model, adopted by the United Nations Commission on Sustainable Development (UNCSD)[3]
- Driving force – Pressures – State – Impact - Response (DPSIR) model, used by European Environment Agency[4,5], Eurostat and European institutions.
- Framework for the Development of Environment Statistics (FDES) which was developed in 1984 and endorsed in 1995 and developed in 2013 by the UN Statistical Commission[6].

According to Burkhard and Müller (2008), the PSR model provides a good basis for the analyses of environmental issues and the DSR model is more focused on the human demand and activities that affect the environment. For overall analyses and description of the components and interrelations in the human-environmental systems, the DPSIR model is considered to be the most applicable and finds the broadest recognition. The purpose of the model is to identify and describe the processes and interactions within the human-environmental systems in a manner that emphasizes the infinite cause-effect chain of relationships in past, future and recent developments (Burkhard and Müller, 2008) (see Figure 1).The United States Environmental Protection Agency (EPA) provides "Tutorials on Systems Thinking using the DPSIR Framework"[7] that includes also examples for the application of the model for different issues, including water management and river basin management.

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1 http://www.rscproject.org/indicators/index.php?page=what-methodologies-can-be-used-to-develop-indicator-s-or-indicator-set
2 http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/Refer/gd93179.pdf
3 http://www.un.org/esa/sustdev/csd/csd9_indi_bp3.pdf
4 http://ia2dec.ew.eea.europa.eu/knowledge_base/Frameworks/doc101182
5 http://www.eea.europa.eu/publications/TEC25
6 http://unstats.un.org/unsd/environment/fdes.htm
7 http://www.epa.gov/ged/tutorial/index.htm

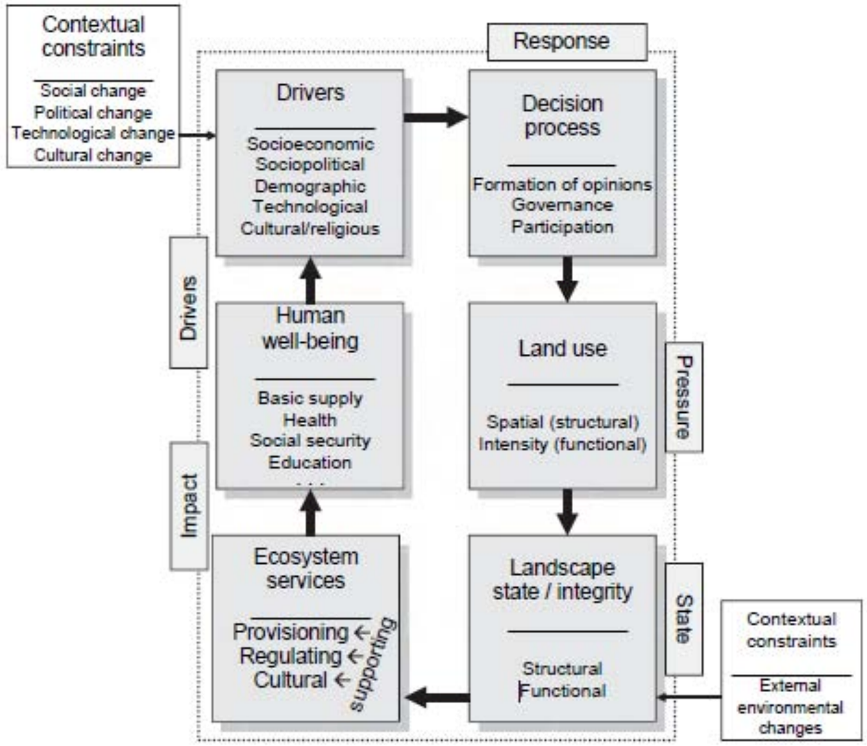

Figure 1. DPSIR-based model of human-environmental systems (Source: Burkhard and Müler, 2008)

3.5. How can we manage the uncertainty associated with our understanding of socio-natural processes and its influence on resource availability and hydrological risks?

The concept of uncertainty can be understood under three different perspectives (Wynne, 1992):

- *Technical* (or conventional) *uncertainty* which refers to the unavailability of data and, more generally, information and knowledge. In this case the problem is related to the lack of reliability or thoroughness of the historical data, a frequent situation in hydrology. In order to overcome this problem scientists develop models, thus simplifying complexity. Some of the uncertainties related to the hydrological inverse methods (hydrological modeling) are those associated with: (1) model parameter estimates and (2) model parameter resolution (see Vasco et al., 1997) or, more importantly, (3) model structural uncertainty (completeness/adequacy) (Gupta and Nearing, 2014; Gupta *et al*., 2012, and Gupta *et al*., 2008).

- Uncertainty in terms of *indetermination.* In these situations the system parameters and their interrelationships are unknown, since they are so complex, and consequently the model results become completely unreliable.
- Uncertainty in terms of *ignorance,* which occurs when 'we ignore what we do not know'.

In the context of the evolving paradigm for water management these knowledge limitations are of vital importance: we recognize that uncertainty is inevitable when dealing with socio-ecological systems. We must therefore strive to understand its relevance in the system we are studying and, to the extent possible, identify the potential fluctuations and their repercussions on the rest of the system being modeled. The need to adequately manage uncertainty in complex systems is the most relevant factor, in an epistemological sense, which demands multi-disciplinary approaches and the participation of a diversity of actors and interests in decision-making processes.

4. ECONOMIC CONSIDERATIONS IN EVOLVING WATER MANAGEMENT DEBATES

The paradigm of IWRM incorporates two basic economic principles: cost recovery and the polluter-pays principle. However, under current ecosystem-based approaches to water resources management, the goal is no longer only to attain good chemical quality. Rather the goal is to preserve and restore adequate ecosystem form and function or, under Water Framework Directive (WFD) terminology, good status (chemical and ecological for surface waters, and chemical and quantitative for groundwater). In broader terms, the goal has become to protect and enhance the services provided to society by the good functioning of aquatic ecosystems, that is, to use an ecosystem approach (Wallis *et al*., 2011; SCBD, 2004) for resource management. It would therefore be appropriate to substitute the term of polluter pays for the more ambitious concept of payment for the deterioration of ecological function of water ecosystems or, more broadly, for loss of ecosystem services.

The WFD, perhaps the most ambitious legal initiative to incorporate economic considerations into water management practice, uses this broader approach and establishes that the cost of water services should incorporate both *environmental* and *resource costs*, in addition to the *financial costs* associated with the provision of these services, and requires adapting the water pricing system accordingly (Art. 9, WFD). It also requires that the Program of Measures that is adopted in each River Basin Management Plan to achieve good status objectives (Art. 11, WFD) is designed so that the combination of measures selected is the most cost-effective in relation to the established goals (Annex IIIb of WFD and European Commission, 2003). However, the practical implementation of these requirements has been challenging, in spite of concerted efforts on the part of the Commission to establish common guidelines (see for instance European Commission, 2003), and the reports from the DG Eco 2 Working Group)[8]. The evaluation of the experience of the first hydrographic districts' planning cycle (2009-2015) shows that significant amount of work still needs to be done to adequately define environmental and resource costs and establish agreed upon methodologies for their calculation (European Commission, 2012). From the perspective of the economic assessment of water policy

[8] European Drafting Group (DG Eco 2) was set up in September 2003 under the Common Implementation Strategy (CIS) Working Group 'Integrated River Basin Management' (WG 2B).1 WG 2B asked the DG Eco 2 to prepare a non-binding information sheet on the definition and assessment of environmental and resource costs in the context of the implementation of the WFD and to present practical examples for the calculation of ERC from the Member States (Görlach and Interwies, 2004).

measures, more work is also necessary to develop a common methodological approach for the calculation of cost-effectiveness of the measures (Tremolet Consulting, 2006; Berbel *et al.* 2011).

Different reasons can help explain these challenges. According to Naredo (2013 and 2006), they result from a reductionist approach to water management: on one hand the continuing dominance of the hydraulic paradigm that treats water exclusively as a productive (economic) resource and, on the other, a standard economic approach to cost recovery that considers water as an input for economic activities and therefore valued exclusively in monetary terms. These limited perspectives fail to account for the complex reality of water and its associated ecosystems, particularly since many of the social benefits or ecosystem services provided by well-functioning aquatic ecosystems, are not exchanged in the marketplace and therefore cannot be valued in monetary terms. La Roca (2013 and 2011) also points out that, in addition to clear methodological challenges to estimate financial and environmental costs of water services, there has been a significant resistance to incorporate economic criteria into water resources management from traditional water users that have strived to maintain their historic privileges, obtaining private benefits from the use of cheap water resources while externalizing the costs or impacts of this use.

The persistence of the traditional hydraulic paradigm and standard economic perspectives therefore limit our ability to rigorously and comprehensively calculate costs that are outside their standard analytical and accounting frameworks. Different approaches are being proposed to overcome these limitations. Over the past few years there has been an increasing amount of academic and practical work developed that advocates the use of an ecosystem approach to incorporate the wide range of services and benefits provided by aquatic ecosystems (Wallis *et al., 2011;* Vlachopoulou *et al.* 2013; Spray and Blackstock, 2013) while at the same time warning of the potential risks involved in using this approach too narrowly (La Roca, 2013). Naredo (2013) proposes a broader eco-integrative approach to adequately account for the complex, multifaceted nature of water resources and the costs associated with its use.

4.1. What are the new information and data requirements to estimate the cost of water services? A proposal from the perspective of eco-integrative economics

Multiple official guidelines, reports and academic papers have been published over the past several years in the context of the WFD implementation process that propose traditional (neoclassical) economic approaches to estimate the environmental and resource costs associated with water services (Martín-Ortega *et al.*, 2011; Görlach & Interwies, 2004; or Brower *et al.* 2009; to name just a few that refer to the broader international scientific literature). The traditional economic approach attempts to estimate the so-called *total economic value* of environmental resources, that is the sum of the use and non-use value of these resources (Wright, 2007). The *non-use value* cannot be easily expressed in monetary terms since they are not exchanged in the marketplace. Neoclassical economics attempts to estimate their monetary value through indirect methods such as the stated preference methods (contingent valuation, choice modeling, etc.). The results of these studies are specific to a region and moment in time, since they are highly subjective. Given the limited resources available to carry out these estimations, a benefit transfer approach is often used to apply the environmental monetary values obtained in a specific study site to a different policy area (Brower, 2000). However, this benefit transfer approach entails its own risks, mainly due to the site specificity of the cases and the limited homogeneity between them (USEPA, 2009).

In the case of the implementation of article 9 of the WFD, the scientific literature (and the official guidelines that have been developed in different countries and by the EC), proposes considering the financial costs of water services, and the environmental and resource costs associated to these services, as discrete entities that can be added up (see Figure 2). The logic behind this approach is that the financial cost can be calculated through the accounts of the economic agents that provide water services. Once this amount is known the environmental and resource costs need to be estimated in monetary terms and added to the financial cost in order to obtain the *full cost* (or total economic value) of water services that the WFD requires. The goal is then to adapt the water pricing system to the resulting cost structure, with the possibility of applying adequately justified exceptions.

Given the conceptual and methodological challenges of calculating environmental and resource costs in precise physical units and even more so, in monetary terms, Naredo (2007) proposes an *eco-integrative economic* approach, in which these three components of the *total economic value* are seen as interrelated. This approach focuses exclusively in the hydrological cycle due to the complexity of extending economic analysis to water associated ecosystems and landscapes. Using this approach, water managers must conjunctively analyze these components in order to adequately and effectively account for all of them and design economic instruments and reasonable water tariffs.

Naredo (2013) suggests that the study of the natural and artificial flows of water in a specific region from a systemic or physical balance perspective is the most effective method to identify the costs associated with the provision of water services and the conservation of qualitative and ecological status. It is also an ideal approach to understand to what extent water flows (and their associated costs) are independent from each other, thus avoiding double accounting. From this perspective Naredo suggests the simultaneous use of three types of water accounts: quantity, quality and cost accounting (see also Valero *et al*., 2006).

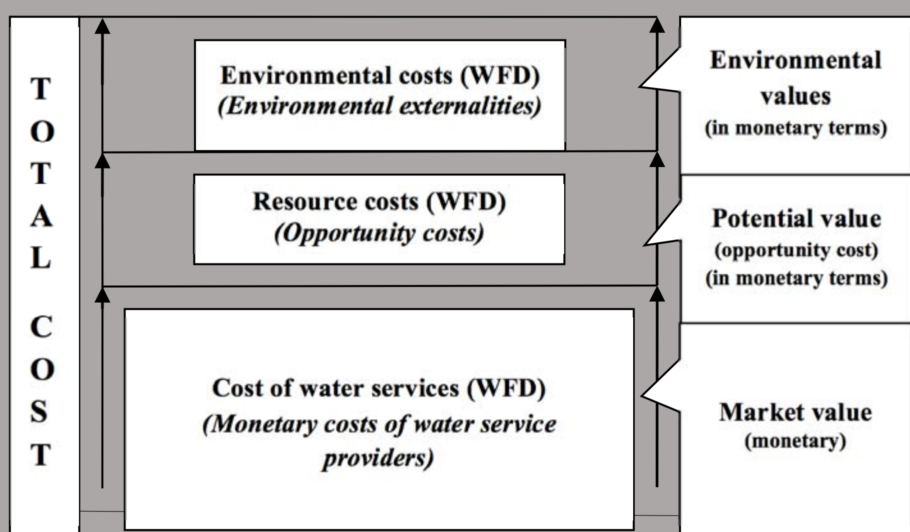

Figure 2. Total cost of water services estimated through the traditional economic approach applied to the requirements of the Water Framework Directive (Source: Naredo, 2013)

The *quantitative water accounts* refer to the hydrologic balance in the geographical region being analyzed (river basin district, watershed or other chosen boundary): the balance between precipitation and inflows from other regions or systems, natural outflows, abstractions for different uses and return flows, determine water availability. Accurate quantitative water accounts are essential to assign costs and prices according to water availability and use and the costs associated with the maintenance of the socio-natural hydrologic cycle under different scenarios.

In order to develop *water quality accounts* Naredo suggests using a balance of differences of *physical and chemical potentials* of water. Under natural conditions water flows into a system at high altitudes and with good quality conditions. Therefore there are two fundamental concepts that allow for the quantification of the potential differential associated with water quality: the *physical potential*, which is related to elevation, and the *chemical potential*, which is related to its salt and contaminant load. From this perspective, environmental costs can be estimated as the units of energy that would be necessary to return water to its starting physical (elevation) and chemical conditions, assigning a market price to these energy units in order to translate costs to monetary terms.

The *cost accounting* derives from the other two type of accounts combined with information on energy prices and energy requirements for each change in potential (both physical and chemical). It is also necessary to have information on available technologies (water treatment, pumping, etc.), their applicability to the specific region being analyzed and their implementation and operational costs.

4.2. How can monetary and physical magnitudes be combined?

In addition to the implementation of the full cost recovery and the polluter pays principles, the WFD requires taking into account cost-effective criteria when selecting the most adequate combination of measures to achieve planning goals (Annex III, WFD). However, attempts to perform a cost-effective analysis of alternative measures to achieve ecological goals or to value the contribution of natural ecosystems to human welfare meet with the limitations of knowledge and information both within disciplines (economics, ecology, hydrology, etc.) as well as in the use of trans-disciplinary approaches. In the field of economics, for instance, we find that classic valuation approaches based on monetary prices are insufficient to adequately handle goods and services for which there are no markets, and that are not easily reduced to market logics.

In order to overcome these limitations, Naredo (2007, 2013) proposes assigning market prices to the energy necessary to obtain the resources and restore them to their original state (altitude and chemical potential), which will be added to the costs of providing water services. Energy costs are calculated as the sum of the actions necessary to maintain the hydrological cycle (water quantity and quality) in the best possible health (status, in WFD terminology) while supplying the population and economic activities with the necessary water resources. Naredo does not estimate the costs associated with ecosystem restoration because the complexity of defining the initial and final state is much greater than the complexity associated with the flows of water, which can be simplified through the inflows and outflows of the hydrological cycle. Such complexity would require geographically-specific detailed analysis to be developed.

Attempting to value environmental costs or the contribution of natural ecosystems to human welfare, in other words, valuing ecosystem services, requires different metrics, they cannot be expressed exclusively in energy and monetary terms. The information and knowledge necessary for this valuation is still being developed (La-Roca, 2013).

4.3. What are the main obstacles to internalize the environmental costs associated with water services and what progress has been made toward their evaluation?

Under standard economic practice, environmental considerations are externalities outside the system, impacts that result from the use and consumption of water but are not compensated through the water pricing system. The main obstacle to overcome this scenario is the difficulty of precisely quantifying or valuing the degradation of complex natural ecosystems that result from human actions. It is difficult to translate that degradation into replacement costs and determine the price to pay by those that have caused it.

Naredo (2007, 2013, Valero et al. 2006) proposes overcoming this limitation by relating the *environmental degradation* resulting from economic and human activity with the *exergy loss*—or energy required—associated with all the materials that take part in the productive process. The negative balance or thermodynamic irreversibilities that are associated with the economic metabolism thus becomes a powerful and synthetic quantitative indicator of the direct environmental damages that result from economic activities, that then spread out and affect ecosystems and their associated natural spaces in different ways. The replacement cost of these direct losses is an equally powerful synthetic quantitative indicator of what we could consider their *direct environmental costs.*

If instead of considering all materials and substances that are mobilized in the global economic metabolism we focus only on one, water, the complexities that derive from the previous reasoning are obviously simplified. According to Naredo, as above mentioned, in the case of water it would be necessary to distinguish between two levels: *dimensions*, which refer to water as an element; and *systems*, which are related with the organisms, ecosystems and landscapes that are dependent on water and its territorial support. In terms of dimensions, water is understood in the conceptual framework of the hydrologic cycle, which operates according to generally accepted laws and norms, thus facilitating the delimitation and quantification of the environmental and resource costs that derive from its possible and effective replacement. However, in the systemic level, which is the object of study of ecology, there is a significant leap in complexity and a greater amount of irreversibility of some processes. It is thus much harder to quantify precisely replacement costs.

The establishment of a common cost estimation methodology is complicated by the variety and complexity of conservation and restoration costs. This results from the challenges of undertaking ecosystem restoration processes and the great diversity of water-dependant organisms, ecosystems and landscapes. The WFD attempts to systematize the diversity through the concept of *reference conditions* for each type of water body in different river basins. This approach recognizes that, in the systemic level identified above, the calculation of the conservation or restoration costs are linked to the specific measures that are identified for each geographic-specific situation, which vary depending on the type of ecosystem and level of degradation of each *water body*.

The availability of enough good quality water in the first *dimension* level is a prerequisite for the conservation of ecosystem integrity in the more complex systemic level. Therefore understanding the necessary measures and associated costs for the maintenance of water quality and quantity in a water body is a necessary first step for the conservation of the associated organisms, ecosystems and landscapes.

4.4. How can we value the ecosystem services that derive from more sustainable water use patterns?

The identification and valuation of environmental services provided by water-dependant ecosystems is an integral part of more advanced water management approaches. The concept dates back to the 1990s with the introduction of the Ecosystem Approach by the 1992 Convention on Biological Diversity and the resulting efforts to value ecosystem services (see for instance Constanza *et al*.'s 1997 seminal article in *Nature*). However the valuation of ecosystem services as a methodological approach became institutionalized by the 2005 Millennium Ecosystem Assessment, which attempts to assess the consequences of ecosystem change for human welfare (see table 1).

Table 1. A classification of water-dependent ecosystem services according to the categories identified by the Millennium Ecosystem Assessment

Categories	**Examples**
Provisioning	Provision of primary goods (food, fibers, wood)
	Biophysical support of fishing (continental and marine waters), hunting and grazing
	Water supply
	Contribution to energy production
Regulating	Coastal protection
	Water purification
	Carbon sequestration
	Climate regulation
	Flood control
	Biological control
	Waste decomposition
Cultural	Tourism, recreation, landscape and aesthetic quality
	Spiritual and religious benefits
	Education and research
Supporting	Contribution to primary production (for instance, fish banks)
	Seed dissemination through water currents
	Sediment formation and circulation
	Erosion control

Source: Millennium Ecosystem Assessment (2005)

Since then the concept finds broad acknowledgement in science and management. These are some of the platforms facilitating information sharing and networking on the topic of ecosystem services: the Ecosystem Assessment Platform[9] of the Biodiversity Information System for Europe (BISE)[10]; the Ecosystem Service Partnership (ESP)[11] that also provides the interactive

[9] http://biodiversity.europa.eu/ecosystem-assessments
[10] http://biodiversity.europa.eu/
[11] http://www.es-partnership.org/esp

ESP Visualization tool[12]; and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)[13]. There are also a significant number of initiatives at the European and global level. USA initiatives in the area of ecosystem services include: the ecosystem service research center of the United States Environmental Protection Agency (EPA)[14] which includes EnviroAtlas[15], a web-based tool that combines maps, graphs, analysis tools, and interpretive information for the United States; the National Ecosystem Services Partnership (NESP)[16]; the United States Department of Agriculture (USDA) Forest Service initiative "Valuing Ecosystem Services"[17]; and the Global Observatory for Ecosystem Services (GOES)[18].

The classification typologies of ecosystem services also evolve through time (for a review see Haines-Young and Potschin, 2009). The state of the art for the different categories excludes Supporting services from the list. A project undertaken by the European Environmental Agency (EEA) developed a Common International Classification of Ecosystem Services (CICES). The classification and the report can be found on the website: http://cices.eu/ The concept of ecosystem services finds broad acknowledgement in the European Union legislation, for instance in the EU Biodiversity Strategy to 2020[19], the Environment Action Programme to 2020[20], or the Blueprint to Safeguard Europe's Waters[21].

The difficulty of identifying and valuing ecosystem services derives from the diversity of dimensions that are encompassed by the concept (productive, ecological, cultural, etc.). Furthermore, ecosystem services often result from interrelations between different ecosystem components, thus adding complexity to any systematization and evaluation attempt. Even the classification of ecosystem services in non-overlapping categories is problematic. However, a strict partition of the set of ecosystems services, in exhaustive and mutually exclusive classes, is a necessary condition wherever an arithmetic approach is envisaged (for instance for avoiding double accounts) (La Roca, 2014, personal communication).

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12 http://esp-mapping.net/Home/
13 http://www.ipbes.net/
14 http://www.epa.gov/research/ecoscience/eco-services.htm
15 http://enviroatlas.epa.gov/enviroatlas/index.html
16 http://nicholasinstitute.duke.edu/initiatives/national-ecosystem-services-partnership#.UuEyouXZCc_
17 http://www.fs.fed.us/ecosystemservices/index.shtml
18 http://www.goes.msu.edu/index.cfm
19 http://ec.europa.eu/environment/nature/biodiversity/comm2006/2020.htm
20 http://ec.europa.eu/environment/newprg/
21 http://ec.europa.eu/environment/water/blueprint/pdf/COM-2012-673final_EN_ACT-cov.pdf

In terms of costs, Naredo (2013) highlights the difficulty of valuing environmental factors that are not directly associated with the quantity or quality (physical and chemical potentials) of water as a resource, that is, factors that support life or provide ecosystem services. The methodology he proposes for valuing the environmental costs of water services can be temporally and spatially adapted, but the calculation of the ecosystem costs cannot be adapted to such precise approaches. Impacts on water related ecosystems have greater irreversibilities than the balance of the hydrologic cycle, thus complicating the estimation of replacement costs. The greatest challenge derives from the transition from inert materials (water) to the living world (water-dependant ecosystems), which also responds to physical and chemical laws, but cannot be explained exclusively through them.

The interrelationships between living organisms, human society and the geographical spaces where they occur can be expressed in terms of the provision or reception of ecosystem services. The complexity and multiple ramifications of these interrelations make their systematic evaluation difficult. The attempt is further complicated by the difficulty of segregating the aquatic component of environmental costs from other costs of conserving and restoring organisms, ecosystems and landscapes within the geographical space being analyzed, since they are closely intertwined. Progress therefore needs to be made in the understanding of socio-ecological systems and the effects of these interrelationships.

Many of the knowledge limitations discussed in this section are to some extent insurmountable, inherent to the complexity of socio-natural systems. Institutional arrangements are necessary to deal with these uncertainties (in the sense of ignorance) and the need to manage water resources and associated ecosystems in this uncertain and partially understood context. It may therefore be necessary to shift the emphasis from the quantification and deterministic approach to valuating trade-offs and management alternatives, toward a more deliberative approach, where interested actors can jointly discuss values, preferences, risks and alternative outcomes (La Roca, 2013). In this sense the dynamic modeling approach discussed below can be seen as a step in this direction.

In spite of the limitations discussed in this section, there are initiatives that are attempting to provide guidelines for valuing ecosystem services, such as the Economics of Ecosystems and

Biodiversity (TEEB)[22]. Based on its work, the EC issued the report "A synthesis of approaches to assess and value ecosystem services in the EU in the context of TEEB"[23]. This report, together with the Mapping and Assessment of Ecosystems and their Services in Europe (MAES)[24] discussion paper, are key documents aiming to support EU Member States in addressing one of the main actions of the EU Biodiversity Strategy[25], Target 2, Action 5. This Action aims to map and assess the state of ecosystems and their services in the national territories of EU Member States by 2014, assess their economic value, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020.

Other platforms that integrate information on different initiatives, tools and practices for the valuation of ecosystem services for decision-making are the Nature Valuation and Financing Network[26] and Ecosystem Valuation[27]. The appropriate choice of indicators is a key step in the process of measuring ecosystem services for environmental needs, and these platforms provide a set of possible indicators for each service. Staub *et al*. (2011) also suggest a set of indicators for ecosystem services. The EEA published a Core Set of Indicators (CSI) Guide[28] addressing environmental issues, though it is not focused on the ecosystem service analysis.

All these resources can supplement a research on water related ecosystem services, after the services of importance and interest are recognized.

[22] http://www.teebweb.org/
[23] http://ec.europa.eu/environment/nature/biodiversity/economics/pdf/EU%20Valuation.pdf
[24] http://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf
[25] http://ec.europa.eu/environment/nature/biodiversity/comm2006/pdf/2020/1_EN_ACT_part1_v7%5B1%5D.pdf
[26] http://www.fsd.nl/naturevaluation
[27] http://www.ecosystemvaluation.org/uses.htm
[28] http://www.eea.europa.eu/publications/technical_report_2005_1

5. NEW INFORMATION TECHNOLOGIES AND WATER RESOURCES MANAGEMENT: NEW OPPORTUNITIES AND DEMANDS RESULTING FROM THEIR AVAILABILITY

The proliferation of information and communication technologies (ICT) has caused profound changes in the availability of information about our planet (remote sensing, GPS, spatial climate sensors, etc.); in its storage and processing capabilities (database management, geographic information systems, cloud computing, etc.); and in its distribution and dissemination (internet, web services, web-based applications, mapping technologies, mobile applications, etc.). These processes obviously also pertain to water resources information, so that the availability of key data for sustainable water management will evolve in relation with the development of the ICTs.

ICTs have changed society. The continuous increase in computing power and the growth of the Internet have changed the way in which society manages information. New technologies like faster computers, broadband internet, huge storage and cloud computing create new environment of data and information sharing.

The Internet provides communication infrastructure for countless networks associating human beings and the environment. Internet connection allows remote management of the monitoring systems of sensors observing factors such as soil moisture, crop water retention and weather information. Information sharing about natural and man-made systems on a global scale is crucial for solving critical problems (*Location matters: Spatial standards for the Internet of Things, September, 2013, http://www.itu.int/techwatch)*. Observation and management systems (sensors, imaging and geospatial processing) were created by different professional communities to solve different kinds of problems.

A set of specialized ICT are the Geographic Information Technologies (GIT), which help to collect, manage, and analyze data about the resources, landscape features, and socio-economic characteristics of an area in space and time. Their capability to visualize spatial information is an important feature for communication, dissemination and knowledge sharing. GITs include the ICT tools as Geographic Information Systems (GIS), Global Positioning Systems (GPS), Remote Sensing (RS) and Web-based tools. GITs are increasingly used in combination. The strength of each technology is applied to deal with integrated approaches. Web-based tools provide new ways of information sharing and real-time data visualization, Remote Sensing (RS) provides Earth's surface images, and the development of web GIS can be regarded as a major advancement opening many new opportunities, such as real-time maps, frequent data updates and sharing of spatial information by users all over the world. Through GIS overlay functions, knowledge from different disciplines is brought together, enabling spatial modeling of processes and dynamics of local human-ecosystem inter-linkages (*http://www.inforesources.ch/pdf/focus07_3_s.pdf*).

The effect of wireless technologies on society is tremendous and profound. Wireless communications between devices can be provided by the cell phone infrastructure. Other physical networking technologies such as RFID (*Radio-frequency identification*), WLAN (*Wireless Local Area Network*) and Bluetooth are better suited to communication between sensors and mechanical systems. Wireless networks are incredibly valuable in emergencies and disasters.

The explosive growth of mobile communications provides a wide range of opportunities. A mobile phone can also be thought of as a sensor. Smartphones typically include a gyroscope, accelerometers, GPS, Wi-Fi, Bluetooth, sound, light, time, near-field communications (NFC), compass, camera etc.

New ICT also with tremendous potential are Ubiquitous Sensor Networks (USN), networks of intelligent sensor nodes that could be deployed "anywhere, anytime, by anyone". USN could generate applications in a wide range of fields, including environment and habitat monitoring, disaster management, security, intelligent transport systems etc. The main components of a USN are Sensor Network, Network Infrastructure and Access, and Middleware. USN can be used in three broad categories: detection, tracking and monitoring (e.g. detect temperatures exceeding a particular threshold, track workers in dangerous work-environments, monitor inhospitable environments, behaviour of animals in their indigenous habitat etc.).

Currently, the telecommunications industry is undergoing a revolution as it migrates from today's separate networks (for voice, mobile, data etc.) to a single, unified IP-based next-generation network (NGN).

The new computing paradigms of Cloud and Grid computing also offer more opportunities for data and information management through provision of new services as SaaS (Software as a Service), IaaS (Infrastructure as a Service), PaaS (Platform as a Service) and SOA (Service-

Oriented Architecture). This distributed computing contributes to enhance features such as ubiquitous access, reliability, scalability, virtualization, exchangeability, location independence, cost-effectiveness etc. The resources that can be shared in grids and clouds could be physical (computational power, storage devices, communication capacity) and virtual (software, applications, services).

Advances in technologies allows us to collect increasing amount of scientific data (in experiments, observations, simulations etc.), which respectively leads to a leap forward in the development of data storage, processing, handling and analysis. The progress determines the development of new areas of knowledge such as data mining, scalability, artificial intelligence (AI) and many others.

In the field of IWRM the propagation of Smart Water Management (SWM) in agriculture, domestic and industrial water use sectors, as well as the wider aspects of socioeconomic development is associated with many public benefits. For example Smart metering technologies play an important role in real time measuring of water consumption, leak identification at the consumer level and may contribute to change consumers' awareness about their water use. Smart water-metering technology can enable water utility companies to track usage more accurately at the consumer level and implement water-pricing plans to encourage water conservation[29]. Water use in manufacturing plants can also be managed more efficiently using ICT. Another example of SWM is the use of SCADA (*Supervisory Control And Data Acquisition*) in water and sewage systems in big cities to gauge and control flows, which provides monitoring and analysis tools for water managers. These systems can be integrated into Web-based architectures.

The use of Earth Observation (EO) technologies such as satellite based monitoring can be very useful as it can provide a cost-effective alternative or complement to field data collection. The main advantage of EO data is that it provides coverage over large and remote areas with systematic, repetitive data captures. For example, flood risk studies use LiDAR (*Light Detection and Ranging*) technology to create highly accurate Digital Elevation Models (DEMs) for improved floodplain mapping. EO products range from simple satellite images to more complex remote sensing applications such as climate change detection, mapping of land cover and land

29 http://www.itu.int/net/itunews/issues/2011/01/36.aspx

use, snow cover maps, wetland and water quality monitoring, pollution source detection, and other project-specific monitoring, and analysis services[30].

Weather forecasting and climate monitoring has also benefited greatly from ICT development. The World Weather Watch system for observation includes three core components[31]: Global Observing System (GOS), Global Telecommunication System (GTS) and Global Data Processing and Forecasting System.

Satellite imagery and aerial photography provide visual information assisting water managers in more accurate distribution of available water resources. The UAVs (*Unmanned Aerial Vehicles*) can be used in wetland mapping, river hydraulic modeling, soil moisture monitoring etc.

ICT use can play a crucial role in environmental protection, mitigation of local effects of climate change, energy efficiency, disaster management, water utility business and a wide range of many other fields interconnected with IWRM.

5.1. What are the challenges and opportunities of the new sources of information that are provided by ICTs?

ICTs open a wide array of possibilities to obtain, process and disseminate information for water resources management. The latter is particularly relevant in a context of a growing social and political support for open government and open data standards. In fact it could be argued that the information innovations that derive from the evolution of new information technologies will give way to a new and more efficient public administration.

However, there remain significant challenges to take full advantage of the opportunities offered by the constantly evolving ICTs, challenges that derive from the inertias of existing models of information generation and management and that limit the potential of these new technologies to transform information into knowledge. Some examples serve to illustrate the magnitude of these inertias (Moreira, 2013):

- Only small percentage of the WWW contents (4% out of about 8 billion web pages, according to the person in charge of the Spatial Information System of Andalusia regional

30 http://www.eurac.edu/en/research/receivingstation/default.html
31 http://www.itu.int/net/itunews/issues/2011/01/36.aspx

government) are available through publicly available search engines such as Google. Therefore about 96% of digital information is protected by access codes (the so-called deep WEB) (Moreira, 2013).

- Public administrations use a wide array of programs and applications that request personal information from the public. However, too often these applications are independent of one another and do not take advantage of potential synergies or develop "one-stop" government procedures. These would be possible if governments changed their data management approach.

- The information used for water resources management is often exclusively local, in spite of the availability of global information that would allow for different management scales.

5.2. What are the primary limitations to a fluent exchange of information among different public administrations?

Inertias from the past and a high level of mistrust between different administrations result in the coexistence of different systems of organization, control and dissemination of information for each institution. While existing technology allows for the existence of a single information system, information generation and dissemination continues to be poly-nuclear and disperse. Each information provider, either individually or collectively, generates its own information structure and expects others to adapt to it, instead of working collectively to integrate information within a common system.

In the European Union there have been several initiatives that attempt to harmonize existing public information systems, limit duplicities and redundancies and improve public access to information. The INSPIRE Directive (Directive 2007/2/EC establishing an infrastructure for spatial information within the EU); existing legislation on the right to public access of environmental information (Law of Access to Public Information 55/2000, Directive 2003/4/CE and their various national transpositions; and the Directive on the re-use of public sector information, Directive 2003/98/EC, known as the 'PSI Directive') are landmark steps in this direction. However, public administrations are still reluctant to accept the public right to access environmental information and an individualistic approach continues to dominate information management. Public administrations have still largely not reorganized their information management procedures and systems in order to facilitate knowledge generation and information integration. On the contrary, they maintain traditional procedures but rely on information technologies to carry them out. This results in a significant contradiction between the great potential of the ICTs and the individualistic approach to information generation and management that continues to predominate.

Another dimension of this issue deals with the lack of attention to the new experiences of distributed and collaborative data generation advocated by the ICT. It is necessary to pay attention to and enhance the different platforms of social exchange and collaboration that allow forging social learning and knowledge on water. The pending issue of water policy in the field of information is to ensure that information gives rise to knowledge truly useful for participatory planning and management. This implies the need to facilitate the conditions in which knowledge produced through collaborative methods is disseminated and shared in an open, free and easy way, in accordance with the characteristics and potentialities of the new networked society. The collaborative generation of information has, surely, institutional implications concerning changes in the geometries of power, that is, potential changes in the identity of the agents that control information and, as a result, the decision-making processes.

From a technical point of view, the integration of various data types from different sources in common data standards is a problem that has to be solved by the joint efforts of many international organizations for standardization. The standards enable management interoperability among multi-user systems, tools and solutions within the heterogeneous environment. The standards and specifications intend to achieve consistent management of interconnected elements. Several organizations are working on standardization issues: the Open Geospatial Consortium (OGC), the World Wide Web Consortium (W3C), TeleManagement Forum (TMF), Globus Alliance, Open Grid Forum (OGF) and many others. The OGC collaborates with over twenty different Standard Development Organizations.

Geospatial standards must meet many interoperability requirements and the OGC has begun work on GIS-related interoperability issues since 1994 and has tackled Earth imaging, Web Mapping, and GML. For example KML (Keyhole Markup Language) is an encoding standard enabling users' unique spatial data to be displayed on the map provided by Earth browsers (Google Earth, Bing Maps or WebGL Earth). Existing Internet standards, such as HTTP, XML, SSL/TLS, developed at W3C, IETF, etc., a range of different wireless standards such as 2G (e.g., GSM), 2.5G (e.g., GPRS) 3G/WiMAX (e.g., IMT), play an important role in the IT communication.

GML is a joint OGC/ISO standard that defines an XML grammar for encoding and exchanging geospatial content. GML is a part of the interoperability platform enabling a single software program to control and access data from multiple Earth-imaging devices on satellites or aerial platforms. GML is embedded in international encoding standards for domains such as weather, aviation, hydrology, geology, emergency response etc.

Standards' harmonization is critical to ensure interoperability, ease of implementation and networks operations. As there are still many standardization gaps, the investments in developing and implementing open spatial standards could bring additional socioeconomic value.

5.3. Data quality control and its implications for water planning

The quality of hydrologic data highly conditions water planning processes and outcomes. There are different possible reasons for the poor quality of hydrologic data:

- In many instances, hydrologic information used is not sufficiently precise because centralized planning institutions are removed from (and not coordinated with) local sources of knowledge and information. In the recently completed WFD planning cycle, some European countries such as Spain, found that river basin plans relied on vast amounts of information generated by large River Basin Agencies. This information was often not locally validated and was sometimes inaccurate. Decentralized and cooperative network planning institutional arrangements could serve to overcome these limitations by informing and complementing centrally produced models and plans with local knowledge and expertise, thus providing for robust data quality control mechanisms. Network planning would allow for the multiplication of resources (staff, technologies, integration and cooperation) and increase the trust both in the information being generated as well as between players in the planning process.

- In the European Union, the WFD planning process has resulted in a significant improvement in the quantity, quality and availability of water resources information (hydrological, chemical, biological, etc.). However, the significant budgetary restrictions that are resulting from the economic crisis that started in 2007-8 are limiting the development and consolidation of these improvements. Furthermore, some experts argue that the information necessary for water management under the traditional hydraulic paradigm (primarily hydrologic and chemical quality information) is deteriorating while the new information gathering networks (remote sensing, biological indicator networks, etc.) are not yet consolidated.

- A similar problematic transition is perceived with respect to information generation technologies. For instance, conventional meteorological and hydrological manual measuring stations are being replaced by automatic measuring stations and remote sensing tools (for instance the SAIH network - *Sistema Automático de Información Hidológica* or Automatic Hydrologic Information System in the case of Spain). While the traditional manual measuring network is deteriorating, the territorial coverage of the new automatic measuring systems is still incomplete.

- Data quality, data gathering and quality control processes are key components of the metadata that must always accompany information systems developed with new technologies. Unfortunately this is seldom the case, although some efforts are underway to harmonize data and metadata and guarantee the traceability of the information.

5.4. What are the uncertainties associated with climate change scenarios and their relation to the uncertainties in water resources data and information?

The three types of uncertainty discussed in Section 3 above (*technical uncertainty, indetermination* and *ignorance*), can also be applied to the climate change debate. However, when dealing with the challenge of climate change it is the second type of uncertainty that is currently most relevant. It is an uncertainty characteristic of the new environmental risks that will likely dominate the XXIst century and have been well categorized and characterized by Ulrich Beck (1992).

Uncertainty in terms of indetermination is an integral part of climate change scientific work, where equally probable potential future scenarios are presented to policy makers not as certain information on future climate, but as possible future situations that will need to be managed. This explicit recognition of uncertainty on the part of scientists and experts, together with other factors such as the existence of powerful interest groups, have probably contributed to the popular perception of climate change science as the main source of uncertainty in the environmental field, and particularly in water resources and risk management. A clarification and identification of traditional and new sources of uncertainty with respect to environmental risk, and their relative importance is still needed.

6. MODELING HYDRO-SOCIAL SYSTEMS: REFLECTIONS ABOUT KEY INFORMATION AND DATA REQUIREMENTS

A water management perspective adapted to the current challenges requires a systemic approach to water resources, overcoming the simple, reductionist and static approaches that still persist (Ostrom y Cox, 2010). The development and use of dynamic modeling techniques can help us move in the right direction, since they provide simplified but effective representations of the evolution of the whole study area at different spatial scales and from different viewpoints, but always under an integrative perspective (Fagan *et al.*, 2010). Building dynamic models is a laborious process since it requires going beyond the requirements of traditional hydrologic model building (Hannerz and Langaas, 2007; UNESCO, 2008). Dynamic models incorporate the views and perspectives of managers, politicians and stakeholders in the characterization and diagnostic phases as well as in the definition of objectives and management alternatives. This approach enables the combination of the skills and technical expertise of the analyst with the range of incommensurable perspectives that affect socio-ecological systems (Martínez Fernández and Esteve Selma, 2004).

The combination within the same model of natural and social parameters—the essence of hydro-social models—, implies such level of complexity that the models can only hope to represent specific geographic and hydro-social realities (Martínez Fernández *et al*., 2013). Their results can therefore not be extrapolated to other settings, at least not entirely. The development of dynamic models also requires the combination of new kinds of information with the physical parameters that are necessary for traditional modeling approaches (George *et al*., 2011). It therefore requires a new socio-political and technical framework to deal with water resources management challenges in order to overcome current limitations to the involvement of the public and stakeholders in the definition of management alternatives. In essence, then, dynamic modeling is the necessary approach within the current water management context.

6.1. To what extent does the availability of information limit the development of hydro-social models? What kind of information is necessary to improve their simulation capacities?

The lack of good quality information is the most significant limiting factor for a successful modeling exercise, particularly when dealing with complex hydro-social realities. It is important to differentiate between the lack of information about the system prior to the design of the models, which limits their correct definition (conceptualization); and the lack of information about each of the processes once they have been identified and defined, that is, once the model has been conceptualized. The greatest limitations derive not so much from the identification of the parameters to be analyzed or modeled, but rather from the lack of data or experience in modeling the behavior of these parameters or in gathering information for modeling (De Lange *et al*., 2010). Models are thus often limited by the uncertainty and conflicts that result from trying to estimate the parameters and components since their behavior is unknown.

The lack of precise information about the various subsystems or components of hydro-social realities (hydrological, economic, social, etc.) greatly limit the development of hydro-social models. This is particularly true if they require information with sufficient spatial or temporal resolution to accurately simulate the behavior of a system. As a result, too often only "Black Box" models are developed—made up of simple regressions or empirical relationships between the different components—, which greatly limit the understanding of the system being modeled, and the transparency of the information or rationale that leads to a public policy decision.

In order to improve modeling capacities and to overcome the limitations of opaque descriptive models, good quality complete data would be required, with wide spatial and temporal coverage, and relating to all the elements, processes and flows that are included in the model (Kirchner, 2006). However the inverse is often the case, where the lack of data conditions or limits the design of the model.

Scale aspects of knowledge bases are also very important, particularly in order to better understand how to consolidate information gathered at different spatial scales. Bridging scales enable better integration of local knowledge into global models and data sets, i.e. integration of scientific and indigenous knowledge, which may strengthen the accuracy and contribute to its translation into effective policy strategies addressing global environmental changes.

The challenges in bridging scales are particularly significant in terms of understanding cross-scale interactions. Databases are scale-specific and most environmental analyses focus on a particular scale of interest rather than on cross-scale linkages (Reid *et al.*, 2006). Consistency in data form and quality is essential for data analysis.

Scaling is often considered together with Data Mining (extraction of implicit, previously unknown and potentially useful information from data). Data Mining uses semi-automatic discovery of patterns, associations, changes, anomalies, rules, and statistically significant structures and events in data (Gupta G. K, 2011). For instance, data processing uses various approaches of reduction of Large Datasets such as data aggregation, dimensional reduction, compression, discretization etc. The aim is to increase the speed of processing and to fit the data in a suitable way. Accordingly, complex algorithms, specialized hardware, parallelism and effective visualization are used in order to improve data analysis and to increase the understanding of the results.

6.2. Where are the greatest information deficiencies, in the natural or the socioeconomic subsystems?

It is challenging to attain a global understanding of the social subsystem and of its component variables. Socioeconomic information is diverse and heterogeneous: it can cover different geographical, and sometimes non-comparable, dimensions (for instance local agricultural information versus national agricultural trade magnitudes); quantitative and qualitative information; static data versus temporal time-series, etc. (Halpern *et al.*, 2013). Furthermore, socioeconomic variables are very site-specific and not easily transferable to other systems, as opposed to natural variables that respond to universal physical laws (hydrology, climatic variables, digital elevation models, etc.).

Dynamic hydro-social models give significant weight to qualitative socioeconomic data, information that has not traditionally been a part of model building efforts. This requires clearly defining the necessary level of precision of the information, data sources, accessibility, the methodologies employed to obtain this information, data treatment approaches, etc. Qualitative information is typically very robust, because it is obtained from expert knowledge (understanding expert knowledge in the least technocratic and most open sense of the term), but is not very precise and thus is challenging to incorporate into quantitative models (University of Ljubljana, 2012). Some argue that it may be an error to try to introduce “human” factors “inside pre-existing hydrologic models" but, on the contrary, that we might try to “translate” the “natural” factors in order to include them into social science modeling (Tom Evans, 3rd SWAN Progress meeting, Tucson October-November 2013)[32].

[32] Available at: http://swanproject.webhost.uits.arizona.edu/

In addition to the challenges of complexity and dispersion of data, hydro-social models have to deal with a basic lack of information. A clear example is the lack of comprehensive information about water demands and use, since there are often no up-to-date and precise registries of some water sources (mainly groundwater) and sectors (specially, irrigation). Nevertheless, the assessment of information accurateness and accessibility has to be refined taking into account different national or regional traditions and institutional regimes.

In terms of the available information on the natural subsystem, the deterioration of traditional hydrologic and climatic information records mentioned before presents an additional difficulty that needs to be overcome. Willaarts *et al.,* (2012) also point to challenges resulting from the necessary identification and interpretation of the interrelationships between the flows of water, as a substance with different quantities, chemical characteristics and potential, and the associated ecosystems and landscapes. This challenge, as commented in section 3 above, has not yet been fully resolved.

Finally, the interrelationships and flows between the different system components, particularly between physical and social subsystems, are not sufficiently understood. Significant efforts are needed to better understand these relationships, such as the territorial dimension of water and the services it provides.

6.3. What are the most appropriate scales for social and hydrological modeling?

The definition of the physical and temporal scale for the analysis and management of water resources is a key decision that determines the nature of the problem, the identification of the actors involved, and their relative position in the decision-making process. It therefore clearly affects the power balance within the system.

In general, dynamic modeling efforts use the river basin as the territorial scale for analysis since it reveals processes and interrelationships that are not apparent at smaller (more detailed) scales and, in general, is able to provide an integrated and holistic view of the natural water flow patterns (Pedraza, 2007). The river basin is also the territorial unit that is proposed in the context of the IWRM paradigm. However, the selection of this scale is not undisputable (Blöschl and Sivapalan, 1995) since socio-political networks and interconnections often transcend the boundaries established by the physical division of the river basin. Institutional and administrative boundaries, commercial flows, socio-cultural identities rarely coincide with physical boundaries.

The dominance of the physical characteristics as the defining factor for management and analysis is currently being questioned, as was discussed in section 3 above.

In what pertains to the water-territory relationships, changes in scale profoundly affect the design, behavior and outcome of the models that represent them. Very often modelers only have access to information on a small part of the space-time continuum in which processes take place, thus conditioning the understanding of reality and, therefore, model conceptualization, establishment of parameter values and calibration.

In terms of the temporal dimension, it is clear that complex systems can present distortions over time or imperceptible flows in short time-frames. Modelers therefore favor working with long time-series for input and calibration data.

6.4. Are there effective ways of modeling and incorporating information on abstract variables such as changes in behavior?

Some models already incorporate this kind of information—changes in water consumption patterns by irrigators or water use changes as a result of expected inflows of new sources of water such as desalinated or transferred resources—in their own internal structure as well as in the generation of possible scenarios (Hurlimann *et al.*, 2009). The key to model these variables is to carefully describe the determining factors, what sets them off, how they operate and how they affect other variables. Therefore, the correct conceptualization of the model is essential and in turn requires a significant amount of information about the socioeconomic components. The main challenge is that these variables do not respond to straightforward rules or laws like those that govern physical processes. They are complex behaviors and phenomenon, random, uncertain and highly reflexive that evolve in time and space and are rarely documented in a systemic fashion. These limitations make their incorporation as variables in a model difficult and challenging (Alvisi *et al*., 2007).

In order to calibrate and establish the parameter values of model variables for which there are no empirical data series it is necessary to thoroughly review existing information about similar systems in order to adapt this information to the reality being simulated. At the same time, it is important to rely on local and stakeholder expertise, a key input to limit uncertainty.

Depending on the goal of the modeling exercise, the abundance and level of detail of the variables being used can vary from their identification as an element or magnitude to consider, to the inclusion of time-series or estimative functions developed from consultations with experts or bibliographical review. However it is important to keep in mind that sometimes simple models can provide very good results if carefully defined and calibrated. An excess of information and detail is not always required.

7. TRANSPARENCY AND PUBLIC PARTICIPATION AS KEY COMPONENTS OF THE NEW WATER GOVERNANCE: RESULTING INFORMATION NEEDS

Traditional transparency and public participation efforts have focused on the need to disseminate information to the public rather than on collaborative generation of information for water planning and management. This has been the dominant *rational comprehensive planning* approach, where public participation is not *inherent* to the planning process, but rather *instrumental* to improve knowledge in the diagnostic phase. In the context of this approach public participation is not seen as a means for the common identification of objectives, strategies and alternatives, or for decision making.

The most advanced versions of the IWRM paradigm such as the WFD, draw upon this experience and incorporate public participation as an act of *governance* where, starting from a participated identification of problems, possible alternative solutions are jointly identified. This revised approach implies that problems, goals and objectives should be identified together with the public and stakeholders, who also participate in the identification of alternative strategies, measures and proposed actions. The growing recognition of the complexity and uncertainty associated with socio-ecological systems necessarily demands this new epistemological approach to public participation.

In this new context, transparency requirements imply that the information that is generated during water planning and management processes must be accessible to the public, both in terms of physical accessibility through internet as well as in terms of information that is understandable by different audiences. Public participation also requires the use of public forums for debate and exchange of information. Public input on problem diagnosis, definition of objectives and alternatives needs to be taken into account and influence management decisions.

In the EU, environmental legislation in general, and water legislation in particular regulate the right of public access to environmental information (Directive 2003/4/CE) or the requirement of public participation processes (art. 14, Directive 2000/60/CE). Transparency, information and public participation requirements are closely interrelated since the latter requires publicly accessible good quality information for decision-making.

The emphasis on public participation mechanisms to legitimize public policy decision-making processes found its theoretical grounding in the deliberative democracy theoretical framework (Cohen, 1989; Fishkin, 1991; Gutman & Thompson, 2004). However, a systematic framework for the evaluation of the outcomes and impact of collaboration in water planning often appears lacking—both in terms of monitoring and evaluating the quality of the collaborative process, and in terms how it may have influenced water management outcomes. The lack of rigor in applying core concepts frequently results in water planners, and their government agency supervisors operating in an environment where terms such as 'involve', 'consult', 'collaborate' and 'partner' retain a cultivated ambiguity. Some (see Poh Ling Tan *et al*., 2008) have claimed that the outcomes expected of deliberative forms of collaboration are naïve and unrealistic underscoring limitations to current political and social theories of collaboration, deliberation and social learning. Furthermore, after more than two decades of general acceptance and widespread implementation of this approach, there is a growing body of work that is critically questioning the limits of the *participatory governance* approach to natural resources management and its true impact on final decisions (Ranciére, 2006, and Swyngedouw, 2011). This critical work is framed within the debates of *post-politics* or *post-democracy* in the context of the global neoliberal globalization processes.

In a paper on linking science with environmental decision-making that summarized the conclusions of the 10-year SAHRA[33] research project (scientific starting point for the work of SWAN) its authors conclude with the following statement (Liu *et al.,* 2008): "Finally, although involving the stakeholders and decision-makers in the entire process of model development, implementation, and analysis can help enhance the transparency and credibility of the modeling results, there might still exist additional limitations of decision-makers not selecting a scenario due to political or other concerns/considerations." A similar frustration was expressed by Andalusian water managers in the context of the SWAN Seminar on *New paradigms in water resources and risks management: Key water data and information for sustainability*, held at the University of Seville in January 2013; or by the previous director of the Catalan Water Agency in the final seminar of the PART-DMA[34] research project held in Barcelona in November 2012.

What motivates the *externalization* (del Moral, 2013) of key operational and final decisions following deliberative planning and decision-making processes? Where do the so-called

[33] See: http://www.sahra.arizona.edu/ for more information.
[34] http://blogs.uab.cat/partdma/

"political" decisions come from? Why don't they fit within the logic of scientific, integrated and participatory decision-making processes that precisely aim to understand, anticipate and drive sustainable decisions? Don't these scientific and policy processes aim to integrate science with environmental decision making or at least understand under what conditions this integration can take place? The following pages offer some preliminary ideas and perspectives on of these questions.

7.1. To what extent are EU legal requirements on transparency and public participation fulfilled in hydrologic planning processes under the WDF in Spain?

The Spanish experience with participatory water planning processes in the context of the WFD has had mixed results (Ballester and Parés, 2013; Espluga et al., 2011; Hernández-Mora and Ballester, 2010). Spanish water policy is still largely immersed in the old hydraulic paradigm, where public participation is understood as a means for disseminating information and legitimizing policy decisions that are still taken within the closed traditional water policy community (irrigators, hydroelectric company and large construction companies) quite independent of more open and participatory processes. Furthermore, leaving aside considerations about the formal and substantive quality of the public participation processes undertaken in the different river basin planning districts, too often there has been a *political externalization* of key planning decisions.

It is however important to recognize that some progress has been made in terms of transparency in water planning and management, albeit modest and uneven. The Spanish branch of Transparency International undertakes a periodic comparative analysis of transparency in water planning and management in the different river basin management agencies in Spain (se De Stefano *et al.*, 2012; and Transparencia Internacional-España, 2013). The resulting Index for Transparency in Water Management (INTRAG or *Índice de Transparencia en la Gestión del Agua)* has been applied in 2010, 2011 and 2013, and showed that overall transparency improved from an average of 51.2 in 2010, to 59.6 in 2011 and 62.9 over 100 in 2013. However, results differ significantly for different agencies ranging from 33,5 to 93,5 over 100 in 2013, as well as between the different elements being evaluated[35] (see table

[35] For more information see: http://www.transparencia.org.es/INTRAG/INTRAG_A%C3%91OS_ANTERIORES.htm

2), which shows the progress made by some and that there is still significant room for improvement.

Table 2. Components and variables of the 2013 Transparency Index of Water Management

Components	Subcomponents	Number of variables
Information about the river basin management agency	Basic institutional information	5
	Water-related laws and regulations	1
Relations with the public and stakeholders	Public information and attention	12
	Public participation	2
Transparency in the planning processes		16
Transparency in water management and use	Water management	12
	Information on water uses	5
	Compliance with current legislation	5
Economic and financial transparency	Accounting and budgetary information	4
	Transparency on income and expenses	4
Transparency in public contracting and licensing	Public contracting procedures	4
	Relations and operations with purveyors and contractors	8
	Follow up and control of public works	2

Source: www.transparencia.org.es

The INTRAG is a good example of a useful indicator for transparency in water management. Its conceptual approach is comprehensive and flexible enough to be applicable to other countries or regions (in fact, Brazil and Portugal are currently adapting the index to their own institutional settings). It is made up of 6 component or thematic areas which refer to the main areas of activity of the agencies responsible for water management in Spain (Table 2). However, INTRAG only evaluates the information being made available to the public, that is, active transparency. It does not measure the quality of the information or its usability, or the response of the River Basin Agencies to the requests for information from the public, that is, the compliance with the right to information legislation, which is also important legal obligations.

7.2. What type of information is particularly relevant to inform public participation processes for water governance?

The information required to inform public participation processes for water governance depends upon the water planning and management goals. In the context and logic of the WFD, fully in line with the IWRM paradigm, the information required must facilitate answering the following planning and management questions:

- How much water do we have, and who uses it?
- What is the current state of our waters (ecological, chemical, quantitative)?
- What is the cost of current and required water services (financial, environmental and resource costs)?
- What are our goals?
- What measures can we implement in order to achieve them and what is the most cost-effective combination of measures?
- How is the implementation of the measures helping us achieve our goals? Do we need to adapt our Program of Measures to better reach our goals?

At the same time, the information provided must meet several requirements: quality and reliability; ease of access (internet); regularly updated; sufficient and adequate to inform planning, participation and management objectives; detailed and traceable; and adapted (accessible in terms of content) to the different publics.

7.3. Are there positive experiences that can help us advance along these lines?

Public participation and transparency are essential components of decision-making processes aimed at jointly identifying challenges, alternatives and potential solutions. Public participation must be present at every step of the planning and decision making process: from the collaborative development of information (for instance through the integration of information and knowledge from different institutions and sources, particularly local knowledge); the recognition and incorporation of different interpretations of reality and associated problems (for instance trough different modeling approaches); and the development of poly-centric and shared decision-making mechanisms. Existing water management challenges require public participation processes that are not purely formal but, rather, substantial and politically-binding, that is, moving up the ladder of public participation originally proposed by Arnstein in 1969 (see Table 3).

Table 3. The ladder of public participation in water management

Support for local initiatives	Higher levels of participation – delegation of power.
Joint action	Collaborative efforts (working groups) to deal with and resolve specific problems.
Co-decision	Joint definition of problems and alternative solutions.
Public consultation	Selection between predetermined alternatives. Limits input of ideas and does not allow for the joint definition of problems, nor the participated evaluation of the implementation process.
Information	Necessary but insufficient condition for public participation. Uni-directional.

Source: Adapted from Arnstein (1969)

8. SOME FINAL REMARKS AND QUESTIONS FOR FURTHER DISCUSSION

1. IWRM is the dominating paradigm for sustainable water management today. The Water Framework Directive represents perhaps the most ambitious and complex legal effort to put the principles of IWRM into practice in the EU's member states. Other national legislations also incorporate IWRM prescriptions. However, this model faces resistance from the previously dominating hydraulic paradigm, as well as the contradictions that emerge from the practical experiences in its implementation at different scales (from regional to global). The criticisms that it has received in the recent past focus on the following main aspects:

    - The river basin as the undisputed scale for integrated management and water governance. While it may be the ideal scale of hydrologic characterization, its appropriateness as the ideal scale for governance is under dispute.
    - The larger hegemonic economic thought in which IWRM prescriptions are integrated, particularly the commodification processes and monetary reductionism of natural resources.
    - The weaknesses and failures of public participation processes that have accompanied actual water resources planning and management experiences and that are an integral part of the IWRM theoretical framework.

2. Water management today presents significant information challenges. Information must simultaneously fulfill requirements that are to some degree opposed and antagonistic but also mutually necessary, in close interaction with one another or, as Edgar Morin would say, *dialogically* related (see Morin 1977, 80).

    - Information versus data;
    - Information needed to improve management versus information dissemination to improve transparency and facilitate public participation;
    - Real versus modeled data;
    - Quantitative versus qualitative data;
    - Real time versus delayed data;
    - Physical versus socioeconomic data;

- Conventional network versus new networks (remote sensing, etc.) data.

3. The profound paradigm shift in water management has had important implications for information and data requirements. The transition from the promotion of hydraulic infrastructures as the primary water policy goal to economic and ecosystem-based water management, and the recognition of water as a patrimony has required not only new information, but also new methodologies for gathering and generating this information. Some of the main new debates about the limitations and insufficiencies of the now discursively dominant of IWRM paradigm revolve around the following issues:

   - Estimating the costs associated with ecosystem restoration is infinitely more complex than calculating the costs associated with water flows, since these can be simplified through the balance of the hydrologic cycle.
   - The valuation of ecosystem services requires using metrics other than monetary valuation, as well as site-specific studies. The methodologies and information necessary for these valuations are still under development.
   - The incorporation of the social dimension brings with it elements of complexity and uncertainty in addition to those inherent to natural systems. Therefore the understanding, representation and management of water as an eco-social patrimony poses new challenges that require information that is still being developed.

4. The selection of the scale for water management has direct implications for information and data availability and requirements: local versus global scale for information gathering; central planning (models) versus local planning (real network data). Related to this issue the next questions arise:

   - What are the possibilities and real potential of different alternatives for information generation and what are the difficulties and challenges inherent to each choice?
   - What are the institutional conditions for its implementation?
   - Are public information systems organized to facilitate the knowledge generation and information exchanges or are there still important imbalances between the potential of the new ICTs and the individualistic behavior that still dominates information management?

5. Too often in the final stages of decision making processes there is a *political externalization* of key final operational decisions. Water managers (or politics) impose decisions that are not coherent with scientific, integrated and participatory processes that precisely aim to understand, anticipate and direct sustainable management decisions. There is a lack of understanding about these informal decision making processes. Research about the links between science and politics must incorporate information about the factors that drive and help explain these fundamental mechanisms.

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10. REFERENCES

ALLAN, A. (1999) "Water in international systems: a risk society analysis of regional problemsheds and global hydrologies", in *Sustainability; Risk and Nature: the Political Ecology of water in Advanced Societies*. Oxford, European Science Foundation School of Geography, p 73-82.

ALLAN J. A. (2006): "IWRM: The New Sanctioned Discourse?" In (ed.) P. P. MOLLINGA *Integrated Water Resources Management: Global Theory, Emerging Practice and Local Needs*, Ajaya Dixit and Kusum Athukorala. New Delhi: Sage Publications: 38-63.

ALVISI, S., FRANCHINI, M. and MARINELLI, A. (2007): "A short-term, pattern-based model for water-demand forecasting". *Journal of Hydroinformatics* 9 (1) (January): 39.

ARNSTEIN, S. R. (1969): "A Ladder of Citizen Participation" *JAIP*, Vol. 35, No. 4, July 1969, 216-224.

BALLESTER A. and M. PARÉS (2013) *Democracia deliberativa y política de agua. experiencias de participación en el contexto de la directiva marco del agua en España*. Proceedings of the VIII Congreso Ibérico de Gestión y Planificación de Agua "Cambio de planes: Análisis crítico del primer ciclo europeo de planificación hidrológica y la expectativa de planes comunes para España y Portugal en 2015", Lisbon, Portugal, December 5-7,2013. Available at: http://revistas.lis.ulusiada.pt/index.php/8cigpa/article/view/328

BECK, U. (1992), *The Risk Society*, London, SAGE.

BECK, U. (2002) (1999): *La sociedad del riesgo global*. Madrid, Siglo XXI.

BERBEL, J., MARTIN-ORTEGA, J. and MESA, P. (2011) "A Cost-Effectiveness Analysis of Water-Saving Measures for the Water Framework Directive: The Case of the Guadalquivir River Basin in Southern Spain". *Water Resources Management* 25:623–640

BLÖSCHL, G., Y SIVAPALAN, M. (1995): "Scale issues in hydrological modeling: A review". *Hydrological Processes* 9 (3-4) (April): 251-290.

BROUWER, R., BARTON, D., BATEMAN, IJ., BRANDER, L., GEORGIU, S., MARTIN-ORTEGA, J., NAVRUD, S., PULIDO-VELAZQUEZ, M., SCHAAFSMA, M. and WAGTENDONK, A, (2009) Economic valuation of environmental and resource costs and benefits in the WFD: technical guidelines for practitioners. Available at:

http://s3.amazonaws.com/zanran_storage/www.aquamoney.org/ContentPages/2483937804.pdf

BROUWER, R. (2000): "Environmental value transfer: State of the art and future prospects", *Ecological Economics*, 32: 137-152.

BUDDS, J. and L. HINOJOSA (2012): "Restructuring and rescaling water governance in mining contexts: The co-production of waterscapes in Peru", *Water Alternatives,* 5(1): 119-137.

BURKHARD, B., MÜLLER, F. (2008): Drivers-Pressure-State-Impact-Response. In: Jørgensen, S.E. & B.D. Fath (Eds.): Ecological Indicators. Vol. [2] of Encyclopedia of Ecology, 5 vols. Oxford: Elsevier: 967-970.

CASTRO, J. E. (2011): “El proceso de democratización de la gestión de servicios públicos esenciales de agua y saneamiento”, *Hábitat y sociedad*, 2: 49-85. http://www.habitatysociedad.us.es

COHEN, J. (1989): "Deliberative Democracy and Democratic Legitimacy", Hamlin, A. and Pettit, P. eds., *The Good Polity*. Oxford: Blackwell. pp. 17–34.

COHEN, A. and S. DAVIDSON 2011. The watershed approach: Challenges, antecedents, and the transition from technical tool to governance unit. *Water Alternatives* 4(1): 1-14.

COOK C. and K. BAKKER (2012) “Water security: Debating an emerging paradigm”, *Global Environmental Change,* 22 (2012) 94–102

COSTANZA, R., R. D’ARGE, R. DE GROOT, S. FARBERK, M. GRASSO, B. HANNON, K. LIMBURG, S. NAEEM, R.V. O’NEILL, J. PARUELO, R.G. RASKIN, P. SUTTONKK and M. VAN DEN BELT (1997) "The value of the world's ecosystem services and natural capital", *Nature*, 387: 253-260.

DE LANGE, W.J., WISE, R.M., FORSYTH, G.G. and NAHMAN, A. (2010): “Integrating socio-economic and biophysical data to support water allocations within river basins: An example from the Inkomati Water Management Area in South Africa”. *Environmental Modelling & Software* 25 (1): 43-50.

DEL MORAL, L. (2013): *El paradigma actual en la gestión de los recursos y los riesgos hídricos. Necesidades de información consecuentes*. Available at: http://www.upo.es/ghf/giest/GIEST/otros_documentos/869_PonenciaKD_LMoral.pdf.

DEL MORAL, L. and D. SAURÍ (1999) “Changing Course. Water policy in Spain”, *Environment*, vol. 41, nº 6, pp. 12-36.

DEL MORAL, L. and A. DO Ó (2014) “Water governance and scalar politics across multiple-boundary river basins: states, catchments and regional powers in the Iberian Peninsula”, *Water International*, DOI: 10.1080/02508060.2013.878816.

DE STEFANO, L., N. HERNÁNDEZ-MORA, E. LÓPEZ GUNN, B. WILLARTS, P. ZORRILLA and R.LLAMAS. (2012): "Public participation and transparency in water management", in: *Water, agriculture and the environment in Spain: Can we square the circle?,* L. De Stefano y R. Llamas (eds.) CRC Press / Balkema, Taylor & Francis Group, pp: 217-225. Available at: http://www.fundacionbotin.org/fb-water-agriculture-and-the-environment-in-spain-can-we-square-the-circle-seminarios-internaci-787798051267687.htm

ESPLUGA, J., BALLESTER, A., HERNÁNDEZ-MORA, N. and J. SUBIRATS (2011) "Participación pública e inercia institucional en la gestión del agua en España", *Revista de Estudios e Investigaciones Sociales*,134:3-26.

EUROPEAN COMMISSION [COM], (2012a) *Report to the Commission, the European Parliament and the Council on the implementation of the Water Framework Directive (2000/60/CE). River Basin Management Plans,* COM(2012) 670 final, Brussels, 14.11.2012

EUROPEAN COMMISSION (2003) Economics and the environment: The implementation challenge of the Water Framework Directive, WATECO: A guidance document. Brussels.

FAGAN, J.E., REUTER, M.A. and LANGFORD, K.J. (2010): “Dynamic performance metrics to assess sustainability and cost effectiveness of integrated urban water systems”. *Resources, Conservation and Recycling* 54 (10): 719-736.

FAGGI, P. (1996) "Water in developing countries: productive and strategic values", in Allan, J.A. and Radwan, L. (coords), *Proceedings of the European seminar on water geography: Perceptions of the values of water and water environments*, SOAS, University of London, pp. 113-116.

FEITELSON, E. (1996): "The implications of changes in perceptions of water in Israel for peace negotiation with Jordan and the Palestinians", en Allan, J.A. and Radwan, L. (coords), *Perceptions of the values of water and water environments. Proceedings of the European* *seminar on water geography*, London 6-10 September 1996, SOAS University of London, pp. 17-22.

FISHKIN, J. (1991): *Democracy and Deliberation: New Directions for Democratic Reform*. New Haven: Yale University.

GARNÅSJORDET, P. A., ASLAKSEN, I., GIAMPIETRO, M., FUNTOWICZ, S., and ERICSON, T. (2012): "Sustainable Development Indicators: From Statistics to Policy", *Environmental Policy and Governance*, 22(5), 322–336. doi:10.1002/eet.1597

GEORGE, B., MALANO, H., DAVIDSON, B., HELLEGERS, P., BHARATI, L. and MASSUEL, S. (2011): "I- An integrated hydro-economic modeling framework to evaluate water allocation strategies I: Model development", *Agricultural Water Management* 98 (5): 733-746.

GIORDANO, M. and T. SHAH (2013): *Non-Integrated Water Resources Management*, . En: "Integrated Water Resources Management in the XXIst Century", VI Botín Foundation Water Workshop. P. Martínez Santos & M. Aldaya (eds.) Taylor & Francis Group, (in press)

GÖRLACH, B. and E. INTERWIES (2004): *Assessing Environmental and Resource Costs in the Water Framework Directive: the Case of Germany*, Federal Environmental Agency (Umweltbundesamt), Berlin.

GUPTA G. K*,(2011): Introduction to Data Mining with Case Studies.* Prentice-Hall, India.

GUPTA H.V. and G.S. Nearing (2014): "Debates on Water Resources: The future of hydrological sciences: A (common) path forward? Using Models and Data to Learn: A Systems Theoretic Perspective on the Future of Hydrological Science", *Invited Commentary*, Water Resources Research.

GUPTA H.V., M.P. CLARK, J.A. VRUGT, G. ABRAMOWITZ and M. YE (2012), "Towards a Comprehensive Assessment of Model Structural Adequacy*",* Opinion Paper, *Water Resources Research*, 48(8), 1-16, W08301; doi:10.1029/2011WR011044

GUPTA H.V., T. WAGENER AND Y.Q. LIU (2008), "Reconciling Theory with Observations: Towards a Diagnostic Approach to Model Evaluation"*, Hydrological Processes*, Vol. 22 (18), pp. 3802-3813, DOI: 10.1002/hyp.6989.

GUTMANN, A. and D. THOMPSON (2004): *Why Deliberative Democracy?,* Princeton University Press, Princeton, New Jersey.

HAINES-YOUNG, R.H. and POTSCHIN, M.B. (2009): Methodologies for defining and assessing ecosystem services. Final Report, JNCC, Project Code C08-0170-0062, 69 pp.

HALPERN, J., GOMEZ- LOBO, A., and FOSTER, V. (2013): *Information and Modeling Issues in Designing Water and Sanitation Subsidy Schemes*. Policy Research Working Papers.

HANNERZ, F. and LANGAAS, S. (2007): "Establishing a Water Information System for Europe: Constraints from Spatial Data Heterogeneity". *Water and Environment Journal* 21 (3). http://onlinelibrary.wiley.com/doi/10.1111/j.1747-6593.2007.00073.x/abstract.

HERNÁNDEZ-MORA, N. (2013): *La transparencia y la participación pública como instrumentos fundamentales de la nueva gobernanza del agua: las necesidades de información consecuentes*. Available at: http://www.upo.es/ghf/giest/GIEST/otros_documentos/870_PonenciaKD_N_Hernandez.pdf

HERNANDEZ-MORA, N. and A. BALLESTER (2010): "Public participation and the role of social networks in the implementation of the Water Framework Directive in Spain", *Ambientalia Special Issue – Ten years of the Water Framework Directive: An Overview from Multiple Disciplines*. Available at: http://hdl.handle.net/10481/21688

HEYNEN, N.; MCCARTHY, J.; PRUDHAM, S. and ROBBINS, P. (eds.) (2007) *Neoliberal Environments: False promises and unnatural consequences*. London-New York: Routledge.

HURLIMANN, A., DOLNICAR, S. and MEYER, P. (2009): "Understanding behavior to inform water supply management in developed nations – A review of literature, conceptual model and research agenda". *Journal of Environmental Management* 91 (1): 47-56.

HUTCHINSON, CH.F., R.G. VARADY AND S. DRAKE (2010): " Old and New: Changing Paradigms in Arid Lands Water Management", in G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*, Springer Science & Business Media, pp. 311-332

KANDZIORA, M., BURKHARD, B., MÜLLER, F. (2013): Interaction of ecosystem properties, ecosystem integrity and ecosystem service indicators – A theoretical matrix exercise. *Ecological Indicators*, 38, 54-78.

KIRCHNER, J. W. (2006): "Getting the Right Answers for the Right Reasons: Linking Measurements, Analyses, and Models to Advance the Science of Hydrology". *Water Resources Research* 42 (3).

LA ROCA, F. (2013) *La incorporación de los servicios ecosistémicos a la gestión del agua,* Proceedings of the VIII Congreso Ibérico de Gestión y Planificación de Agua "Cambio de planes: Análisis crítico del primer ciclo europeo de planificación hidrológica y la expectativa de planes comunes para España y Portugal en 2015", Lisbon, Portugal, December 5-7,2013. Available at: http://revistas.lis.ulusiada.pt/index.php/8cigpa/article/view/321

LA ROCA, F. (2011) *Balance de la política de recuperación de los costes de los servicios del agua en el Estado Español, 2000-2010*, Proceedings of the VII Congreso Ibérico sobre Gestión y Planificación del Agua "Ríos Ibéricos +10. Mirando al futuro tras 10 años de DMA" 16/19 de febrero de 2011, Talavera de la Reina. Available at: http://www.fnca.eu/vii-congreso

LIU, Y., GUPTA, H., SPRINGER, E. and WAGENER, T. (2008): "Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management", *Environmental Modelling & Software,* 23, 846-858.

MARTÍN-ORTEGA, J., GIANNOCCARO, G. and BERBEL, J. (2011): "Environmental and Resource Costs Under Water Scarcity Conditions: An Estimation in the Context of the European Water Framework Directive", Water Resources Management, 25:1615–1633

MARTÍNEZ FERNÁNDEZ, J. and ESTEVE SELMA, M. A. (2004): "The dynamics of water scarcity on irrigated landscapes: Mazarrón and Aguilas in south-eastern Spain". *System Dynamics Review* 20 (2): 117 - 137.

MARTÍNEZ FERNÁNDEZ, J. (2013): *La modelización de los sistemas hidrosociales. Necesidades de información y datos clave*. Available at: //www.upo.es/ghf/giest/GIEST/otros_documentos/868_PonenciaKD_Julia_Martinez.pdf.

MARTÍNEZ FERNÁNDEZ, J., ESTEVE SELMA, M. A., BAÑOS GONZÁLEZ, I., CARREÑO, F. and MORENO, A. (2013): "Sustainability of Mediterranean irrigated agro-landscapes". *Ecological Modeling* 248: 11-19. doi:10.1016/j.ecolmodel.2012.09.018.

MARTINEZ-CORTINA, L., GARRIDO, A. and LOPEZ-GUNN, E. (2010) Re-thinking water and food security: fourth Botin Foundation water workshop. *Re-Thinking Water and Food Security: Fourth Botin Foundation Water Workshop* [Available at: http://www.fundacionbotin.org/fbwater-workshop-40september-200941-8216re45thinking-water-and-food-security8217-seminarios-internacionales_fundacion-botin-areas-de-actividad_observatorio-de-tendencias-8691267687.htm

MILLENNIUM ECOSYSTEM ASSESSMENT (2005): *Ecosystems and Human Well-being: Synthesis,* Island Press, Washington, DC. Available at: http://www.millenniumassessment.org/documents/document.356.aspx.pdf

REID, W.V., BERKES, F., WILBANKS, T.J. and CAPISTRANO, D. (eds.) (2006). *Bridging Scales and Knowledge Systems: Concepts and Applications in Ecosystem Assessment,* Island Press, Washington, DC.

MOLLE, F. (2009): "River-basin planning and management: The social life of a concept" *Geoforum,* 40(3), 484-494.

MOREIRA, J. M. (2013): *Los nuevos paradigmas en la gestión de los recursos y los riesgos hídricos y las necesidades consecuentes de datos e información para una gestión sostenible del agua*. Available at: www.upo.es/ghf/giest/GIEST/otros_documentos/865_PonenciaKD_JM_Moreira.pdf

MORIN, E. (1977): *La Methode I: la Nature de la Nature*. Paris: Seuil. Translated into English: *Method: Toward a Study of Human Nature: Vol. I, The Nature of Nature*. New York: Peter Lang Pub. Inc., 1992.

MOSS, T. (2012): "Spatial fit, from panacea to practice: implementing the EU Water Framework Directive", *Ecology and Society* 17(3): 2.

MOSTERT, E. , M. CRAPS and C. PAHL-WOSTL (2008): "Social learning: the key to integrated water resources management?", *Water International*, 33:3, 293-304

NAREDO, J. M. (2013): *Costes y cuentas del agua. Aproximación a los recursos naturales y el medio ambiente desde el enfoque ecointegrador.* Disponible en: http://www.upo.es/ghf/giest/GIEST/otros_documentos/867_PonenciaKD_Naredo.pdf.

NAREDO J. M. (2007): "Costes y cuentas del agua. Propuestas desde el enfoque ecointegrado r", Keynote paper presented at the Seminar on Water Costs and Water Accounts in Catalonia in relation to the WFD, Catalan Water Agency, 18-19 June 2007. Available at http://www.eflus.com/index.php?option=com_docman&task=cat_view&gid=87&limit=5&limitstart=0&order=name&dir=ASC&Itemid=109.

NAREDO, J. M. (2006) *Las raíces económicas del deterioro ecológico y social. Más allá de los dogmas*, Siglo XXI de España, Madrid

OSTROM, E. and COX, M. (2010): “Moving beyond Panaceas: A Multi-Tiered Diagnostic Approach for Social-Ecological Analysis”. *Environmental Conservation* 37 (4): 451- 463.

PAHL-WOSTL, C., LEBEL, L., KNIEPER, C., NIKITINA, E. (2012): “From applying panaceas to mastering complexity: Towards adaptive water governance in river basins” *Environmental Science & Policy,* 23, 24-34.

PAHL-WOSTL , C., P. JEFFREY, N. ISENDAHL & M. BRUGNACH (2011) Maturing the New Water Management Paradigm: Progressing from Aspiration to Practice, *Water Resources Management*, 25: 837–856.

POH LING TAN, JACKSON, S., OLIVER, P., MACKENZIE, J., PROCTOR, W. and AYREET, M. (2008) *Collaborative Water Planning: Context and Practice*. Literature Review. Volume 1 http://npsi.gov.au/files/products/track/pn21213/pn21213.pdf

PEDRAZA, E. A. (2007): *Efectos de Escala sobre la Simulación del Flujo de Agua Superficial en Áreas Urbanas usando modelos basados en la Onda Cinemática*. Tesis Doctoral de la Universidad Nacional de Córdoba. http://www.efn.uncor.edu/archivos/doctorado_cs_ing/pedraza/TESIS_RP_Capitulo_03_ff.pdf

PITA, M.F., DEL MORAL, L. PEDREGAL, B., LIMONES, N. and N. HERNÁNDEZ-MORA (2014) "Nuevos Paradigmas en la Gestión de Recursos y Riesgos Hídricos: Datos e Información Necesarios para una Gestión Integrada del Agua", *Boletín de Geógrafos Españoles* (accepted).

RACO, M. (2013): *State-led Privatization and the Demise of the Democratic State. Welfare Reform and Localism in an Era of Regulatory Capitalism,* Wey Court East, Ashgate Publishing Ltd.

RANCIÈRE, J. (2006). *Hatred of democracy.* London: Verso.

REISNER, M. (1986) *Cadillac desert: The American West and its disappearing water*. New York: Viking Penguin.

SCBD (SECRETARIAT OF THE CONVENTION ON BIOLOGICAL DIVERSITY) (2004). The ecosystem approach (CBD guidelines). Montreal: Secretariat of the Convention on Biological Diversity; 2004 [50 pp.].

SPRAY, C and BLACKSTOCK, K (2013) Optimizing Water Framework Directive River Basin Management Planning Using an Ecosystem Services Approach, CD2012_17. Available online at: crew.ac.uk/publications

STADDON, CH. & JAMES, N. (2012) *Water Security: genealogy of a new paradigm*, Working Paper #2, SWAN Project. University of West England, Bristol Group for Water Research.

STAUB, C., OTT, W. ET AL. (2011): Indicators for Ecosystem Goods and Services: Framework, methodology and recommendations for a welfare-related environmental reporting. Federal Office for the Environment, Bern. Environmental studies no. 1102: 17 S. Available at: ftp://ftp.wsl.ch/ALR/Papers/papers_ALR_2a/Indicators_Ecosyste_Goodand_Services.pdf

SWYNGEDOUW, E. (1999) "Modernity and Hybridity: *Regeneracionismo*, the Production of nature and the Spanish Waterscape, 1890-1930", *Annals of the Association of American Geographers*, 89 (3), pp. 443-465.

SWYNGEDOUW, E. (2007) "Dispossessing H_2O", IN: *Neoliberal Environments: False promises and unnatural consequences*, Heynen, N., J. McCarthy, S. Prudham and P. Robbins (eds.) Routledge, pp. 51-62.

SWYNGEDOUW, E. (2011) "Interrogating post-democratization: Reclaiming egalitarian political spaces", *Political Geography*, 30(7):370-380

TRANSPARENCIA INTERNACIONAL-ESPAÑA (2013) *INTRAG results 2013 - Transparency Index for Water Management in Spain.* Available at: http://www.transparencia.org.es/intrag/INTRAG_2013/%C3%8Dndice_INTRAG_2013.htm

TRÉMOLET CONSULTING (2006) Analysis of member states and Pilot river basin submissions on the state of play for cost-effectiveness analysis in the WFD. A draft report for the department for environment, food and rural affairs, UK. Available at: http://randd.defra.gov.uk/Document.aspx?Document=EP01032_4622_FRP.doc

UNESCO (2008): Data Requirements for Integrated Urban Water Management. *Urban Water Series*. http://books.google.es/books/about/Data_Requirements_for_Integrated_Urban_W.html?hl=es&id=DPnbltoGn00C.

UNIVERSITY OF LJUBLJANA (2012): *Project: "Qualitative Modeling from Data"*. http://www.fri.uni-lj.si/en/research/projects/8889/project.html.

USACE (2010) "National Report: Responding to National Water Resources Challenges, Building Strong Collaborative Relationships for a Sustainable Water Resources Future", U.S. Army Corps of Engineers, Washington, D.C., August 2010, page 28.

U.S. ENVIRONMENTAL PROTECTION AGENCY SCIENCE ADVISORY BOARD [USEPA-SAB], (2009). *Valuing the Protection of Ecological Systems and Services. A report of the science advisory board*. EPA-SAB-09-012/ May 2009/ www.epa.gov/sab

VALERO, A., UCHE, J., VALERO, A. MARTÍNEZ. A, NAREDO, J.M. and ESCRIU, J. (2006): *Fundamentals of Physical Hydronomics: A new approach to assess the environmental costs of the European Water Framework Directive.* Available at: http://teide.cps.unizar.es:8080/pub/publicir.nsf/codigospub/0386/$FILE/cp0386.pdf

VAN MEERKERK, I., A. VAN BUUREN & J. EDELENBOS (2013) "Water Managers' Boundary Judgments and Adaptive Water Governance. An Analysis of the Dutch Haringvliet Sluices Case", *Water Resources Management*, 27:2179–2194

VASCO, D. W., DATTA-GUPTA, A. AND LONG, J. C. S. (1997): "Resolution and uncertainty in hydrologic characterization", *Water Resources Research* 33, (3): 379-397

VLACHOPOULOU, M., COUGHLIN, D., FORROW, D., KIRK, S., LOGAN, P., and VOULVOULIS, N. (2013): "The potential of using the Ecosystem Approach in the implementation of the EU Water Framework Directive" *Science of the Total Environment* 470–471: 684–694

WALLIS, C., SEON-MASSIN, N., MARTINI, F. and SCHOUPPE, M. (2011): "Implementation of the Water Framework Directive: When ecosystem services come into play". 2nd "Water Science meets Policy" Event, Brussels, 29 & 30 September 2011

WHITE, G. F. (ed.) (1956) *The Future of Arid Lands: Papers and Recommendations from the International Arid Lands Meetings*, Washington, DC: American Association for the Advancement of Science, 257–271. (Publication no. 43 of the AAAS). https://ia600401.us.archive.org/12/items/futureofaridland00whit/futureofaridland00whit.pdf [last day consulted 16th February 2014]

WILLAARTS, B., VOLK, M. y AGUILERA, P. (2012): "Assessing the Ecosystem Services Supplied by Freshwater Flows in Mediterranean Agroecosystems". *Agricultural Water Management* 105: 21- 31.

WRIGHT, S. (2007): "Decision-Making in the European Water Framework Directive: the Potential Consequences of a Neoclassical Approach", *Conference of the Australia and New Zealand Society for Ecological Economics (ANZSEE) "Re-inventing Sustainability: A Climate for Change*", 24 pages: http://curis.ku.dk/ws/files/8072379/Wright_Stuart.pdf

WYNNE, B. (1992): “Uncertainty and Environmental Learning: Reconceiving Science in the Preventative Paradigm” *Global Environmental Change*, 2, (June), 111-127.

Chapter 3

-Deliverable 4 (Supplement 1)-

Water and Urban Growth in Tucson Metropolitan Region: a Remote Sensing Approach

Authors: Schneier-Madanes, S. (CNRS), Hartfield, K. (UoA), Marsh G. (UoA), and Curley, E. (Pima County).

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1. INTRODUCTION

The relationship between urban growth and water/wastewater infrastructure is very significant in today's urbanized world, particularly in a water scarce region like the US Southwest[1]. The State of Arizona is especially illustrative of this relationship. The urban population of Arizona is growing at some of the highest levels observed in the United States and the two largest cities, Phoenix and Tucson, anchor an urban corridor of about two hundred miles containing six million people. Portions of this urban corridor, known as the Sun Corridor, even extend south into Mexico (Figure 1).

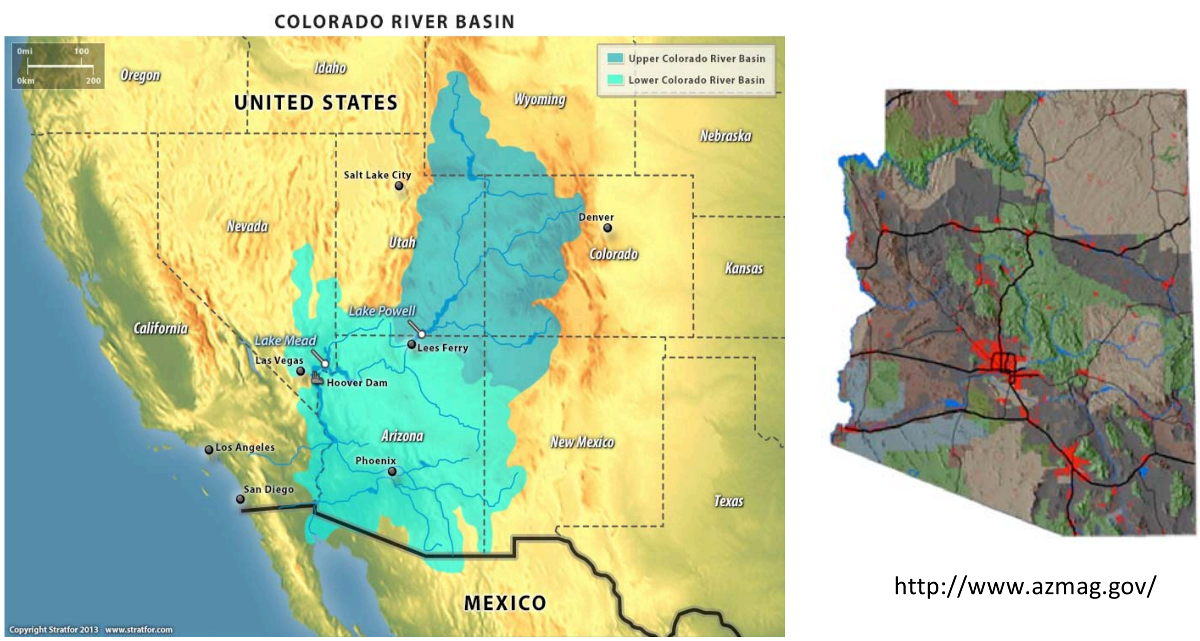

Figure 1. Arizona and the Desert Southwest

This study utilized remote sensing to understand the impact of urban growth on the natural environment in the Tucson Basin. Our study aimed to show how multi-temporal remote sensing could demonstrate the impacts of the built environment, particularly water and wastewater infrastructure, on the natural desert habitat.

The accuracy of multi-temporal maps derived from remote sensing data has improved significantly with the application of new classification algorithms. Recent work has been

[1] The arid west is defined by rainfall with Tucson averaging around 12 inches of precipitation annually between 1981 and 2010 (http://www.wrh.noaa.gov/twc/climate/tus.php).

particularly helpful in demonstrating the added value of utilizing new Object Oriented and Classification and Regression Tree (CART) classifiers. This research created a multi-temporal (1984-2010) view of land cover change along the Tucson – Phoenix urban corridor focusing on an area of significant growth within Pima County and utilizing Landsat Thematic Mapper data with CART classification techniques.

These classifications created multi-temporal maps of changing urban residential, urban commercial/industrial, agriculture, roads, bare ground, natural desert cover, riparian, and water. These data were then integrated into an ongoing analysis of changing urban and water policy and allocation within the region which provided an enhanced ability to evaluate the correlation of water availability and use, socio-economic drivers, and the direction and magnitude of land use/cover change.

2. BACKGROUND

The Tucson Metropolitan area[2], with a population of more than one million people and more than 200 square miles is located in the Sonoran desert, a water-scarce region rich in biodiversity and culture. The metropolitan area includes the historical City of Tucson as well the newly incorporated towns of Oro Valley, Marana, and Sahuarita along with unincorporated urban areas of Pima County.

Tucson was started as an agricultural settlement by Native Americans, along the Santa Cruz River which flows north through the area. In the 18th century, missionaries and settlers from Spain established a fortified town, the *Presidio*, which forms today's urban core. [3] Prior to becoming a part of the United States, Tucson was a classic Mexican frontier town particularly in the downtown areas known as the "Old Pueblo". The Anglo pioneers definitely changed Tucson through the gold and silver mining, the railroad, and warfare with Indian Tribes. During the twenties, federal expenditures (university, defense) and the economic activities associated with copper, cotton, cattle, citrus and climate (the five C's) fueled its growth. At the end of World War II, the metropolitan area included two cities, Tucson and South Tucson and many new subdivisions in the unincorporated area. As a whole, in the fifties, the metropolitan area had around 122,764 residents on 25 square miles (Akros, Inc. Wilson Preservation Coffman Studios).

After World War II, Tucson went from a small Southwestern city to a metropolitan area, with the transition of ranchlands to subdivisions. Increasing difficulties with ranching, such as drought or legal challenges to grazing leases, combined with growing expectations of lucrative land sales, fueled the development of an active real estate market. The urban core developed around the Hispanic town and mostly expanded eastward in the valley through construction and annexations. Infill came later with new construction within developed areas.

Tucson also experienced major changes due to the expansion of the defense industry and tourism which brought workers (blue and white collar) and retirees to the area. Between 1970 and 2010 Tucson's population nearly doubled, while the population of the county (Pima County)

[2] From its incorporation as an American territory to World War II, the Tucson region has phenomenally changed. With a strong military presence and the development of agriculture and mining plus commercial activities (the stage route - railroad), Tucson became noted for the five C's: "Copper, Cotton, Cattle, Citrus and Climate."
[3] Michael F.Logan speaks about a shared regional identity between Tucson and Albuquerque, New Mexico.

tripled [4]. The city expanded on the valley floor, eastward and gradually outside its boundaries, into unincorporated areas. Two-thirds of the Metropolitan Area population lived in subdivisions which sprang up around its corporate limits and, in the 1970s, subdivisions began to press against the federally owned lands to the east - the Saguaro National Park. During the 1980s, the city annexed approximately 76 square miles of land, mostly uninhabited lands in the east and south east, doubling its total size. However, due to the socio-spatial distribution of residents inside and outside the urban core, its per capita income is 33 percent lower than suburban per capita income (US Census Bureau 2000). The three newest towns of the metropolitan area were incorporated at different moments and have experienced significant residential and commercial growth. The Town of Oro Valley, incorporated in 1974, has 41,000 residents in 35 square miles and has become an affluent enclave on the north which emerged as a regional center for the biotech industry. The Town of Marana, incorporated in 1977, includes 35,000 residents on almost 120 square miles and is primarily an agricultural center (cotton) which is rapidly developing into a suburban community. [5] Marana began to grow through an aggressiveannexation policy (it currently has four times the surface area of Oro Valley with approximately the same population) which has important implications on water, wastewater and reclaimed water management. The latest of the new incorporated areas is the Town of Sahuarita which is located 15 miles south of Tucson and east of the Tohono O'odham Nation on the way to the Mexican border. Sahuarita was incorporated in 1994 and has 25,000 residents, but does not include nearby Green Valley, one of the first retirement communities in Arizona.

Even though the entire metropolitan area constitutes a functional unit, there is not a centralized metropolitan government, and each city and town has expanded following its own growth strategy based on its history, economy and socio-political characteristics. Water supply follows this pattern and several major water agencies/companies serve the area. Wastewater management is chiefly the responsibility of Pima County which provides integrated regional service.

[4] It has been estimated that each year new construction consumes approximately ten square miles of desert.

[5] Indeed, the 2007 American Community Survey showed that—at that time—the median income for a household in the town of Oro Valley was $74,015, which was more than 50% higher than Tucson median ($36,752) although It is also nearly 50% higher than the US median ($50,007). The estimated average household income in Marana is $64,332 per year (2007), which is nearly 50% higher than Tucson median ($36,752)

3. THE STUDY AREA

The remote sensing study area included the four jurisdictions that form the Tucson metropolitan area: the City of Tucson (COT), Oro Valley (OV), Town of Marana (M) and Town of Sahuarita (S) as shown in Figure 2.

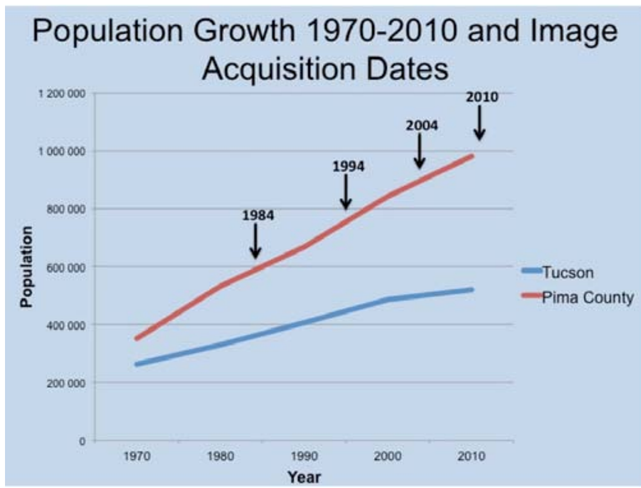

Figure 2. Population growth 1970-2010 and image acquisition dates.

The impact of population growth on the environment, infrastructure, and regulatory structure was explored using historical Landsat 5 Thematic Mapper data from May and June of 1984, 1994, 2004, and 2010.

The image data were radiometrically calibrated, atmospherically corrected, and orthorectified prior to performing a land use/ land cover classification. A CART algorithm was utilized to create a map with nine classes encompassing the natural and built environment within the study are*a.*

All four maps produced had overall classification accuracies above 91%. The built environment was then singled out to measure the growth and impact of man on the natural environment within the four jurisdictions. Figure 3 and Figure 4 compare 1984 and 2010 land cover classification maps showing the changes in the study area. Over the 26 year time period the percentage of the built environment increased in all four regions.

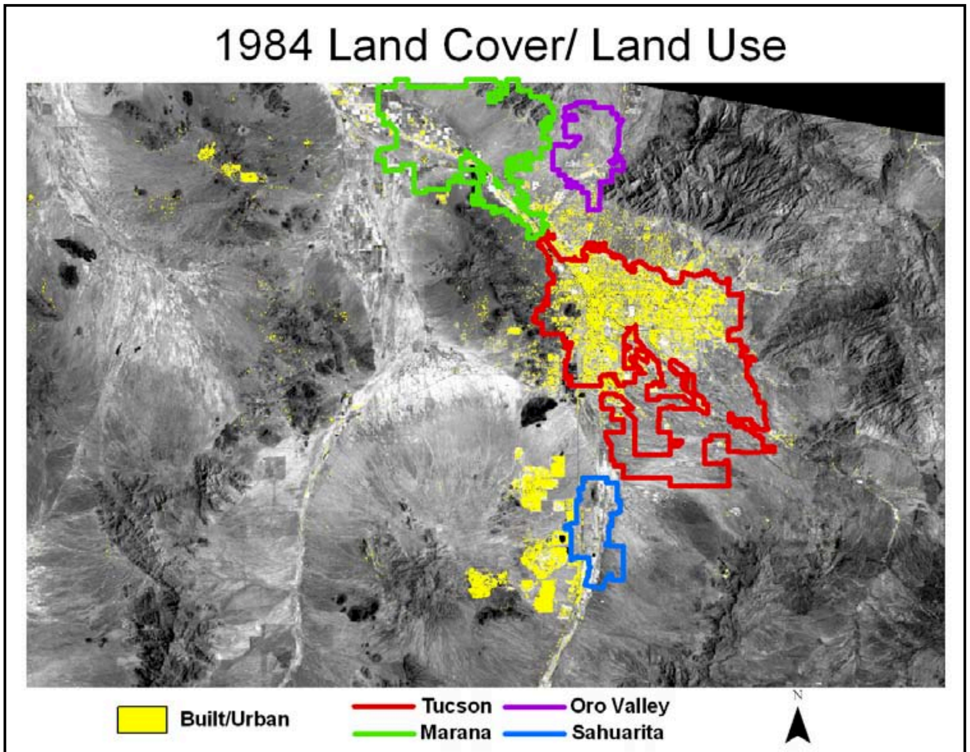

Figure 3. 1984 Land cover/Land use

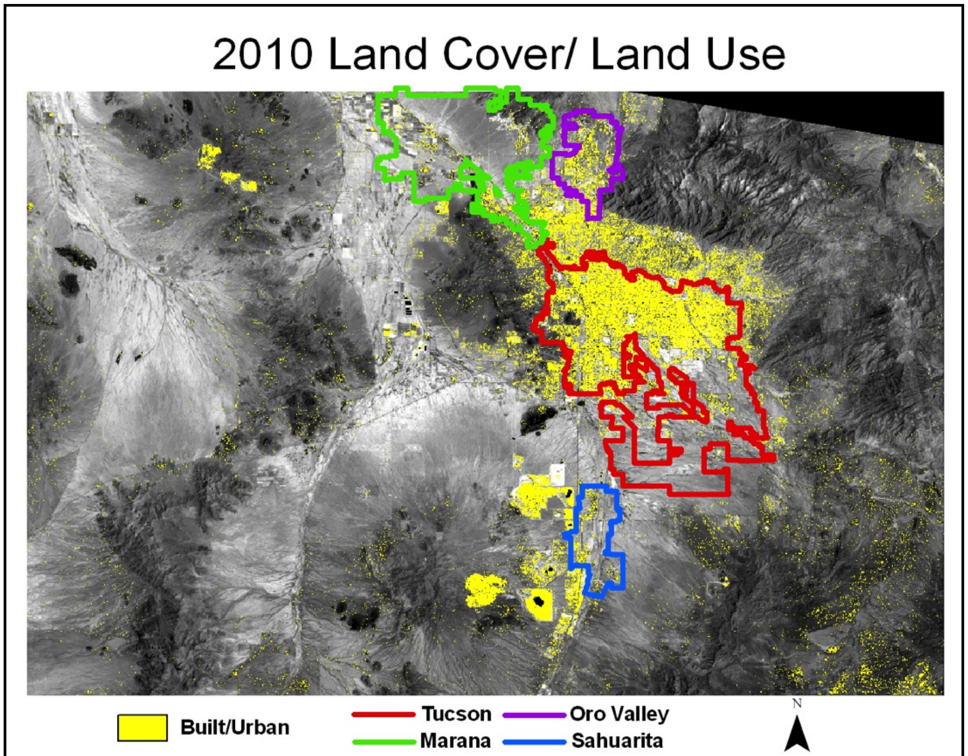

Figure 4. 2010 Land cover/Land use

The remote sensing analysis shows how the growth of the built environment has clearly altered the natural environment (evident through comparison of the land cover classification maps).

A more detailed analysis of the remotely sensed images identified what types of land cover were most impacted by the growth of the built environment. The majority of this growth between 1984 and 2010 came at the expense of the natural desert environment. Housing developments have replaced agriculture and golf courses have been placed over desert landscapes. The population boom and urban sprawl have impacted many aspects of the natural environment, particularly water resources and supply.

Some urban growth occurred on the edges of rivers and washes altering riparian areas (blue area on Figure 5). As Hayden said, “The built environment interferes with natural processes. An impervious surface – concrete highways, asphalt roads, housing developments, commercial malls, industrial areas – prevents rain from penetrating the ground, causes heavy runoff that can provoke erosion and also put toxic waste in the soil and in the aquifer” (Hayden, 2003). In addition “heat islands” develop in built areas where air circulation is not possible i.e. no trees. Built environment also stops habitat corridors and provokes the disappearance of species from the urban area unless they can adapt.

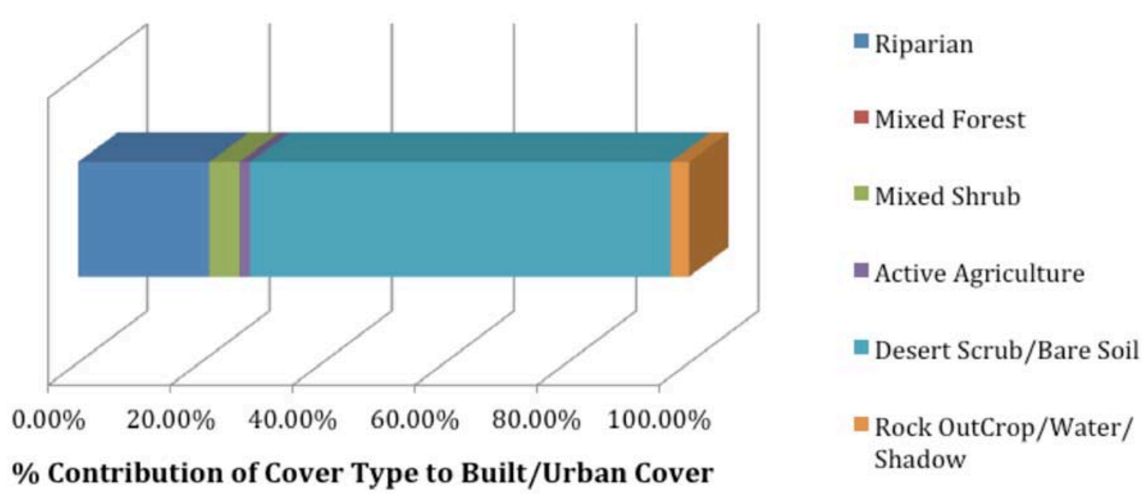

Figure 5. Contribution of natural cover types and urban cover (%)

4. PATTERNS OF URBAN GROWTH AND WATER/WASTEWATER INFRASTRUCTURE (1984-2010)

The natural landscapes have little by little been threatened by urban encroachment and fragmentation as a consequence of the conversion of ranch lands into urban landscapes. To go further in understanding the relationship between urban growth and water /wastewater, two major structural elements were explored: infrastructure and governance.

The increase in infrastructure over a 26-year period comes along with the increased amount of residential and commercial buildings as well as the construction of elaborate destination resorts for the tourist industry. This pattern repeats itself throughout Pima County and is evident in all four study areas (Tucson, Oro Valley, Marana and Sahuarita). The amount of urban growth was shown by the water and sewer connections and the number of wells. The increase in the amount of water connections was very high in all four jurisdictions. Oro Valley for example, went from having around 2000 water/sewer connections in 1984 to approximately 11,000 in 2010. Wastewater infrastructure (new treatment plants and conveyance lines) expanded as did the reclaimed infrastructure that allowed golf courses and resorts to multiply (Clavreul et al., 2011).

4.1. Water supply

Throughout its history, Tucson[6] relied on surface water but, beginning in the 20th century, and especially with the post-war urban development, it shifted to groundwater, located mostly between 100 and 500 feet deep. The groundwater was provided by two main aquifers, the Tucson Basin (or Upper Santa Cruz aquifer) and the Avra Valley aquifer on the west. However, despite natural recharge of the aquifers, since the 1950s the water demand became higher than the replenishment, provoking a general decrease in groundwater level (Benites-Gambiriaso et al., 2010). The increases in population, along with the copper mining and farming activities, within the region have also increased the demand for groundwater pumping, leading to subsidence and the significant degradation of the riparian habitat that once existed.

As regards the water demand, the main factor has been the shift since the 1980's from agricultural demand to municipal demand. Water production and distribution is a mosaic in

[6] The name of the city is connected to water : « Stook-zone » means « water at the foot of Black Mountain »

Tucson Metropolitan Area which counts about 150 different providers. The biggest provider is Tucson Water which provides 75% of the water in the Metropolitan Area within and outside the city limits. Several other public water providers, controlled by their own elected board of directors, serve the area as well as 20 very small private water companies.

Urban activities had a large impact on the water table. Decreases in water levels lead to land subsidence jeopardizing infrastructure and water storage capacity. Urban activities also polluted the aquifer (like TCE near the airport) and several landfills raised contamination issues. All these events fuelled the search for new water resources like the Colorado River's allocation through the Central Arizona Project (CAP)[7] or the idea to reuse treated wastewater as a new resource.

The first CAP delivery in 1992 created a large social conflict because of quality issues[8]and its direct use was halted in 1994. Tucson Water developed a technology for groundwater recharge in central Avra Valley to recover a blend of water (groundwater + CAP) which is delivered to customers after treatment. The aim is to decrease groundwater mining and avoid subsidence. Treated wastewater has been utilized as a new water resource since 1984 to irrigate golf courses and public parks through the reclaimed water system – "the purple pipe network".

To control water demand, the City started in the 1980's an intensive awareness campaign that made Tucson a poster-child for water conservation in the West. Now, the residential water use (indoor and outdoor) GPCD (Gallons per Capita per Day) for Tucson Water customers is 89 GPCD which is less than other major Southwest cities like Las Vegas at 222 GPCD in 2011 or Phoenix at 123 GPCD in 2008.[9] Currentlys, new projects are implemented in Tucson with several aims: increase the reclaim water use, catch storm water to control flood and use that water or at a smaller scale develop harvesting water or grey-water use.

[7] The CAP is a system of canal pumping stations and storage facilities that enable water to be brought from the Colorado River to central and southern Arizona. The project was completed to Tucson in 1992. To reach the terminus of the canal south of Tucson, the Colorado River water runs 336 mile and has to be lifted 2900 feet.

[9] Source: Arizona Water Meter: A Comparison of Water Conservation. Programs in 15 Arizona Communities, Western Resource Advocates, 2010 and Source: http://www.lvvwd.com/conservation/drought_measures.html, 2013

4.2. Leap-frog development[10]

Post-war growth in Tucson was largely a private endeavour. Developers simply acquired parcels of land and formed subdivisions with varying degrees of care and skill.

The major growth pattern that is evident from the remotely sensed data is that of leap-frog development - dense suburban developments that skip over empty land to establish a new urban fringe (Hayden, 2003). Newly urbanized areas, along with water infrastructure, spring up beyond existing urban boundaries so that developers avoid paying the higher costs of urban land and obtain more flexibility in developing larger tracts of land.

The real estate market started to boom with the massive arrival of migrants from the Eastern and Midwest United States. Moreover, the customers have always showed a preference for single-family housing - the ranchette lifestyle and the retirement communities (like Green Valley in the 1960's).[11] These preferences together with cheap land and water had important consequences. Indeed, developers and builders would buy lots where the land was cheap (in non-urbanized Pima County) and build subdivisions. Growth developed to the east and northeast and then to areas northwest of the City of Tucson.

The northwestern and northeastern portions of the Tucson metropolitan area were continuing to grow most rapidly (Figure 6). It is estimated that in 1992 two thirds of all residential permits were issued north of the north boundary of Tucson (the Rillito River), in the higher elevations of the Catalina Foothills. Although these low-density communities are expensive to service, Tucson Water supplies water and Pima County provides wastewater services as they are an integral part of the urbanized area.[12]

[10] Like in the game where one player crouches down and another player vaults over the first.

[11] The 1960s saw the establishment of retirement communities, special age-restricted subdivisions catering exclusively to the needs of senior citizens who wanted to escape the harsh winters of the Midwest and the Northeast. Green Valley, south of Tucson, was another such community and was designed to be a retirement subdivision for Arizona's teachers.

[12] In 1970 a slow-growth movement appeared in Tucson with elected officials advocating infill and a limit to the expansion of the city. One facet of the slow-growth movement was the effort to revise water utility practices, including raising water rates and charging residents' service fees that were related to delivery costs. The political resistance to growth lasted only a few years and ended with the electoral defeat of most of the slow-growth proponents. Recently, Tucson Water has established requirements, so no building permits are issued in areas without adequate infrastructure.

The earlier north-south direction of growth continued to expand following Interstate 10 and Interstate 19 in relation to transportation and trade activities with Mexico.[13] The abundance of cheap private land in the unincorporated areas located next to large blocks of state trust lands (which have not been released for development) has also encouraged leapfrog development.[14]

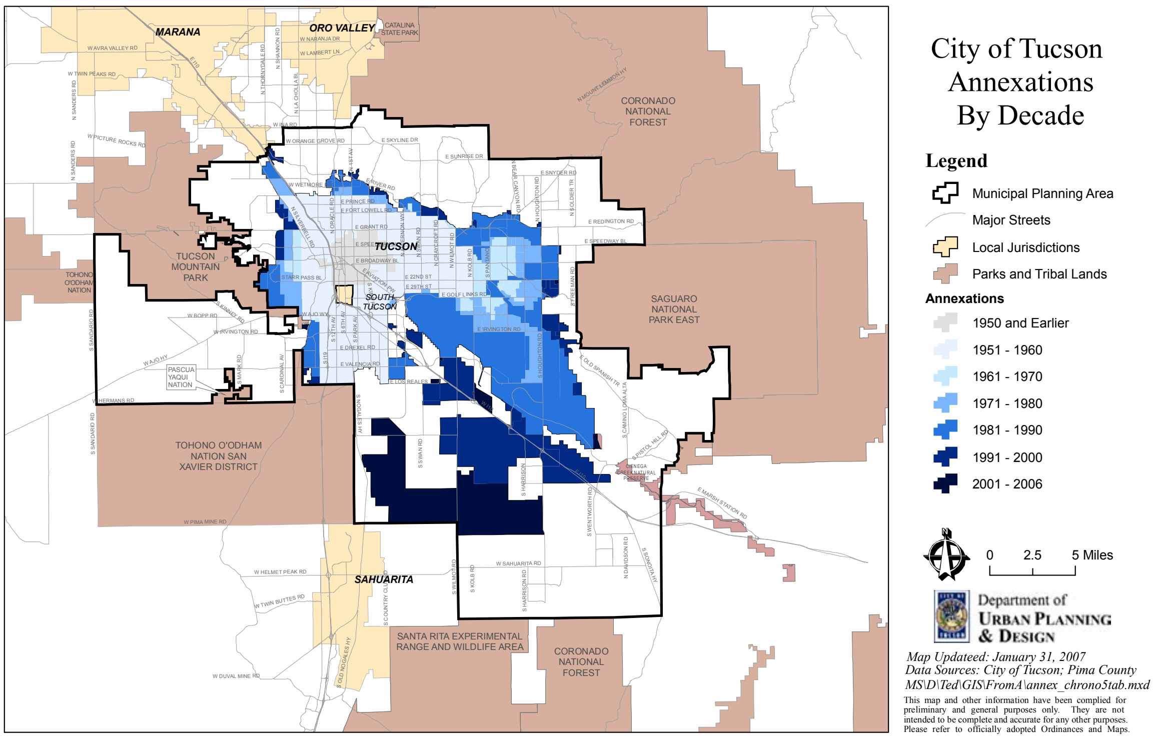

Figure 6. City of Tucson annexations by decade.

4.3. Water regulation

To cope with groundwater issues, during the 1980s, the state of Arizona established Active Management Areas (AMA) - Tucson Metropolitan Area is located in the Tucson AMA – which have specific regulations enforced by the state via the Arizona Department of Water Resources.

The aim is to control water demand and reach the "safe-yield" (balance between withdrawal and replenishment into the aquifer) within the AMA limits which include the metropolitan, mining and

[13] The City of Tucson. 1993. Tucson, *The People and the Place-Highlights from the 1990 Land Use Survey*.
[14] Over time, this has left vacant or underdeveloped land throughout the City's urban core.

agricultural activities. Subsequently, another regulation obligated all new developers in the AMA to prove that 100 years of water supply is available in the area under construction.[15]

Many neighborhoods were built beyond the reach of existing water and sewer services. The builder therefore created a private water company to serve the development's homeowners or financed the extension of the infrastructure (Logan, 2006). The Rita Ranch development, in far southeast Tucson just north of the Town of Sahuarita, is a good example of this procedure. The area that now contains the Rita Ranch housing development had no water connections in 1984 and by 2010 had nearly 10,000 connections (Figure 7).

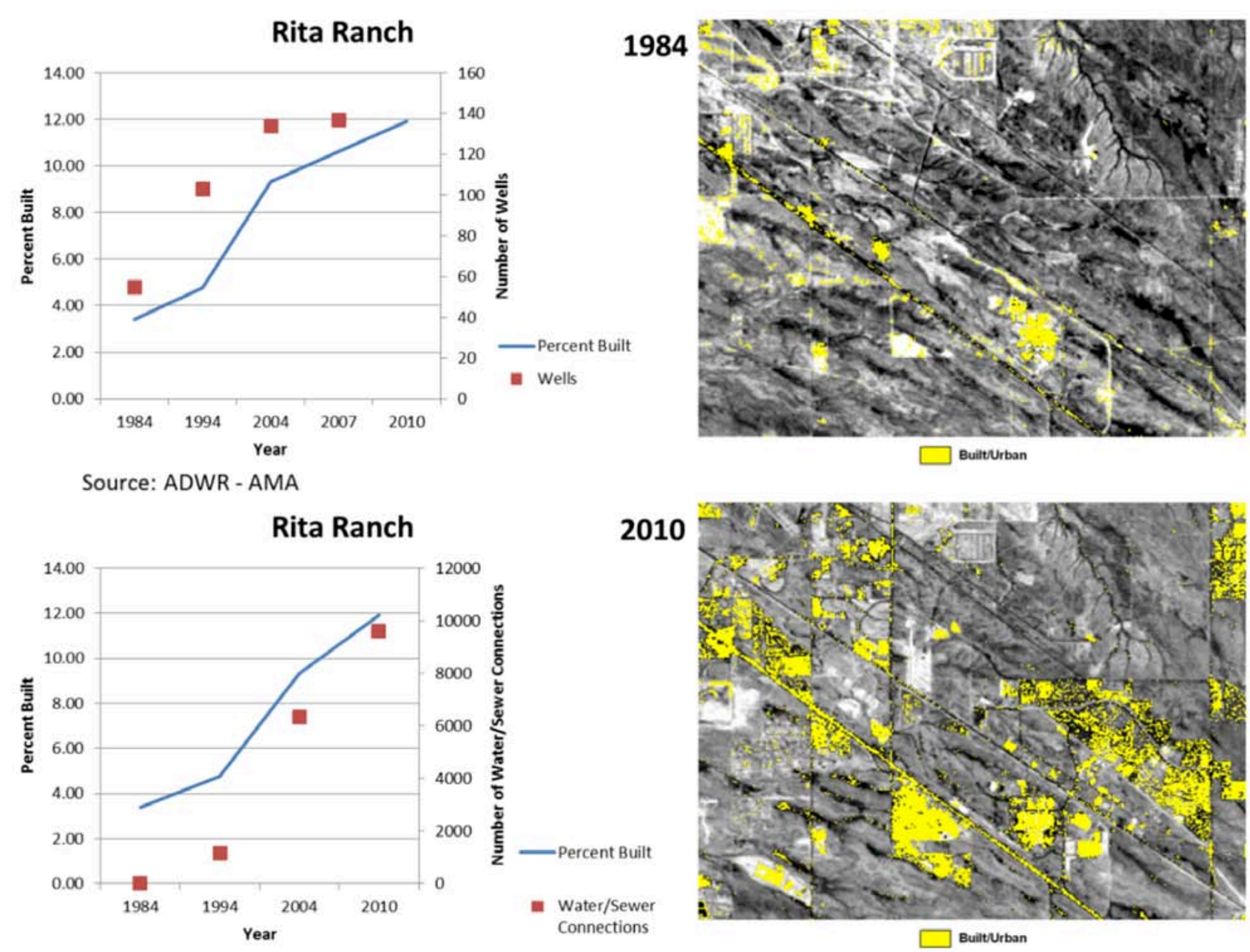

Figure 7. Rita Ranch housing development and water connections evolution (1984 and 2010)

15 In the Tucson Region two kinds of water exist: wet water and paper water (water credits, assured water supply designations, water rights…). That separation can lead to hydrological contradictions like recharging the aquifer in one place to have the right to withdraw water in another.

Another example would be Dove Mountain in Marana that went from 0 to almost 10,000 water/sewer connections by gaining water and wastewater services even though the development was many miles from the urban boundary (Figure 8; Clavreul et al., 2011).

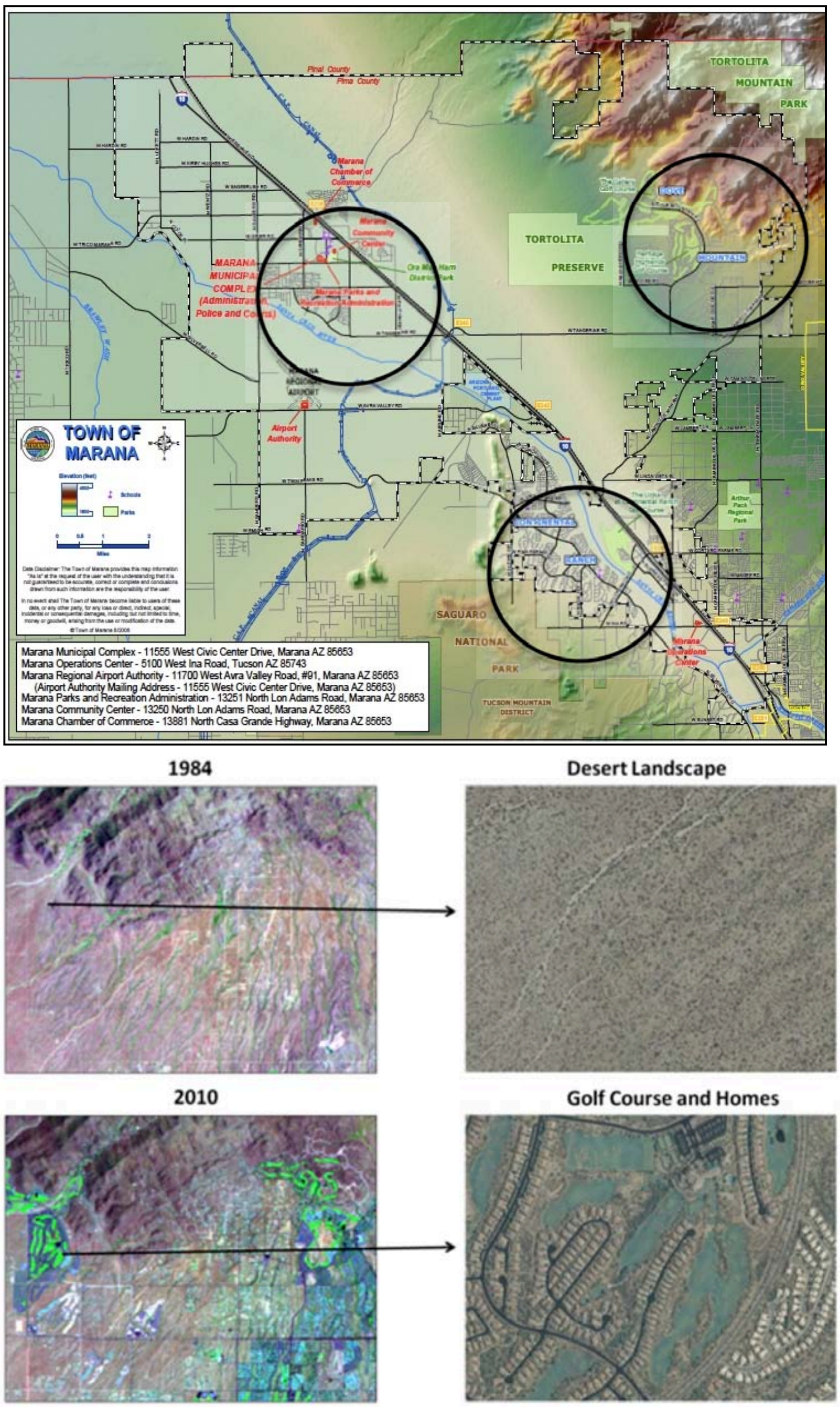

Figure 8. The picture on the top shows the Marana's Urban Development: three poles of growth (downtown (NW), Continental Ranch housing developments (S) and Dove Mountain (NE). The bottom pictures highlights an area in Dove Mountain that went from completely undeveloped in 1984 to containing two golf courses in 2010.

4.4. Wildcat development

In addition to regulated development, unregulated development or “wildcat subdivision”[16] became common in the areas outside the metropolitan area, particularly to the south and west of Metropolitan Tucson where little subdivision activity had occurred by that time. This creation of new residential parcels, without the limitations of subdivision regulation, results in development devoid of any basic infrastructure or improvements typically paid for by the developer.

In regulated development, impact or development fees are charged to new development as a means of paying for the facilities and infrastructure needed to serve that development (Tucson and Pima County, 2008). Each new house must pay these fees to its governing jurisdiction. Legal framework for how municipalities and counties set impact fees is set by state law. All jurisdictions have guidance for assessment of impact and development fees.[17]

Despite its negative implications, wildcat subdivision, or lot splitting, is directly encouraged by State law, which maintains that a parcel division of less than six portions is not considered to be a “subdivision”, and prevents any jurisdiction from denying approval or requiring a public hearing for these parcels.[18]

Wildcat development often devalues property, and can create significant hardships and sometimes real hazards for its residents. As the value of land increases there is a growing trend for private ranchlands and rural holdings to be developed as wildcat subdivisions: in 1997, 41% of the new residential dwelling units were not part of platted subdivisions and most of these were issued in “ex-urban” areas, or rural area outside the metropolitan area.

[16] The expression wildcat development refers to the independent and solitary nature of the « wildcat » which is actually a bobcat, a medium sized member of the mountain lion family.

[17] The City of Tucson currently assesses impact fees for water, roads, parks, police, fire, and public facilities. The County has impact fees for transportation only. Impact fees apply to all new developments and have specific benefit areas, for example, the Southwest Infrastructure Plan (SWIP) and the Houghton Area Master Plan (HAMP).

[18] What is often not realized is that lot splitting can proliferate into many more “splits” of the same parcel For example, if a property owner of 100 acres were to first lot split his parcel into five 20 acre parcels, each of the five subsequent owners would also have the right to lot split their 20 acre parcels again five times, so that now there are 25 property owners of four acres each. Depending on the minimum zoning, which could be as small as one acre per house, these four acre parcels could be again split, perhaps resulting in a wildcat subdivision of as many as 80-100 parcels and perhaps 200 or more residents, all without basic improvements, particularly potable water.

5. CONCLUSION

The knowledge gained from this research aims to inform future urban planning and water /wastewater policy. Multiple challenges exist, particularly for urban sustainability and water resources. This research demonstrates that the authorization (and financing) to build long sewer outfalls (+/- 8 kilometers) to existing urban infrastructure is most highly correlated with successful patterns of "leap-frog" development. In addition, the rapidly growing access to land use mapping and the increased accuracy of remote sensing analysis allows a new level of scientific precision in the exploration of significant policy and growth questions.

For example:

- In the 1980s the Groundwater Management act was enacted in Arizona that stated all wells must be registered. Using remotely sensed data we can examine whether this registration process impacted growth rates at all.
- We can also use similar classification techniques utilized in this study to explore additional issues with urban growth in the Sun Corridor near the US-Mexico border.
- Impervious surfaces also impact aquifer recharge and the amount of impermeable materials can be estimated using land cover classifications.
- Concrete surfaces have also been shown to contribute to the urban heat island effect which impacts water usage due to increased temperatures. Remote sensing can be used to estimate temperature changes in the Tucson Basin over the last two decades and whether there is a correlation with water usage.

Remote sensing can significantly assist in the analysis of urban growth patterns and the underlying causes and impacts. This adds a very important and powerful tool to our toolbox for research and discussion of these very important topics.

6. REFERENCES

Arizona Town Hall. 1996. *Arizona's Growth and the Environment- A World of Difficult Choices*. Sixty-Eighth Arizona Town Hall, May 5-8, 1996. Phoenix: Arizona Town Hall.

Akros, Inc. Wilson Preservation Coffman Studios, LLC HDR, 2007. *Tucson Post World War II Residential Subdivision Development 1945 – 1973*, prepared for the City of Tucson, Urban Planning and Design Department Historic and Cultural Resources. http://cms3.tucsonaz.gov/sites/default/files/imported/resources/publications/wwii_102207.pdf

Benites-Gambiriaso E., Schneier-Madanes G., Cattan N. 2010. *Water and Urban Sprawl : A State of the Art. Research Report.* Tucson, UMI3157-Partners University Fund - PIRVE CNRS

Burchell, Robert W., Naveed A. Shad, David Listokin, Hilary Phillips, Anthony Downs, Samuel Seskin, Judy S. Davis, Terry Moore, David Helton, and Michelle Gall. 1998. *The Costs of Sprawl-Revisited*. Transit Cooperative Research Program Report 39. Washington, D.C.: National Academy Press.

Clavreul D., Duczinski D., Schneier-Madanes,G. 2011. *Water and Urban Sprawl : Marana Case Study. Research Report.* Tucson, UMI3157-Partners University Fund - PIRVE CNRS.

Colby B.G., Jacobs K.L., *« Arizona Water Policy – Management Innovations in an Urbanizing, Arid Region »*, RFF Press, 2007

Gammage, G. 1999. *Phoenix in perspective: Reflections on developing the desert*. Tempe: Arizona State University, College of Architecture and Environmental Design, the Herberger Center for Design Excellence.

Gober, Patricia. 2006. *Metropolitan Phoenix: Place Making and Community Building in the Desert*. Philadelphia: University of Pennsylvania Press.

Hartfield, K. ,Marsh S., Schneier-Madane,s G., Curley, E, 2013. *Remote sensing of urban change: water in the Tucson basin of Arizona*. In : COUREL M-F., TASHPOLAT T., TALEGHANI M.(ed.), WATARID 3 : Usages et politiques de l'eau en zones arides et semi-arides, Paris, Hermann.

Hayden, Dolores, 2003. *Building Suburbia: Green Fields and Urban Growth, 1820-2000*, New York: Pantheon Books.

Heim, Carol E., 2001. « Leapfrogging, Urban Sprawl, and Growth Management : Phoenix, 1950-2000 », *American Journal of Economics and Sociology*, Vol. 60, N°1, Special Issue : City and Country : An interdisciplinary Collection, Jan. 2001, pp. 245-283.

Jenks M., Burton E., Williams K. (éd.), 1996, *The Compact City : a sustainable urban form ?*, Oxford, E & FN Spon, 260 p.

Kelso, Maurice M. et al. 1973. *Water Supplies and Economic Growth in an Arid Environment: An Arizona Case Study*. Tucson: University of Arizona Press.

Kupel, Douglas E. 2003. *Fuel for Growth: Water and Arizona's Urban Environment*, Tucson : University of Arizona Press, 294 pp.

Le Goix, R. *« Les « Gates Communities » aux Etats Unis – Morceaux de villes ou territoires à part entières »,* Thèse de doctorat, 2003.

Leplus S., Sevaux N. , Schneier-Madanes, G.2010.*Water and Urban Sprawl : the Tucson Region Case Study. Research Report.* Tucson, UMI3157-Partners University Fund - PIRVE CNRS.

Lindstrom, Matthew J. et Bartling, Hugh eds., 2003. *Suburban Sprawl: Culture, Theory, and Politics*, Lanham, MD: Rowman & Littlefield.

Logan, Michael F. 2006. *Desert cities: the environmental history of Phoenix and Tucson*. University of Pittsburgh Press, 240 pp.

Morrison Institute for Public Policy, 1998. *Growth in Arizona: The machine in the garden*, edited by J. S. Hall, N. J. Cayer, and N. Welch, Tempe: Arizona State University.

Ouellet, Michel, 2006, « Le smart growth et le nouvel urbanisme : synthèse de la littérature récente et regard sur la situation canadienne », *Cahiers de géographie du Québec*, vol. 50, n° 140, pp. 175-193.

Planning department of the City of Tucson. 2002. *Census 2000: The Basics - Focus on Tucson.* http://www.tucsonaz.gov/planning/data/census/census2000basic/basicpubs/funfacts2000.pdf

Power T. and Barrett R., 2001 - *Post-cowboy economics - Pay and prosperity in the new American West*. Washington, Island Press, 185 p.

Riebsame W., 1997. - Atlas of the New West - Portrait of a changing region. Boulder, University of Colorado Center of the American West, 192 p.

Sakrison R., 1997, *Water Use in Compact Communities: The Effect of New Urbanism, Growth Management and Conservation. Measures on Residential Water Demands*, Summary of doctoral dissertation for the Department of Urban Design and Planning, College of Architecture and Planning, University of Washington, Seattle, Washington.

Schneier-Madanes, G., Curley E.,Valdes J, Maddock T, Marsh S., Hartfield K., *Challenges Of Urban Growth, Water And Wastewater, The Southern Arizona Story.* Technical Report (In Preparation)

Sheridan, Thomas E. 1995. *Arizona: a history*. Tucson: University of Arizona Press, 434 pp.

"Sonoran Desert Conservation Plan. GIS Coverage of Perennial Streams, Intermittent Streams and Areas of Shallow Groundwater", Pima Association of Governments (PAG), 2000a., January 2000.

"Third Management Plan; 2000-2010 for the Tucson Active Management Area .Arizona Department of Water Resources (ADWR), 1999.

Travis W., 2007. - New geographies of the American West - Land use and the changing patterns of place. Chicago, Island Press, 356 p.

Tucson (Ariz.), and Pima County (Ariz.). 2008. *Water infrastructure, supply & planning study a City of Tucson and Pima County cooperative project*.
http://www.tucsonpimawaterstudy.com/Reports/Phase2/FinalReports_Ph2.html

Valdes J., Maddock III T., *« Conjunctive Water Management in the U.S. Southwest »*, in Schneier-Madanes, G and Courel, M-F, *« Water and Sustainability in Arid Regions*, Springer Editions, 2009.

Wenum, John Dale, 1970. *Annexation as a Technique for Metropolitan Growth: The Case of Phoenix Arizona*. Tempe: Institute of Public Administration, Arizona State University.

Chapter 4

-Deliverable 5.2-

Stakeholders Committee Recommendations for building the Feasibility Study -1

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1. INTRODUCTION – THE SWAN PROJECT

SWAN (Sustainable Water ActioN: Building Research Links between EU and US), is a four-year International Cooperation Project granted by the European Commission (FP7-INCOLAB-2011). Its main goal is to reinforce links between EU and US research in the field for sustainable water management. The project promises to develop a transatlantic dialogue in response to the need for interdisciplinary and multiregional collaboration regarding water issues in the 21st Century. International collaboration is a must to find sustainable solutions to the twin threats of socioeconomic development (with increases in anthropogenic demands on the environment) and climate change (which is changing the resources availability and the nature and persistence of environmental risk and hazard).

The SWAN project involves five European Union Member States (Bulgaria, France, Netherlands, Spain and United Kingdom) and the USA. The European teams belong to the *National Institute of Geophysics, Geodesy & Geography* (NIGGG; Bulgaria), the *Centre National de la Recherche Scientifique* (CNRS, France), the *UNESCO-IHE Institute for Water Education* (Netherlands), the *Universidad de Sevilla* (US; Spain), and the *University of the West of England* (UWE; United Kingdom). The American team is from the *University of Arizona*.

The SWAN project is coordinated by the French CNRS (Centre National de la Recherche Scientifique) which created an International Joint Unit (UMI3157) in collaboration with the University of Arizona (UA) in 2008[1]. This extension of the UMI broadens its current activities from a bi-national focus to one that incorporates ideas, disciplines and methods from across Europe and therefore it marks an important evolution of the UMI concept. By connecting the USA with Europe, scientific cooperation has the mission to enhance on-going activities, bring new projects, and establish a foundation for future collaboration. In order to explore how the UMI will promote the development of a transatlantic dialogue on water, a “Feasibility Study” into the establishment of some sort of enduring institutional structure is included among the planned outputs of the SWAN project. Another key component of SWAN is the development of research stays for the European team researchers at the iGlobes-UMI (the successor to UMI3157, reauthorized by CNRS and UA in 2013) located in the UA.

[1] A “UMI” is a thematically focussed CNRS-led research institute embedded at a university or institute outside of France. Another example is CIRHUS (UMI 3199 CNRS-NYU) the Center for International Research in the Humanities and Social Sciences, whose goal is to foster collaboration between CNRS and New York University.

The need for an integrated European dialogue with the USA has become urgently apparent. On one hand, Europe is a leading world player in water science, policy and management (institutional, scientific and technological innovation, leading water sector private companies, significant investment capabilities, etc.). Moreover, water sustainability research in Europe represents a critical mass of infrastructure and human resources that has had a significant influence on the development and implementation of water management models including advanced hydrological modeling, participatory decision-making, integrated water resources management (IWRM), and the currently ongoing scientific debates about their potentialities and limitations (See Deliverable 3.1: ”Key data and information requirements in the context of current debates on water management”, by USE team for a critical approach of these models). On the other hand, various US institutions, the UA paramount among them, have shown innovative leadership in searching for new water resources (reclaimed, recycled, desalinization) and addressing the influence of climate change on water sustainability.

Moreover, the USA and Europe appear to represent two very different models of what might be called “hydro-citizenship”. While the European model is centrally mandated, and in some cases overlies pre-existing national models as is the case of Holland’s Watterschappen, the American one is more democratically based (e.g. CAP public engagement process). By working together with US institutions, Europe’s influence will increase and the quality of its achievements will improve. The European experience in building an integrated approach of water management to ensure water use sustainability (i.e. Water Framework Directive, water agencies at river basin scale, etc.) has much to offer to the USA with regard to water policies, all the more since the USA is known to have entered a phase of necessary change regarding their national water management systems. In particular, the arid Southwest region is severely challenged as water resources have been compromised (qualitatively and quantitatively) by population growth and urban expansion. Therefore, an EU/USA alliance can prove mutually profitable as knowledge and expertise are shared between and within regions.

These goals will be achieved through collaboration on comparative analysis of water management issues in different case study locations in the EU and the USA (see Deliverable 2.1 by UWE team – "Water security and sustainability EU/USA”). The uncertainty of model predictions implies the necessity of opening scientific outcomes to public validation. Furthermore, the involvement of stakeholders implies that the scientific activities must integrate with public participation. The elaboration of both geo-spatial databases and visualization tools is linked to the perspective of participatory planning of water resources use. Therefore, any case study based research must be necessarily built on collaboration with stakeholders who are experts in the water management challenges of their region at different scales, and on broader public participation.

2. INVOLVEMENT OF STAKEHOLDERS IN THE SWAN PROJECT

2.1. Goals of the SWAN project: from a Sustainable Water Center to an Organization for a Transatlantic Water Dialogue

The SWAN project constitutes the door that the existing UMI iGLOBES (CNRS/Univ. of Arizona) has opened to European partners in response to the urgent and increasing demand for high quality interdisciplinary and multiregional collaboration, which can serve as models for research and development in diverse domains of water sustainability. This opening aims to expand the current bi-national (US-France) focus, extending the actual research field and function. The goals of the SWAN consortium are to develop joint research activities and prepare the project for an institutional collaboration, in synergy with scientists and stakeholders engaged in all aspects of strategic planning. The SWAN work plan has been organized in three phases: i) opening the activities; ii) increasing scientific cooperation; iii) preparing the institutional arrangement.

European partners – scholars, students and stakeholders – have to develop joint research activities within four work packages and achieve deliverables (reports, publications, international conferences) on integrative hydrological modelling, social and natural sciences interface, data, information and knowledge for water risks management and land use processes related to urban water cycle. These research themes can be developed in a comparative and interdisciplinary perspective. This goal has been mainly achieved during the Period 1 of the Project (March 2012 – August 2013), through the contributions in the progress meetings of all the SWAN teams and through the research stays of several European students to the UMI iGLOBES (CNRS/UoA).

The second period (which started in September 2013) is marked by four major activities: scientific meetings, SWAN central seminar, research stays of students to work in the Tucson case study, and stakeholders workshops, which will contribute to further integrate the partners and foster joint research activities. At the same time, partners have to contribute to the development of the Feasibility Study led by the UMI iGLOBES. This phase of the project enhances the current activity in the USA and disseminates the project in Europe, looking for potential new members to expand the activity during the four years. At the end of the fourth year, a well-defined framework of organization for scientific collaboration will be presented. This project will have a multidisciplinary approach covering fields from physical and natural sciences to social sciences and will be connected to major research centers in the USA and in the EU. It aims to function as a major international network for scientists, students and also stakeholders and communities. This framework will constitute the basis of the Feasibility Study that SWAN aims at submitting to the European Community at its conclusion in 2016. The Feasibility Study is necessary to expand the UMI 3157 (CNRS / UA) into a European platform for scientific collaboration and potential training in the USA. Based on the four years of experience of joint research, a Final Strategic Report on the vision, scope and structure of this research organization, necessary to start its implementation, will be produced. The report will include a short list of potential new partners, and criteria to enhance the process of scientific and institutional integration.

One of the main obstacles to the international circulation of ideas is the existence of national schemes of perception and analysis that shape the world vision of the scientists. Thus, concepts may have different meaning depending of their national context of emergence, which leads to misunderstandings when it comes to scientists defining alternative ways of organizing scientific collaboration. Therefore, the notion of “research center” might differ between the SWAN partners. This notion is indeed a good example of how different national visions are competing in choosing an appropriate denomination for creating an administrative structure oriented towards international scientific collaboration. While a center in most of European countries (and especially in France) is a permanent institution characterized by its areas of research, a center in the USA refers to one or several specific projects with their own funds. Conceived in Europe a general condition for the development of research activities, a center can appear as a binding structure in the American context, as its creation is the result of fundraising and targeted research activities.

From an academic point of view, discussions among the SWAN partners (and outside experts) during the first phase of the project regarding the definition of the Sustainable Water Center (as the format for scientific collaboration was defined in the SWAN proposal) appeared thus to be very “Euro-centric”: in the United States a “center” mostly refers to the existence of funded research projects around a central scientific goal. Even the existence of a French CNRS institution like the UMI on the American territory is based in an agreement that has to be renewed every 4 years. Those first statements imply the necessity to reinforce the academic belonging of UMI to the UA, and to study furthermore the American academic organization: there are already a great number of water-related research centers, on a supra-national level

(United Nations, NGOs, etc.), and on an international level (in European or American academic fields). As a consequence, the feasibility of an institutional arrangement should be innovative but also adjusted to local possibilities inside the UA and USA.

The goal of building an institution for international scientific collaboration, originally denominated "Sustainable Water Center", and now reformulated as an "Organization for a Transatlantic Dialogue on Water", has sense only if it is related to the research practices led by each team and developed in mutual collaboration. The researchers participating in the SWAN project have generated internal debates and raised suggestions related to innovative and stimulating forms of international collaboration. A balanced view of institutional and research directions within the SWAN Project can rely on several observations:

- The independence and autonomy of national scientific programs has to be reaffirmed, in a context of increasing political, economical and social demands of expertise coming from international funding agencies that work towards finding solutions to environmental, health and security issues. In water issues, the call for stakeholders and, more generally, "democratic participation" and responses to "social demand", can sometimes appear as an attempt to build a political and scientific legitimacy in the institutional struggles for the definition of managerial practices rather than a will to satisfy the "public" or the "users". The institutional characteristics and the role of stakeholders have to be carefully defined and incorporated to a new kind of scientific practice in order to avoid the suspicion of political "instrumentalization" of public participation processes.
- From a material point of view, even the most "virtual" scientific network requires some key staff and an institutional and a physical place to do research work, as the UMI iGLOBES provides at the UA. But beyond these conditions, the issue of a scientific leadership remains crucial and the goal, therefore, is to define the optimal *organizational structure for scientific collaboration* that would be the most efficient and adapted to the SWAN objectives in order to study water issues. This organizational structure will have to deal with uncertainty and complexity, and it will require interdisciplinary research and comparative approaches besides specific engineering and management capacities. In that perspective, the consolidation of a scientific network appears as a condition for the eventual institutionalization of a scientific collaboration.
- One of the final proposals might be for a continued round of "networking and capacity

building" embedded within the UMI iGLOBES, that might be in charge of a secretariat based at the UA, and of the construction of a mechanism for student and staff mobility between SWAN partners. The development of this exchange mechanism can build from the positive experience of scholar exchanges within the context of SWAN. The confluence of PhD, post-doctoral and other scholars from different countries, disciplines and conceptual approaches (both SWAN members and others) conducting research stays at the UA for extended periods of time (1 to 6 months) enabled SWAN hosts at UA to establish weekly meetings where visiting scholars discuss their work and attend and discuss presentations from local water managers. Given SWAN's goal to develop collaborative research frameworks, the weekly meetings have had tangible and positive results: a working paper that attempts to provide an integrated framework for water resources research and the development of a common case study site for comparative research: the TAMA (Tucson Active Management Area) Case Study, where scholars will develop part of their work.

To resume the former achievements, three key deliverables are already taking shape:

i. The emergence of *a de facto* "secretariat" within UMI 3157/iGlobes to coordinate collaboration amongst a growing global network of water researchers and students.
ii. A better understanding of how to facilitate academic mobility between partner institutions, including academic calendars, visa rules, logistical arrangements for credit accumulation by visiting students, etc.
iii. SWAN project has enabled the emergence of entirely new networks linking water scholars from around the world. One such is the International Water Security Network (IWSN), based at the University of the West of England and with significant funding "*to explore emergent water security complexes at local, regional and global scales in four broadly conceived world regions: Europe and North America, Sub-Saharan Africa, Latin America and Asia*". The IWSN has already indicated its desire to link to the SWAN project in mutually beneficial ways, some of which will be discussed at SWAN project meetings in Seville, Spain in June 2014.

2.2. Stakeholders participation as a means to achieve SWAN goals

SWAN's scientific approach is taking into account the critics of the traditional ways of studying environmental problems, inspired by "post-normal science" theories, in order to support dialogue between scientists, engineers or modelers of very different backgrounds and different levels of interest on epistemological issues. This approach is meant to be used in fields such as water resources management, emphasizing the uncertainty of model predictions in complex issues and poses the necessity of opening scientific outcomes to public validation. Therefore, the early involvement of “stakeholders” (that is, those with a stake or interest in the issue being analyzed or discussed) in the design and development of research projects, who are experts in aspects of the water management challenges in their region, is needed to explore new scientific practices that respond appropriately and creatively to current epistemological challenges: they can be experts, or lay people involved in the water management challenges in their region, but they can also deal with environmental issues on multiple scales and areas, such as international policies, climate change, biodiversity, etc.

If the SWAN project intends to take into account the arguments advanced by the critics of the traditional expertise of scientists, it must develop its own methodology in a non-dogmatic way: in order to build an interdisciplinary research that is led by the SWAN European students conducting stays at the UA, the collaborative approach to the scientific work through the involvement of stakeholders and researchers from the outset is a defining characteristic of the SWAN project, and it underlines its commitment to:

- Support actions and collaborative research.
- Transparency.
- Extensive and effective communication.
- Active dissemination and product information.
- Intra-project as well as external educational activities.

During the first phase of the project (proposal and early development) a preliminary list of stakeholders was developed by all partners in order to implement scientific collaborations (see table 1 below). However, it became apparent early on that a more focused definition of scientific activity (thematically, at different scales and geographical regions) was necessary before it was possible to clearly identify the stakeholders that were relevant and involve them effectively in scientific work.

2.3. Difficulties of the participatory research process

Stakeholders’ participation is considered a major contribution to the SWAN project: it involves various institutions to contribute to the Feasibility Study (WP5) on a future international scientific collaboration on water issues. In the context of the SWAN Project, three stakeholder workshops have to be organized on months 12, 24 and 36 of the project. These meetings constitute the basis of the Deliverables 5.2 (month 18), 5.3 (month 24) and 5.4 (month 26), which are the Recommendations realized by the International Stakeholders Advisory Board to build the Feasibility Study.

SWAN project partners worked on the project objectives and tasks during the 2nd Progress Meeting organized in Tucson from April 29th to May 3rd of 2013, and during the 3rd Progress Meeting organized in Tucson from October 20th to 31st. The Short Report on the Action Plan for the Feasibility Study (Deliverable 5.1), delivered after the 2nd Project Meeting (May 2013) details how the partners plan to reach a new and sustainable institutional arrangement for further collaboration on water-related research between American and European partners. It includes:

- A scoping of both the scientific objectives and contents of the SWAN project, an overview of its practical realization and the definition of eventual new tasks resulting from this evolution. This prioritization obeys to the necessity of thinking together the scientific and institutional dimensions of the project without concealing the autonomy of scientific research.
- The short report determines an action plan based on the identification of tasks, capacities and risks required to build the feasibility study.
- Other US-European networks in this area.

The various progress meetings and research conducted independently by the national teams have led us all to question the original framework proposed in the DOW ("Description of Work", Annex 1 of the Grant Agreement), regarding the involvement of stakeholders. Indeed, the recommendations of stakeholders are supposed to strengthen one of the main challenges of SWAN: the articulation between the scientific and the institutional dimensions of the project, through the elaboration of an organization what we now call a "Transatlantic dialogue on Water Management", rather than a "Sustainable Water Centre". However, several challenges have arisen during the configuration of the the International Stakeholders Advisory Board:

1. Ambiguous meaning of the 'stakeholder' notion: stakeholders are so diverse that they are often difficult to identify in the research context. They can be persons, entities, organizations, groups inside of an organization, etc. The notion of ''stakeholder'' is a relative term since it makes reference to interests around particular issues. In other words, some groups or organizations may exist over time but become stakeholders only in reference to a

specific issue. Moreover, these issues may be as local as flooding problems in a particular street or as global as climate change or inequality of water services provision in developing nations. Therefore, involvement of stakeholders in a research process must take into account a sociology of the position they have in their context of action, as well as their institutional and economic characteristics, in order to understand their involvement (and their interests) in the water issues analyzed in the project.

2. Stakeholders mapping: as has been discussed throughout this document, SWAN's institutional and scientific objectives are closely related and constantly evolving. As a result, the identification of relevant stakeholders is an ongoing and slow process since several tasks need to be completed: first, specify the research questions; secondly, define what is expected by the research teams from the stakeholders, and conversely, what is expected by the stakeholders from the research teams. This is particularly important from the point of view of the fact that many potential stakeholders have little time and resource to devote to long-term engagement with a project like SWAN. Furthermore, and in addition to the requirement for stakeholder input on the creation of an organization for a transatlantic dialog on water issues, evolving scientific work has resulted in the development of a local case study in the Tucson area to focus the work of visiting researchers and to facilitate collaboration and trans-disciplinary work. As a result, a new typology of stakeholders has been proposed (see Section 2 below) that will be developed in the next phase of the project.
3. Temporality of the research process: it has been difficult to build the collaboration with stakeholders without having a common research goal from the beginning. The relationship with stakeholders is built over time with continuous collaboration in cases of common interest. To this aim, SWAN project has started to incorporate case studies, such as TAMA (Tucson Active Management Area), that allows to build long-term relationships between scientist and stakeholders.
4. Financial challenges: participation of stakeholders in the meetings are important in order to get their point of view and advice on the current study issue. Nevertheless, although the partner institutions have agreed to participate, involving their stakeholders, the organization of the International Stakeholders Advisory Board (composed of American and European members) has been complicated due to the distances and the difficulty to finance the mobility. EU funds cannot be used to pay travel arrangements of stakeholders, since this issue was not included in the initial financial project design. However, the International Stakeholders Advisory Board will be regularly consulted on the base of texts and reports.

In conclusion, the original identification of potential members for the Stakeholder Committee by SWAN partners in the SWAN Agreement has proven to be inadequate for the range of scientific and institutional issues that are the focus of SWAN work. Although the stakeholders' workshops have been incorporated to the research tasks of the SWAN teams, the originally proposed members of the Committee may not be the most relevant with respect to the evolution in long-term objectives outlined above. The involvement and commitment of stakeholders to SWAN's work therefore requires the implementation of a new strategy. One of the challenges is to build new modes of participation included in scientific work.

To this aim, WP5 has been extended by including new tasks related to the participation of stakeholders and its consequences in terms of organization of scientific work. The research conducted up to now in the framework of WP2 and WP3 by Partner 3 (University of West England) and Partner 4 (University of Seville), respectively, refers to water as a complex and uncertain object that is built from various social, political and economical perspectives, and therefore, several multidimensional issues need to be addressed:

- Incommensurability and legitimacy of several positions, which requires to clearly defining explicit choice of narratives and external references.
- Contextuality, transparency and expression of implicit positions, values and interests.
- Integration of skills, sectors, policy, experts and different perspectives into the project.

All those elements imply different approaches to make and perceive science working towards a field of applied research where the stakeholders are known to play a key role. A decision was made to strengthen the analysis on both the specificity of addressing water issues and the involvement of stakeholders into a common organization for a transatlantic dialog on water issues.

Collaboration between stakeholders and researchers requires a risk assessment analysis in order to avoid failure of the feasibility study (Cf. Deliverable 5.3, by the CNRS team). An identification of evaluation criteria will be made in order to provide the basis for an objective assessment of the alignment of project developments with the stated objectives and to take measures to suppress or mitigate the effects of the risks identified (tools to be developed, actions to be undertaken, etc.).

3. ARTICULATION OF THE DIFFERENT LEVELS OF STAKEHOLDERS

3.1. Stakeholders' typology

As pointed out in section 1.3, 'stakeholders' is not a homogeneous or simple category since they are in different institutional levels and, therefore, it is not possible to talk of 'stakeholders' in general terms without defining the specific field of action in which they are involved. One of the main results of the first period of work is the decision of the SWAN participants to identify a typology of stakeholders and differentiate the levels of work with different categories of stakeholders. Three levels have been defined:

- Level 1: *International Stakeholders Advisory Board* for the SWAN feasibility study in order to organize a transatlantic water dialogue network. Its role is to provide advice and insights on how academia and managers can work together to better inform management challenges and relevant research. The identification of this level of stakeholders is one of the main challenges of the feasibility study coordinated by the CNRS team: they do not necessarily come from national stakeholders groups but from international institutions (research, governance) that might have a specific view on a new research network.
- Level 2: *National Stakeholders* that regularly collaborate with the corresponding participating teams in the SWAN project, collaborating in their ordinary activities of research and dissemination, even outside of SWAN.
- Level 3: *Local Stakeholders* that are involved in each case study and work together with the researchers. The list of stakeholders involved in each case study can be very extensive, with stakeholders engaged at different levels.

The development of the feasibility study needs a specific strategy and more inputs from the stakeholders, in conformity with the main developments of the SWAN Project and the differentiation of the three levels of stakeholders. Although there are no explicit criteria to draw the line between the different levels of stakeholders, each team defines them in function of its affinities, its research tasks and its own vision of water management. The challenge is thus to articulate these different levels beyond the national differences, despite the lack of space and time for discussion and dialogue between them. Therefore, the opportunity provided by a transatlantic dialogue comes from the necessity to articulate the local studies of the level 3 and to take the concerns and findings from the case studies to an international exchange, and sharing the knowledge that is coming from different experiences and apply it to a national level (see figure 1).

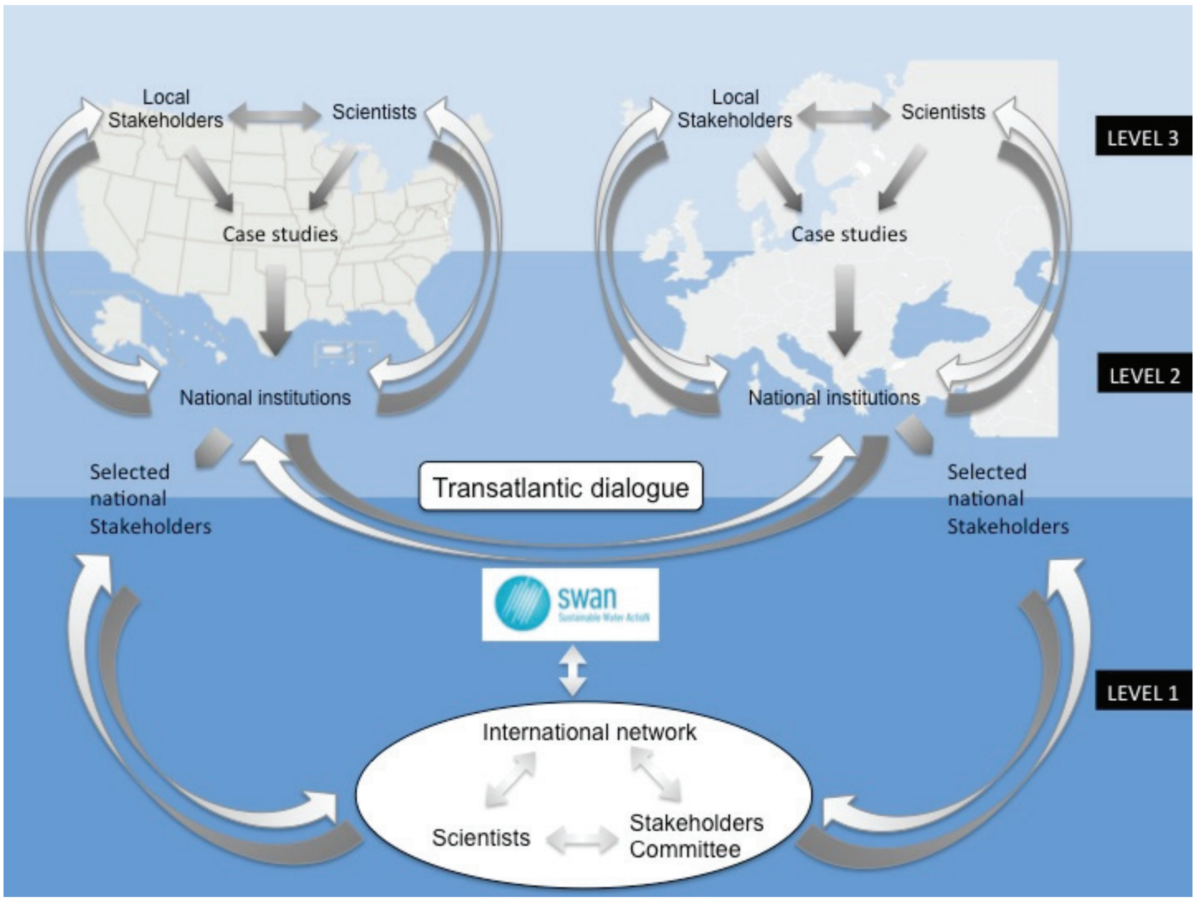

Figure 1. Articulation of the 3 levels of stakeholders

The International Stakeholders Advisory Board (Level1) will advise on issues related to the development of the international institution for scientific collaboration on water issues (Sustainable Water Center as originally proposed in the SWAN DOW, or the Institute for Transatlantic Water Dialogues, as currently envisioned). Owing to the material difficulties arising from bringing together American and European stakeholders, the strategy of the Feasibility study (WP5) is to develop a short survey focused on international scientific collaboration, and send it to the international stakeholders advisory board (levels 1) in order to receive their recommendations for the future scientific organization. This "institutional survey" will benefit from both the experience of the stakeholders' workshops organized in Bristol (2012) and Tucson (2013), and the contributions of all the SWAN partners (especially the documents established by the University of West England and the University of Seville teams for a common methodology). This survey will contribute to define a better strategy to develop the transatlantic dialog on water issues (see section 2.2.). In parallel, this new differentiated strategy will have to be connected with the research activities led by each team:

- Level 1 stakeholders: dissemination of the “institutional survey” to the Stakeholders Advisory Committee by the SWAN coordination and/or by each national team when they are already in contact with them.
- Level 2 stakeholders: collaboration with the national stakeholders which might be invited to the next stakeholders’ workshops, starting from Seville, June 2014.
- Level 3 stakeholders: participatory and interdisciplinary research process on the case studies as a way to implement dialogue between different research teams and stakeholders.

Table 1 (next page) shows the proposed list of members of the (1) International Stakeholders Advisory Board; (2) National Stakeholders and (3) Local stakeholders. Members of the different levels of stakeholders can coincide. Some were proposed from the outset. Only those stakeholders that have agreed to participate and who are already collaborating with SWAN are included in this list. It would be necessary to include names of specific people, not only institutions.

3.2. International Stakeholders Advisory Board: institutional recommendations

As we pointed out in the previous section, the International Stakeholders Advisory Board (Level 1) has to be questioned less about water issues than about the building of an international scientific organization. Valuable information will be obtained by questioning them about the viability, relevance and potential contributions of a new international scientific organization on water issues. Some of the key issues to be addressed are:

- How could a new centre/network improve the way in which they obtain water-related data and information, information analysis and practical solutions?
- What are the specific areas of water-related research areas that require more attention from the scientific community?
- How could a collaborative approach to scientific work between scholars and stakeholders from both Europe and the United States help improve water governance?

Table 1: Stakeholder classification proposal

Stakeholder level	Goals & responsibilities	Members	Team
LEVEL 1: International Stakeholders Advisory board	Advise on the structure, goals and operation of the Transatlantic Water Dialogue Network (TWDN). This consultation will be done either in writing, by phone, electronically, or personally by each member who will report back to SWAN.	Anne Le Strat, **Compagnie des eaux de Paris** Olivier Bommelaer, **OCDE** Pierre Bauby, **Association européenne du service public** Jean-Claude Deutsch, **Association des acteurs de la region Ile-de-France** Traci Case & Rob Renner, **American Waterworks Association**	CNRS
		To be determined	UA
		Mark Everard, **Environment Agency of Bristol** Patric Bulmer, **Bristol Water**	UWE
		Francesc La Roca, **University of Valencia & Foundation for a New Water Culture** Josefina Maestu, **UN Water Decade** Alberto Garrido, **Technical University of Madrid, CEIGRAM and Water Observatory of the Botín Foundation**	USE
		Geographica LTD	BAS-NIGGG
		To be determined	UNESCO-IHE
LEVEL 2: National Stakeholders	Advise on TWDN and on SWAN scientific output (Deliverables and research)	To be determined	CNRS
		David Brookshire, **University of New Mexico** Chris Scott, **University of Arizona**	UA
		Mark Everard, **Environment Agency** Patric Bulmer, **Bristol Water**	UWE
		Francesc La Roca, **University of Valencia & Foundation for a New Water Culture** Luis Babiano, **Spanish Association of Public Water Utilities**	USE
		Maya Drianovska, **Ministry of Environment and Water** Vanya Yoncheva, **National Institute of Meteorology and Hydrology** Albena Vatralova**, Bulgarian Water Association** Teodora Todorova, **Sofia Water** Veselina Kolesheva**, Geographica LTD**	BAS-NIGGG
		To be determined	UNESCO-IHE
LEVEL 3: Local stakeholders	Advise and comment on case study work both in TAMA and in partner research areas.	Ed Curley, **Pima Association of Governments** Claire Zucker, **Pima Association of Governments**	CNRS
		To be determined	UA
		To be determined	UWE
		Alfonso Cárdenas, **EMASESA** (Sevilla Metropolitan Area Water Utility) José Manuel Moreira, **Consejería de Agricultura, Pesca y Medio Ambiente** (Andalucía)	USE
		Ralitsa Kukova, **West Aegean basin Directorate** Kamelia Djanabetska, **Regional Inspectorate of Environment and Water, Veliko Tarnovo** Teodora Todorova, **Sofia Water**	BAS-NIGGG
		To be determined	UNESCO-IHE

This questionnaire also will explore questions on an innovative organization for a transatlantic academic training on interdisciplinary research of water issues. This training could be provided by European and American scholars, and it could lead to the institutionalization of a *certificate* implemented by the CNRS team inside the UA, with the contribution of the affiliated institutions of each SWAN partner. The academic activities (research, classes, etc.) led by the European visiting students and scholars in the UMI and in the UA would be recognized by their affiliated institutions. The training should also be supported by a digital platform, in order to facilitate communication between several international teams: the model of the MOOCS (Massive Open Online Classes), developed in several American universities, might constitute a new model to implement. Further discussion on the subject will take place during the SWAN progress meeting n°4 that will be held in Seville (Spain) in June 12th-13th, 2014.

3.3. Stakeholders Recommendations for the definition of scientific issues

The institutional level concerning the organization of a transatlantic dialog must include scientific issues to achieve the goals of the Feasibility Study. This level includes the stakeholders that each SWAN partner identified and contacted at the outset of the project. They contribute to the scientific work of SWAN, reviewing deliverables and other scientific outputs and participating in progress meetings. They can also provide feedback (via questionnaire or in person) to the Feasibility Study proposals. Given the financial constraints for stakeholders' mobility within the SWAN project (no allocated funds), they tend to participate in the Progress Meetings organized in each country.

3.4. Stakeholders Recommendations for the development of the local case studies

One of the most significant achievements of the SWAN Period 1 is the involvement of each team in a common case study in the Tucson area (Arizona). Students from the partner teams are recruited by the SWAN project as visiting scholars for several months at The UA. This activity, led by team 1 (CNRS) and team 2 (UA), presents several important added values:

- The case study allows linking the activities conducted inside the research Work Packages (1 to 4) by involving the partners in a practical, collaborative, and interdisciplinary work focused on water management in the local area.

- The idea of a research organization focused on the analysis of a specific case study can be developed as a basis for an international scientific collaboration, in order to bridge the gap between the recommendations of the stakeholders' committee, and the "science in practice" oriented on case studies.
- The case study initiated in the Tucson area opens new perspectives for the feasibility study, by presenting an innovative model of organization of scientific work between universities and research centres from EU and USA. This model is based on the exchange of students from different countries and disciplinary backgrounds and their collaborative participation to a common research.
- Until now, this common research has been led by scholars from the CNRS and The UA, with the participation of European students. What is at stake for the SWAN project is a stronger integration of all the other SWAN partners in this research activity, as it has been already initiated with the stakeholders' workshop on the Tucson case study in October 2013.
- The elaboration of other case studies in Europe, involving CNRS and UA scholars might be a way to strengthen the international scientific collaboration between the SWAN partners. However, it must be pointed out that SWAN funds are meant to support the visits of the European students to the UMI CNRS/UA leading to an asymmetric situation, so that additional funds should be collected in order to organize the case studies outside of the USA.

In the context of SWAN's 4th Progress Meeting, a Stakeholders' Workshop was organized at the UA in October 30th (see Stakeholder workshop report, Annex 2). Local experts, members of the UA academic community and SWAN researchers were invited to attend. The goals of the workshop were to identify key management challenges in the Tucson basin region, to evaluate and prioritize the pre-defined research questions, to identify knowledge gaps and propose new research questions, to map a list of relevant stakeholders for Tucson basin region and finally to propose a roadmap for future collaboration. Stakeholder participation did not meet expectations. However, the small turnout together with the presence of UA scholars with significant experience in the TAMA region, allowed for in-depth discussions of the different items proposed. Given the high level of satisfaction of meeting participants, a decision was made to approach future stakeholder interaction following the same model, that is, small groups of stakeholders that represent similar interests in order to allow for an open, frank and in-depth discussion of the different issues.

Stakeholders and researchers participating to SWAN identified a number of water management challenges in the Tucson basin, being some of them of common interest by both groups such as management of water demand under population growth and sustaining both human and natural systems with extremely variable water inputs. Other uncertainties like the shortages of water transfers in the CAP (Central Arizona Project) due to runoff decrease and the influence of changes in societal demand towards achieving safe yield were also remarked. In this framework, several gaps have been identified, and one of the main results of the workshop was the decision to prioritize some research questions about the emerging water management challenges in the Tucson area, the most adequate methodological tools to handle them and the major uncertainties for water management. Other research gaps that should be addressed are related to:

- Hydrology and water availability: impact in natural areas of changes in precipitation, water demand, land use, and water dynamics in TAMA system, environment and ecosystems water needs.
- Socio-ecological modelling: water management and urban needs, groundwater credit system, and connection of private well owners into water management.
- Institutional and policy analysis: format of water management in Tucson under the actual State laws and within the private/public providers' network, development of green infrastructures.
- Water food security and environmental justice: water needs for local food production, rainwater harvesting, and differences between communities.
- Communication between public and administration: institutional changes in function of water needs.
- Potential future pathways in water management and future uncertainty of the water availability.
- One of the main outcomes of this workshop was the mapping of relevant stakeholders for Tucson basin region that should be consulted for the case study.

Chapter 5

-Deliverable 5 (Supplement 1)-

Analyzing New Challenges for Water Management: An outline for a trans-disciplinary approach, based on a review of existing conceptual frameworks

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ABSTRACT/CONCEPT NOTE

This paper attempts to provide an innovative and holistic approach of the complex dynamics between society and its physical environment. Drawing from emergent and well established fields of study, it aims at integrating different paradigms looking at how society interacts with nature and at expanding the boundaries of understanding between science and management of water and land resources. The combination of physical science tools such as climate and hydrologic modeling with human-centric approaches such as ecosystem services, societal metabolism, water footprint assessment, institutional analysis of water management or social uses of water, allows for a transdisciplinary approach to water issues. The approach presented in this working paper builds on disciplines and schools of thought that have rarely been all connected and that could address questions to face new challenges derived from climate uncertainty and water crisis, and bridge knowledge gaps across management jurisdictions. In addition, research processes has to be confronted to an increasing demand of participation from stakeholders no only to decision-making but also to the definition of scientific questions. This paper discusses how the integration of different methodologies and analysis frameworks can help inform future management strategies in the ever-evolving relationship of societies with their ecological systems.

1. INTRODUCTION

This methodological paper is developed within the framework of the SWAN project: "Sustainable Water ActioN: Building Research Links between EU and US". SWAN is a four-year International Cooperation Project granted by the 7th Research Program of the European Commission. It focuses on the creation of a transatlantic dialogue on water, involving five universities and research centers of European Union Member States (Bulgaria, France, Netherlands, Spain, United Kingdom) and the department of hydrology of the University of Arizona. SWAN aims at bridging the gap between science and management by involving decision-makers, stakeholders and the general public in the research processes.

Since the 1960's, the "world water crisis" has generated many interrogations about the scarcity and quality of water resources confronted to population growth (Hardin, 1968; Report Rome 72 Sustainability). In parallel to the constitution of an "international community of water" supported by several world environmental forums since the 70's (Stockholm-1972, Club of Rome-*Limits to Growth-1972*; Johannesburg-2002; Dublin-1992; Rio-1992,2012), the notion of sustainability emerged as a paradigm for development and governance. The problems of sustainability of natural resources have been explained as a consequence of their governance models. New trends of research insisted on the study of management issues, norms and rules (Ostrom, 1990). Later on, the notion of sustainability has also been questioned as a technocratic paradigm along with the failure of the role of science as provider of technical solutions to the growing problems that societies face with their environments (Bakker, 2011). The growing concern on non-academic knowledge and democratization of science has been reflected in new institutional approaches to water management as the European Water Framework Directive in the beginning of the 2000's. But if various critics of the traditional function of expertise and of the links between knowledge and power have been formulated, the consequences on methodological issues haven't fully been analyzed. On that methodological dimension, studies have focused more on the problems of the relativity of knowledge (construction of scientific objects, critics of the notion of truth) than on the integration of disciplines and of "civil society" (Jasanoff, 2007).

This paper is a statement of intent for future integration of conceptual models as a framework for research. It aligns with the critics formulated to scientific expertise by "post-normal science" theory (Funtowicz & Ravetz, 1991, 1994), suggesting that the complexity of environmental issues requires new paths of knowledge production, incorporating multiple scientific, professional and citizen perspectives. Beyond the debate between fundamental and applied research, the hypothesis of a contribution of “democratic participation” to the scientific process leads to an analysis of the specificity of environmental issues: the complexity of water management necessitates a combination of approaches from physical, environmental and social sciences, opened and validated by civil society. However, using multiple conceptual metaphors does not necessarily lead to a better comprehension of human-environment relationship or decision-making support (Raymond et al 2013): the different methods have at least to frame a common scientific object. Modeling this object can be approached in different ways summarized in Box 1.

Box 1: Cross-disciplinarity (Rosendfeld, 1992)

Multidisciplinarity → Researchers work in parallel or sequentially from disciplinary specific base to address a common problem. The total result of the research effort appears as the sum of the partial efforts with a low level of further integration.

Interdisciplinary → Researchers work jointly but still from disciplinary-specific basis in interactive modes of operation in order to address a common problem. Integration efforts are given care and interest but not to the extent that the “input” competences have lost their specificities.

Transdisciplinarity → Researchers work jointly using shared conceptual frameworks that are specifically designed for the purpose of a particular research endeavor and drawing together disciplinary specific theories, concepts, and approaches to address a common problem.

Interdisciplinarity provides the possibility to keep the strengths of a discipline while enriching it with further perspectives and covering gaps in terminology, approach and methodology. This is why this paper presents an interdisciplinary approach attempting to integrate disciplines such as climatology, hydrology, and sociology with transdisciplinary methods such as Societal Metabolism, Ecosystem services and Water Footprint and Virtual Water, to create a holistic approach attempting to answer transdisciplinary questions that can inform water and land management and planning. Furthermore, the importance of transcending science borders is emphasized using the participation of both stakeholders as fellow researchers and direct users of science products.

This work is based on the hypothesis that the involvement of stakeholders can help bridge the gaps and frontiers between disciplines. As the key scientific challenge of the “Anthropocene” as a time where human activities highly impact natural systems (Revkin 1992, Crutzen & Stroemer 2000) is to analyze the relationship between society and nature (Becker 2010), this paper explores how our proposed holistic approach can go beyond existing frameworks to support water resources management and planning, as well as how it relates to current scientific paradigms.

2. BACKGROUND: MAN, WATER AND NATURE

2.1. Ecological challenges in the "Anthropocene": understanding the relations between societies and their environment

Last centuries witnessed an outstanding growth of human population, agricultural production and energy generation. This growth was feasible thanks to an increasing "control of nature" especially regarding water resources: the parallel anchoring of hydraulic science and engineering systems were able to deeply transform natural hydrologic regimes, buffer natural variability and enhance the social uses of water in space and time. Nonetheless, this has come at a cost where in many settings now "nature talks back" (Savenije et al. 2013). Still, facing the negative "reaction of nature" is not the only reason to realize changes in the management of environment. The technological revolution and the following development were turbulent events in human history, opening unimaginable opportunities, as well as increasing risks. Throughout the years, the knowledge on the environment increased significantly and brought the conclusion that intensive technological approach is a good way to manage environment, but it sometimes leads only to short-term solutions, which doesn't incorporate well with the target of sustainability. The science (and slowly policy) realized that the natural functions of ecosystems and their ability to self-regulate are just as powerful tools as technology in some cases and their combination, together with efficient management, can help us create more sustainable future and still cover the demands of the social system. This is also why conservation and biodiversity have found more broad recognition in policy and management during the last years.

The human interferences on the water cycle pose new challenges to the marriage of science and governance. Currently, about 2,600 km^3/year of freshwater is consumed by humans. The estimated planet boundary for freshwater appropriation is 4,000 km^3 (Rockstrom et al., 2009). Nevertheless, many major river basins (i.e. Nile River or the Colorado River) across the world suffer water stress, thus this threshold ignores the importance of local conditions and the role of management in magnifying or ameliorating problems (Molden, 2009). Agriculture represents 70% of total water withdrawal, used to produce food and feed cattle (FAO, 2011), and also embodies the most important driver of land use changes (Foley et al., 2011). With the current trend in population growth and richer meat dietary changes, some studies predict dissatisfied increases of food requirements. Meeting this future food demand can partly be achieved by strategic agricultural intensification, in terms of elevating yields of existing croplands of underyielding nations as long as not irreversible ecosystem damage is caused (Tilman et al., 2011). Additional land will also need to be converted into agriculture leading to environmental concerns such as biodiversity loss and carbon release (Scherr and McNeely, 2008; Gloor et al., 2012). Nowadays about 4 billion metric tons of food are produced per annum, but it is estimated that 30–50% (or 1.2–2 billion tones) of all food produced never reaches a human stomach due to poor practices in harvesting, storage, transportation and distribution, as well as market and consumer wastage (IMECHE, 2013).

In 2007, half of the world's population lived in cities, and this number is projected to be three out of five in 2030 (United Nations, 2007). The level of urbanization is expected to be approximately 70% by 2050 with the percentage increasing from 75 to 86% in developed countries and 45 to 66% in developing countries (UNPD, 2010). In the meantime, anthropogenic emissions altering global atmospheric composition reinforce regional mesoclimate regulation disturbances. Extreme climatic events are expected to be more dramatic under such changing environment (NRC, 2011). Huge urban areas characterized with high density of population and infrastructures usually serve as social, economic and political hubs. Consequently, this poses huge pressure on decision makers as urban areas are vulnerable to storms, urban floods, airborne diseases. In fact, in the past 30 years many of the major weather disasters have been in urban areas and cost billion dollars (NRC, 2012).

Urban expansion poses serious competition on already constrained freshwater resources and available land for agriculture. Intensification of agriculture and production of new water resources (wastewater reuse and desalination) as win-win solutions for this competition are so far only viable under cheap fossil fuels conditions. The transition from an energy system based on fossils stocks, with high power densities, to one based on renewable sources, with low power densities, sits a new competitor on the table (Schneidel and Sorman, 2012). Water and land for energy, for people, for food and for the environment; multiple stakes on finite resources.

In order to understand current and future environmental challenges, it is necessary to first understand the key drivers of the relationship of societies with their environment. The influence of available technology in the dynamics of human livelihood and the evolution of carrying capacities and sustainability of socio-ecological systems is at the center of the Malthusian and neo-Malthusian debates. Indeed, a number of technological revolutions have progressively transformed the ways in which the environment is regulated. As new technology influences the way that society interacts with the environment and new socio-economic structures evolve, new tools and perspectives may be needed to understand and assess human-natural interactions.

This discussion leads to the classical question: how much can global population grow until reaching critical biophysical limits? Concepts like planetary boundaries point at the necessity of quantifying these limits in relation to specific consumption and living standards patterns, and current technology. *Limits to Growth* - based on a system dynamics simulation of the earth's population growth and resource use (Meadows et al. 1972) – and *The First Global Revolution* (King and Schneider 1991) are some of the first modern efforts to understand this question. Nilsson and Persson (2012) argue that global boundary values would need to be reviewed and downscaled in order to gain the necessary degree of "*scientific certainty and political legitimacy*". As sustainability and resilience are site-specific concepts for local and regional scales, the analysis focuses where ecosystems hybridize with societal evolution and complex socio-ecological interactions take place. Given the existing technology, knowledge and practices, the specific socio-ecological systems – such as flood-recession agriculture in Senegal, or the complex engineered landscape of rice-farming in Bali – have their sustainable level of resource use, food production, and productivity. These are likely to change as the socio-ecological system evolves with new technologies, knowledge and social organization.

Thus, beyond the classical question of what are the "limits to growth", how much further can the malthusian vs cornucopian debate be carried forward? For how long will Simon-Ehrlich type of wagers lean in favor of Simon and the power of technological innovations? For how long will technological advances keep pushing the boundary of sustainability? Do socioeconomic dynamics truly depend on the environment, and under which time scales and spatial differentiations? And more importantly: How to analyze – while planning for the future – the current sustainability of resource use versus the influence of new technological advances and new knowledge?

It is necessary to reconcile past debates on the relationship between technology, economic development, social inequality and environmental impacts. An integrative perspective of the role of technology in water management is needed; from utopian and dystopian perspectives on technology as a driver of social progress or distress; through the evolution of constructivism and determinism debates since the industrial revolution; to the promises of "cyberfetichism" for social change and green growth economies as drivers of environmental preservation.

2.2. Water science for water management: scientific expertise questioned by democratic participation

One of the earliest forms of farming is flood recession agriculture, where valley bottoms are planted and cultivated as flood waters recede. The need to regulate access to a variable resource – the area of flooded, thus fertile, land – gave rise to the first complex social structures (Manning 2002; Lafont 2009), which provided mechanisms to ensure some sort of access to land for a range of social groups, given the extent of each year's annual flood and the consequent portfolio of fertile lands available for cultivation. This is one of the early contexts in which the concept of "management" emerged. Flood recession agriculture progressively permitted the existence of large urban centers and Empires in West Africa, Mesopotamia, ancient Egypt and China, as well as transcontinental trade routes (Palerm & Wolf, 1955). It has been argued that the socio-economic structures that developed with flood recession agriculture represent the emergence of social stratification at the institutional level, which led to the highly hierarchical societies and modern nation states in which we live (Park, 1977). The intense specialization of labor enabled by agricultural surpluses allowed for scientific advances that ultimately culminated in technological advances allowing a faster diffusion of knowledge (the printing press, 11th century in China, 15th century in Europe) and the industrial revolution in the late 18th century. The relationship with the environment was again dramatically changed.

Within this last technological revolution, the discovery of reinforced concrete and electricity allowed man to intervene the hydrological cycle in unprecedented ways. Since 10,000 years ago and the appearance of agriculture, only limited flows could be diverted with gravity diversion canals. Now, while dams, canals and pumps intercepted and re-distributed large surface flows within and across basins, rural electrification – a world-wide phenomenon in the mid 20th century – enabled aquifer pumping and the onset of what has turned out to be massive groundwater depletions. This newfound availability of water volumes allowed great economic and social development (growth of irrigated area and agricultural production, drought protection), but environmental impacts and ecological disasters also occurred. Associated chemical advances in pesticide and fertilizer products also led to the Green Revolution, mentioned earlier, which in some cases was a failure due to ecological collapses due to the lack of understanding of complex dynamics of socio-ecological systems (Lansing, 2012).

Since the 19th century, water resources projects and planning have been mostly based on economic impact evaluations. For example, the 1936 Flood Control Act required only that the benefit–cost analysis be positive for a plan to be deemed feasible, and subsequent documents consolidated the concept of “contribution to national income” as the preeminent water resources planning objective (Loucks et al, 1981). Consequently, economic objectives – measured through benefit-cost analysis – have dominated water resources planning in the United States, during much of the past century (from Serrat-Capdevila et al, 2014).

Addressing the need to regulate the intervening power humans on the hydrologic cycle, different paradigms such as Integrated Water Resources Management (IWRM), Resilience of socio-ecological systems and Water Security have emerged, shifted and evolved in the last few decades. These concepts represent ways of assessing how societies are embedded, thrive from, and interact with their natural environment or their ecological contexts. These paradigms originated within specific professional (researcher-practitioner) circles and may reflect their own sector specific perspectives, also obeying to social constraints and trends of the time.

Integrated Water Resources Management (IWRM) emerged as a new paradigm for decision-making in relation to water. This approach adopts the basin scale as the natural unit enabling water issues to be considered both in their broader context and through the more focused lenses of economic efficiency, social equity and environmental sustainability. IWRM can be defined as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). In general terms, IWRM aims at a management based on economic efficiency, environmental sustainability and social equity, with or through public participation. IWRM and its participatory planning approaches can be seen as the nuts and bolts of how to implement the concept of sustainability in water resources management at the basin level (ref. UNESCO IWRM Guidelines at Basin Level).

The Resilience or socio-ecological systems approach – arising from the new-ecology movement (Holling, 2011) – has been a rapidly expanding field in academia but its impact and its uses by management practitioners may not have kept the same pace. Even the more broadly used and appropriated term of adaptation and adaptive management is quite clear in its principles but its real-world applications seem to be discretionary and at the practitioner’s best guess.

Acknowledging that human and natural systems are linked and coevolve together, and that ecosystem response to human use is rarely linear, predictable, or controllable, there are three main characteristics of the "new ecology" movement: (1) the acknowledgement of uncertainty, dynamics, and complexity; (2) the exploration of nonlinear interactions across different-scale systems (and a more global approach to recognizing spatial patterns); (3) and a historical memory of systems and their temporal dynamics (Scoones, 1999). "Resilience" alludes to the capacity of a system to maintain its functionality, to recover and reorganize after a disturbance, and to adapt to change (Holling 2001). The term "adaptive capacity" can be interchangeable with "Resilience". Building resilient systems involves learning, the flexibility to experiment and adopt new solutions, and the ability to respond broadly to challenges (Serrat-Capdevila et al 2014).

Overarching these frameworks is the epistemology of how new information, research findings and understanding are generated, incorporated and operationalized within the structures and mechanisms of control that manage a system in order to "improve" the way that resources are extracted, processed, exchanged and allocated. Even paradigms can come with its owner (a professional or academic sector). What is considered "knowledge" and who does it legitimize? Sustainability and water security for whom and at which cost?

The critics of "normal science" have risen in a context of disenchantment with environmental management institutions, especially with the failure of climate change negotiations and the emergence of global markets as regulators overtaking national policies for environment. Throughout the last decades, the paradigm of "post-normal science" has been developed as an epistemological frame to cope with science limitations to deal with complex problems: "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1991). In science for governance, higher the uncertainty, more important is to separate descriptive and normative sides of scientific assessment: scientist are not the only ones with legitimacy to decide what is sustainable and what is not. Assuming the implications of complexity means assuming new ways of building knowledge and legitimizing narratives: scientists' role is to generate adequate information of sufficient quality to set the table for extended peer-community discussion (Giampietro et al 2006). Science as "truth" creator is challenged by voices of open and participatory science (Holm et al 2013).

These discourses have been translated in western science into practices of integrated assessment (REF) and social multi-criteria evaluation (Munda, 1995). On a different context, Participatory Action Research (Packham and Sriskandarajah, 2005) was developed in Latin American countries routed in community development and rural studies. Recent TICs innovations are also setting a new stage of participation in science through collaborative generation of data and information through social networking.

3. MANAGING WATER IN SOCIO-ECOLOGICAL SYSTEMS: TOOLS ON THE TABLE

The mission of water resources management and planning is to sustainably reconcile multiple demands and water supplies, which can be limited and variable in time and space. In many instances, management has focused on the supply side, with the development of new water sources to cover increasing demands. A few decades ago, demand management started taking an equally important focus in water resources management, with the development of mechanisms and incentives to cover the same necessities with less water. Water resources are also influenced by decisions in many other sectors to which management is intrinsically linked, such as land use planning and land cover change.

The notion of how much water supply can be used, and the natural ecosystems altered, without causing the environment to change or lose its existing functionality is at the core of the water management question. However, once we have taken the water out of the environment, we must also understand how we combine it with labor, energy and other resources to produce goods for well-being, and how we trade and consume these goods that have a specific water footprint. By the same rule, these goods also have an ecological footprint (botanic, biotic, biodiversity footprints as well as an ecosystem services footprint), a land cover footprint and thus a climate footprint. This section presents different disciplines and fields of study relevant to water management that can be interconnected together to provide a more meaningful and multi-faceted analysis to inform water resources management, policy, planning and use.

3.1. Physical sciences

3.1.1. Climate models

Climate models are essentially combinations of mathematical equations that represent different nature processes in the climate system. These processes include radiation on the earth surface, cloud physics, atmospheric and oceanic circulation, chemical cycles, growth of vegetation, etc. Atmospheric models with different resolution have different representation of these aforementioned processes, which in principle aim to reduce the complexity of the computation while ensuring the accurate representation. Initially climate models are built to study the physics of the nature and later on they have been used to generate projections showing consequences of different scenarios, for example, different CO2 concentration or radiation scheme which are likely the consequences of public policy making. Climate models are capable to predict weather only few days ahead of time, but their ability to make reasonable predictions of statistics of weather, i.e. climate prediction, is retained. Thus, climate prediction involves running climate models at least for several seasons and commonly for several years.

Downscaling is a method for obtaining high resolution data from relatively coarse resolution global climate data. Typically, downscaling involves statistical downscaling or dynamical downscaling. Statistical downscaling derives relationship between the small scale variables and the large scale variable using statistical methods, e.g. analogue methods, regression analysis, and so on. Dynamical downscaling using regional climate model process the coarse resolution reanalysis data in more physical way. It is an appropriate way to simulate climate conditions in the future. Reanalysis data refers to the coarse resolution climate data that could be extended even a century into future: it is a combination of observation and model data through data assimilation procedure that is usually done by large climate centers. Furthermore, with the evolution of urban expansion and other land use change, studying their effect also requires the use of regional climate model.

Obviously, the most relevant atmospheric variable in the context of water is precipitation. Extreme precipitation is projected to be more frequent in the future (Dominguez et al., 2013 D.1.1). This might lead to flash floods which will serious damage urban infrastructure and cost people’s lives. Moreover, in many other regions, precipitation serves as important source of water. It is important to understand the trend and pattern of precipitation in the future as well. Standing on a physical level of this integrated approach, regional climate model mainly provides the atmospheric conditions that later will serve as input to the following procedures; namely, precipitation, soil moisture data to hydrologic model for atmospheric and land water partitioning, extreme precipitation data as input to ecosystem service for flood regulation.

3.1.2. Hydrology

Climatic and meteorological data can be used, among other things, as input forcing to drive hydrologic models that simulate the partitioning of water through the physical system with a set of state variables (i.e. snow storage, soil moisture, aquifer storage) connected by flows (i.e. rainfall, evapotranspiration, infiltration, runoff, interflow, recharge, streamflow, baseflow, groundwater flow). As any models, hydrologic models reflect a limited understanding of the physical system; however, they can vary from being very simple to being very complex, they can be either spatially distributed or aggregated, and can be conceptual or physically based. Different sub-disciplines study different aspects of hydrology (physical hydrology, ground and surface water, vadose-zone, water quality, stochastic hydrology, etc.) and linkages with other disciplines and systems, such as for example eco-hydrology.

An integrative modeling approach, using models of different resolution and complexity that serve different purposes but inform each other through feedbacks (Liu et al 2008; Brookshire and Gupta, 2011; Brookshire, Gupta and Mathews 2012) can be used to help understand the feedbacks between hydrology, water management and other human interventions (such as land use change). Spatially distributed high-resolution models are adequate when it is necessary to accommodate in detail the processes in the physical environment such as the land-atmosphere partitioning of water and energy, the role of vegetation, the interactions between surface and groundwater hydrology, and the provision of ecosystem services. Medium and coarse-resolution models are typically better suited to modeling human interventions on the environment such as land use management, engineering infrastructure and its operation in terms of intercepting and moving water within the basin and across different uses. Medium-resolution models allow representing water allocation and re-distribution within the system, while coarse-resolution models can be used to describe socio-economic and institutional aspects of water management over the natural and engineered system, with a resolution at the scale of the sub-watershed (Liu et al 2008).

In addition to providing an efficient way to represent the coupled natural-human system, a major benefit of multiple-resolution modeling is that information and findings can be readily transferred across models and used for model refinement. Information regarding natural processes, climate change impacts and feedbacks in the natural system can be up-scaled to higher level models, while behavioral and policy feedbacks from the socio-economic and institutional models can be used to drive lower resolution models and to assess impacts on the natural system. The integrated modeling approach can also be the basis for Decision Support Systems, simplifying complex systems to maintain the key overall processes and feedbacks, allowing numerous scenarios to be investigated in an efficient manner to inform specific management questions (Serrat-Capdevila et al. 2009, 2013b).

3.2. Disciplines centered on planning and governance analysis

3.2.1. Spatial and water planning

Spatial planning has been defined in different ways among countries in Europe, but it can generally be referred to physical land use planning. The European Environmental Agency (EEA, 2012) defines it as the systematic assessment of land and water potential, alternative patterns of land use and other physical, social and economic conditions, for the purpose of selecting and adopting land-use options which are most beneficial to land users without degrading the resources or the environment, together with the selection of measures most likely to encourage such land uses. Land use planning may be at broad levels such as international, national, district (project, catchment) or large urban agglomerations, and at local level such as villages. It includes participation of land users, planners and decision-makers and covers educational, legal, fiscal and financial measures (FAO/UNEP, 1998).

Experience in recent years in Europe shows that without the integration of water management measures into the process of land management and management of settlements development, both sustainable and efficient use of water and flood prevention cannot be achieved. European Water Framework Directive (WFD) tries to reinforce links between Spatial Planning and River Basin Management Plans (RBMP) but these connections are still weak (Woltjer, Al, 2007, EEA, 2012). Spatial planning can help to deliver River Basin Management Plan objectives by checking that proposed development does not cause deterioration of water bodies, ensuring that the scope of Sustainability Appraisal/Strategic Environmental Assessment for spatial plans includes impacts on water bodies, respecting the limits of the water environment when generating development options, and adopting spatial plan policies that will help to achieve ‘good status’ in water bodies.

In the United States of America Spatial, Planning is recognized as Comprehensive Planning. Accordingly with state laws (Arizona) and American Planning Association (2002), a Comprehensive Planning (local\regional) means the adopted official statement of a legislative body of a government (local\regional) that sets forth (in words, maps, illustrations, and/or tables) goals, policies, and guidelines intended to direct the present and future physical, social, and economic development that occurs within its planning jurisdiction and that includes an unified physical design for the public and private development of land and water. Sometimes comprehensive plans are known by other names including master plan, general plan, regional area plan and local government plan. For most of the places in the United States, it is the only planning document that considers multiple programs and that accounts for activities on all land located within the planning area (whether that property is public or private) (Kelly, 2010). In order to integrate Water and Comprehensive Spatial Planning, one needs to take into account the big diversity of the river basins in the European countries and in the United States.

Spatial planning has an important role to provide future scenarios as well as historical, institutional and territorial context to our methodological integrative effort. Coordination between water and spatial comprehensive planning can be the basis for the integration with all sectors planning. A Territorial Comprehensive Model and its strategic visions and goals can provide new scenarios in which to contextualize water management. More effort is needed to link spatial and water planning, and an integrative approach could provide a foundation for evaluation of the plans progress towards its desired objectives as well as monitoring territorial and social changes. Carter (2007) and the EEA Technical Report (2012) present a significant review of case studies and highlight potential synergies and obstacles for the integration of Spatial Planning and River Basin Management Plans in Europe.

On one hand, potential synergies include long term strategic focus and large areas, influences on a broad range of economic sectors that affect water consumption, pollution and impacts on water bodies, influences on the type and the location of new polluting or water use activities. Spatial Planning can incorporate water management goals, for example efficiency improvement measures in new housing developments at the local scale. Some dimensions of spatial planning are intrinsically linked to water, such as environmental assessments, flood risk management (2007 European Commission Floods Directive) and drought planning. On the other hand, potential obstacles in most European countries come from different focus on water, such as efficiency and restrictions in spatial planning versus requirements for the health of water bodies and the environment. Separated institutions, different administrative structures, and management traditions, are historical conditionings for a lack of connectivity. The differences between the boundaries of spatial planning (administrative) and river basins and aquifers, as well as the different timescales of planning horizons, the lack of shared knowledge and sufficient resources are all obstacles to integration.

Hartfield et al (2014) present an interesting collaborative academic-practitioner perspective of the dynamics of water supply and sanitation infrastructure and urban growth using spatial analysis from remote sensing observations and information from water utilities. Using advanced classification techniques, they create a multi-temporal (1984-2010) view of land cover change along the Tucson – Phoenix rapidly growing urban corridor. These classifications created multi-temporal maps of changing urban residential, urban commercial/industrial, agriculture, roads, bare ground, natural desert cover, riparian, and water. These data were then integrated into an ongoing analysis of changing urban and water policy and allocation within the region which provided an enhanced ability to evaluate the correlation of water availability and use, socio-economic drivers, and the direction and magnitude of land use/cover change.

3.2.2. Socio-technical systems and water governance

The study of water networks has been mainly focused on urban areas, following first studies on large socio-technical systems (Mayntz, Hughes, 1985) such as electricity (Hughes, 1985), transportation or gas (Tarr, Dupuy, 1988) in differentiated societies. These works produce an approach of territories which presupposes a static state of natural resources (watershed), and which is focused on the development and the management of the utilities (contracts, costs, urban governance, etc.). This approach consists in case studies of regional areas or, more frequently, city concessions: in a context of globalization, the research study the local markets of water, the consequences of privatization of the services (as part of a larger reform of the states), and urban management of the networks (Barraqué, 1995; Jaglin, 2001; Meublat, 2001; Schneier-Madanes, 2003). The urban monographs are mostly related to the impacts of national public policies (Barraqué, 2005), but they also describe the mobilizations of users to get back to public services. This approach of water networks permits to build the notion of socio-technical services that reveals to be very useful to understand the problems of water networks in urban areas.

Since the 1990's, this approach has focused on the processes of privatization of water services. The implementation of contracts based on European (and mainly French) models has been used to study the emergence of a "global governance" of water that should have brought technical and economical solutions to the needs of developing countries. However, the many social conflicts that led to remunicipalization of water utilities have also become a growing source of interest since the 2000's and the rise of international protests against the power of private companies. They have limited the studies on the legal dimension of the contracts, without giving sufficient attention to the social contexts of their application.

3.3. Frames of analysis of the interactions between ecosystems and society

3.3.1. Ostrom approach to Social-Ecological Systems

Social sciences have studied environmental issues from several perspectives: the perception of environmental problems, the analysis of decision making, the emergence of environmental justice or the construction of energetic and hydrologic networks. However, they have not paid much attention to the way social structures interact with ecosystems, and they have tended to develop simple theoretical models instead of taking into account the relational dynamics of human and natural worlds. Moreover, most of social science studies about water are focused on the way that socio-technical systems are built, on their management and their failures (with an important literature on the conflicts against privatization of water). One of the main challenges for social sciences is thus to bridge the gap with the natural/ecological conditions of water management (Martinez Allier, 2008).

An attempt to integrate natural/environmental sciences and social sciences has been developed by Elinor Ostrom (2009) in her writings about the sustainability of “Social-Ecological Systems” (SESs). SESs are composed of multiple subsystems (Figure 1) and internal variables within these subsystems at multiple levels. She shows that the “core challenge in diagnosing why some SESs are sustainable whereas others collapse is the identification and analysis of relationships among multiple levels of these complex systems at different spatial and temporal scales”. The analysis of SESs requires knowledge about specific variables and the relations between their component parts, which may be the separate objects of different disciplines, with different frameworks and models used to analyze their parts of the complex multilevel whole. A common, classificatory framework is thus needed to facilitate multidisciplinary efforts toward a better understanding of complex SESs.

Ostrom presented a multilevel framework for qualitative analysis of outcomes achieved in SESs: four interrelated first-level core subsystems of an SES that affect each other as well as linked social, economic, and political settings and related ecosystems (Cf. box 1). The subsystems are: (i) resource systems (e.g., a designated protected park encompassing a specified territory containing forested areas, wildlife, and water systems); (ii) resource units (e.g., trees, shrubs, and plants contained in the park, types of wildlife, and amount and flow of water); (iii) governance systems (e.g., the government and other organizations that manage the park, the specific rules related to the use of the park, and how these rules are made); (iv) users (e.g., individuals who use the park in diverse ways for sustenance, recreation, or commercial purposes). Each core subsystem is made up of multiple second-level variables (e.g., size of a resource system, mobility of a resource unit, level of governance, users' knowledge of the resource system), which are further composed of deeper-level variables.

A FRAMEWORK FOR SESs, BY ELINOR OSTROM

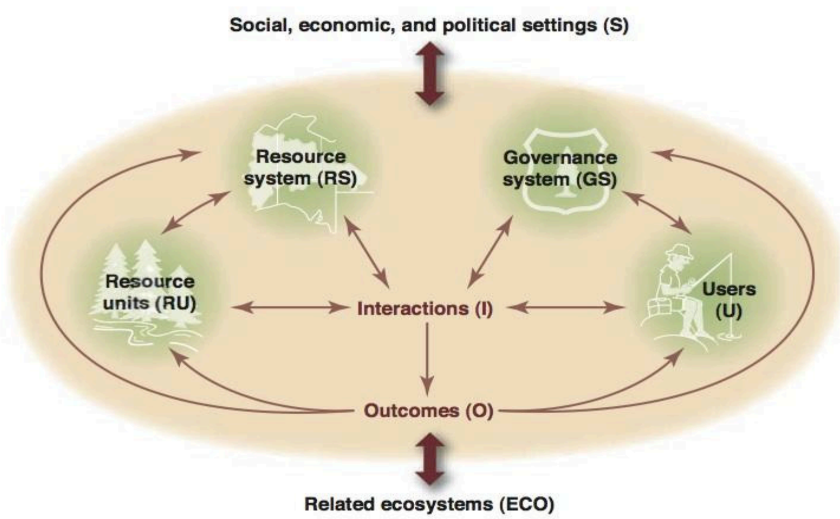

Figure 1. The core sub-systems of Elinor Ostrom's framework for social-ecological systems analysis (Ostrom, 2009)

This framework is useful in cumulating knowledge from various areas of research, and providing a common set of potentially relevant variables in order to collect data, conduct fieldwork or analyzing findings of various SESs. This model implies measuring variables and their interaction in order to study the relevant problem. It goes beyond an institutional analysis, by showing that the inequalities of access to utilities are not linked to "natural" demographic tendencies or to scarcity of natural resources, but to the effective management of natural resources and the economic models of their distribution. It allows the development of a sociological approach integrating the socially differentiated uses of water, in function of local contexts, urbanization trends and community lifestyles in relation with the structure of economic activities and of residential demands, etc.

However, the SESs model does not pay much attention to other important dimensions of social contexts and practices, especially to the neighborhood mobilizations for utilities, and to the socio-environmental conflicts they might generate. Many laws and norms promulgated to regulate water services are the product of conflictive processes where different lobbies act to reinforce their interests and legitimate them on a legal level (a dimension ignored by the SES model). The many environmental conflicts that have taken place in the Americas since the 19th century have been the object of numerous studies (Watson, 1993; Espeland, 1998). Water Wars in the West of USA, constitute a key field of research in terms of understanding the social conditions of water management, and especially the relations of power and the imposition of a vision of the world and of the good ways of administrating it, in conformity with the interests and way of life of dominant classes or groups of interest. As demonstrated by research published by Cronon, Worster (1985) or Riesner (1986), the West of the United States can be analyzed as a hydrological society fashioned by power relations and how hydrological imperatives have structured natural and human spaces. Pincetl (2011) shows as well that the appropriation of natural resources and their transformation into material goods (water to drink, food, etc.) is effectuated through institutional arrangements organized in certain patterns; each regime of accumulation entails a mode of nature appropriation that produces a dynamic resource landscape. The example of water projects in California highlights the difficulties to produce water sustainability, due to potential impacts of climate change on the hydrologic cycle, and to intensive urbanization (80% used by agriculture and demographic pressure to re-allocate water to urban areas).

One of the tasks of social sciences is to identify the different levels of regulation of water management: if in the American West, water is regulated by federal institutions since the 1902 Reclamation Act (water is considered as common good but agriculture is for the privileged user), one has to take into account the relations between federal regulation and the management local water districts. The water wheeling from Colorado River to San Diego County in California, for example, illustrates the transfer of the resource to urban areas by the commercialization of water, initiated not by the market but by the state. This process of "re-regulation of the social metabolism of nature is highly contingent of local variables" (Pincetl, 2011), especially of the local conflicts between the rural users and the urban water wholesalers, and of the power of local economic entities.

3.3.2. Ecosystem services

The topic of ecosystem services (ES) has attracted significant attention in the last decades. There are several national and international ongoing research initiatives in the field of ES such as MA (Millennium Ecosystem Assessment), TEEB (The Economics of Ecosystems and Biodiversity), IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services), RUBICODE (Rationalising Biodiversity Conservation in Dynamic Ecosystems), etc. (Burkard et al., 2012a, de Groot et al., 2010). The definition of ecosystem services to which we refer in this paper is from the 'Salzau Message' on Sustaining Ecosystem Services and Natural Capital (2010): "ecosystem services are the contributions of ecosystem structure and function - in combination with other inputs - to human well-being", where the "combination with other inputs" refers to the anthropogenic inputs in the natural systems which nowadays have increased considerably due to the technological development of humanity. The point is that ecosystems, ecosystem functioning, and ecosystem services are being threatened and degraded by human activities, and the situation will be exaggerated by climate change and biodiversity loss (Burkhard et al., 2012a).

Ecosystem services concept is an approach that integrates analysis of the ecosystems' functions and the benefits people derive from them. It studies the human-environmental systems in a manner that provides qualitative and quantitative data that is crucial for the better understanding of the consequences of human activities on nature and humanity. Its analysis methods develop in a way that provides more efficient and comprehensive data on the interactions between these systems. The approach gives the opportunity for identification, quantification and assessment of the ecological and socio-economic trade-offs and synergies on which decision-making should be based (Burkhard et al., 2012a, 'Salzau Message').

The classification of ecosystem services is structured in three main groups: provisioning, regulating and cultural. Some of them, such as water flow regulation (regulating) – maintaining of water cycle features such as water storage and buffer, natural drainage, flood regulation, irrigation and drought prevention,, water purification (regulating) - the capacity of ecosystems to purify water from sediments pesticides, disease-causing microbes, and freshwater (provisioning) - used freshwater for drinking, domestic use, irrigation, industry, etc. (Kandziora et al., 2013), are directly related to the water resources - water-related. Those are the services that contribute to water quantity and quality in certain time and location. Watersheds' borders are accepted to provide an appropriate spatial scale for analysis with focus on the water cycle, being functional entities. Furthermore, there is a big list of other services that are directly dependent on water resources, such as for example food and energy provision, local and global climate regulation, recreation. The trade-off analysis on different services for a certain area may be useful tool for decision-making.

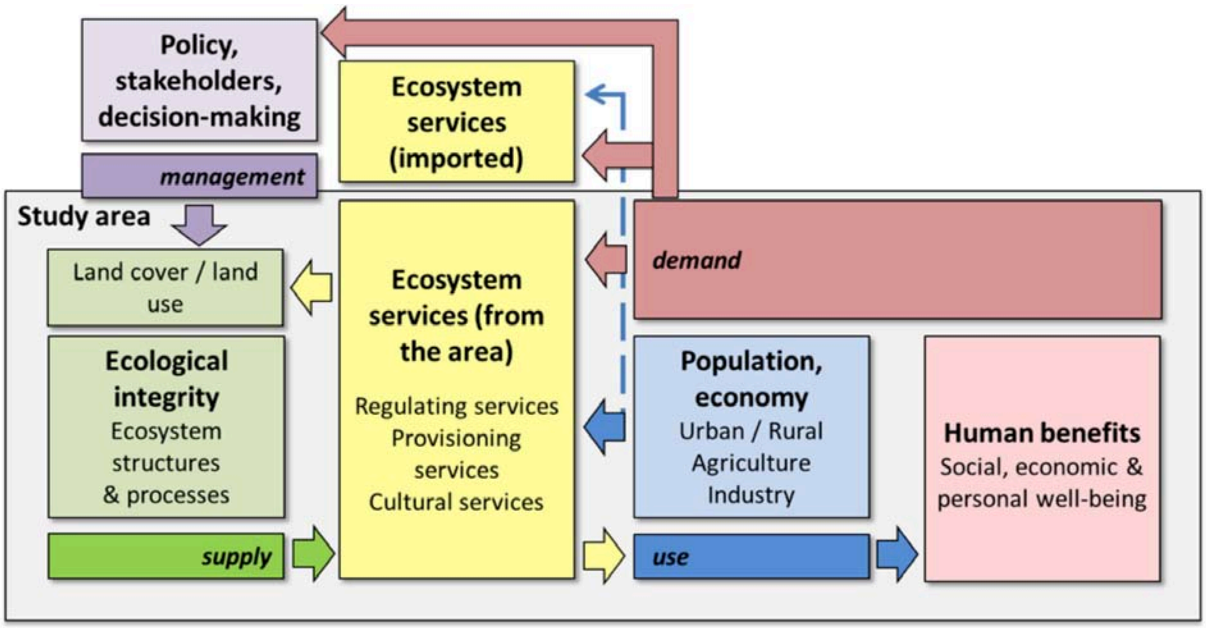

Figure 2. Conceptual framework linking ecosystem integrity, ecosystem services and human well-being as supply, use and demand sides in human–environmental systems. Adapted after Burkhard et al., 2012b.

The *supply* of ecosystem goods and services is assessed on regional level and it refers to the capacity of a particular area to provide a specific bundle of ecosystem goods and services (Figure 2). The *capacity* is the actually used set of natural resources and services that is generated in the area. Therefore, an ES supply map for a certain region visualizes only the provided goods and services that are generated within the borders of the same region – the flow of service within the ecosystem. For the provisioning services there is very often also flow of services from outside the ecosystem (e.g. food provision), while many regulating services on regional level cannot be transported, thus ES providing and benefitting areas have to be physically connected (e.g. flood regulation). The supply is directly determined by the regional ecological integrity of the ecosystem and the structures and processes within it, which are strongly influenced by human actions and decisions such as land cover change, land use and technical progress. Because of this, land cover/land use classifications provide appropriate reference unit for ecosystem service assessment and application in decision-making. The *used* services are the one that are currently consumed in a particular area, but not necessarily supplied by it. Human well-being depends on the benefits derived from the actual use of ecosystem goods and services (Burkhard et al., 2012b). The *demand* for ES is the requirement for optimum realization of a specific activity.

For example, in the case of freshwater provision service, *used* water is the total volume of water that an activity, sector, consumer, etc. receives. The transportation water losses should be excluded: use = abstraction - transportation water losses. The *supply* of freshwater ecosystem service is the volume of used water that comes from the region. The demand for freshwater service refers to the requirement for optimum realization of a specific activity, sector, consumer, etc. (for instance water requirements for crops). The quantitative assessment and mapping of supply, use and demand for a certain area provides visualization and quantitative measure of ES flows (through supply and use maps for an area), critical areas (where demand exceeds use indicating lack of services) and dissipate areas (where use exceeds demand, indicating overconsumption).

Moreover, ecosystem services analysis can help clarifying modeling or other kind of quantitative data, making them more accessible and understandable for practitioners and policy makers. Quantifying, modeling and mapping ecosystem services have become major issues for the ecosystem service concept's application. Mapping is a good tool for representing spatial data, as maps are perceivable and intuitive. The European Union's new Biodiversity Strategy to 2020 puts the task on its member states to map and assess ecosystem services on national levels until 2014. The resulting data will be used for assessing the economic values of ecosystem services and their integration into the European Union's and national accounting and reporting systems by 2020. This is a big challenge for scientists and decision makers.

Methods for quantification of water-related ecosystem services are many and diverse. The assessment can be based on results from hydrological modeling (Nedkov & Burkhard, 2012) or other quantitative methods (Kroll et al., 2012), ecosystem services modeling – InVEST, ARIES, etc. (look: Vigerstol & Aukema, 2011), analysis of spatial and statistical data (Kroll et. all, 2012), expert valuation (Burkhard et al., 2012b, Burkhard et al., 2009), participatory approaches – interviews, participatory mapping, etc.

3.3.3. Societal Metabolism

Grounded in complex systems theory, the societal metabolism concept refers to the processes of appropriation, transformation and disposal of energy and materials in order to sustain a given identity of a socio-ecological system (Martinez-Alier and Schlüpmann, 1987, Giampietro et al 2011). These are considered as hierarchical systems (Ahl and Allen 1996) operating at multiple levels of organization and thus multiple spatial and temporal scales. Societal levels perform at shorter temporal scales framed by wider ecological context. Ecosystems pose the external constraints to societal metabolism, since certain thresholds of ecological integrity cannot be surpassed if the whole system is to be maintained (Madrid et al 2013). Institutional and political organization pose the internal constraints, since they express the desirability of specific metabolic patterns (behavioral patterns of the systems in terms of resources use to maintain their structure and functioning). These constraints show themselves as non-linear interactions along multiple scales. In the case of water, several hierarchical levels need to be considered for a holistic analysis of water metabolism: the water cycle, the ecosystems, the society and the interface between them, the social management of water availability.

The Multiscale Integrated Analysis of Societal and Ecosystems Metabolism (MuSIASEM) has been developed (Giampietro and Mayumi 2000; Giampietro et al 2009, 2011) as a multicriteria quantitative analysis of metabolic patterns for wider integrated assessment of sustainability (Giampietro, Mayumi and Munda, 2006). Based on the flow-fund model (Georgescu-Roegen, 1971), it moves forwards in the conceptualization of natural resources as stock and flows, introducing the concept of funds as variables representing the identity of the system and thus having to be maintained by the use of flows. Fund variables (those remaining the same in the representation) describe the structure and size of the system while flow variables (those changing in the representation) describe its functioning. The combination of these two dimensions generates metabolic indicators (flow/fund intensity ratios of resources use). These variables are quantified from lower levels (individuals, specific economic activities) until the whole social system that interacts with wider levels indicators of ecological performance. Water is considered a flow for social systems, because it provides services to multiple activities, and a fund for ecosystems, because it is the pattern of water availability on earth what shapes ecosystems distribution and if ecosystems identity is to be maintained this pattern has to be stable.

The relevance of MuSIASEM is the capacity to integrate information coming from non-equivalent descriptive domains (different models from different scientific disciplines at different scales) regarding a variety of context-specific relevant variables: energy, water, land use, economic performance, and to check the feasibility of policy scenarios in terms of internal and external constraints. If MuSIASEM was originally designed to analyze agroecosystems (Giampietro, 2003), many applications have been developed for rural systems and poverty analysis (Serrano and Giampietro 2009, Arizpe, Giampietro and Ramos-Martin, 2011, Scheidel, 2013). A second chief line is energy use analysis at macroscale (Ramos-Martín et al. 2009, Giampietro et al 2012, Diaz-Maurin and Giampietro 2013, Sorman and Giampietro 2013). Its application to water use (Figure 3) is a more recent branch (Madrid and Cabello 2012). Current studies are being undertaken at local (urban), regional (river basin) and national (economy-wide) levels. For these purposes, specific integrated sets of indicators have been developed including Water Use Rate (WUR m^3/hour of human activity), Water Use Density (WUD m^3/ha of land used), Water Monetary Productivity (WMP €/m^3 of water supplied), Water Energy Intensity (WEI Kwh/m^3 of water supplied), Ecosystems Water Requirements (EWR ha of land/m^3 of water or million m^3/year for aquatic ecosystems).

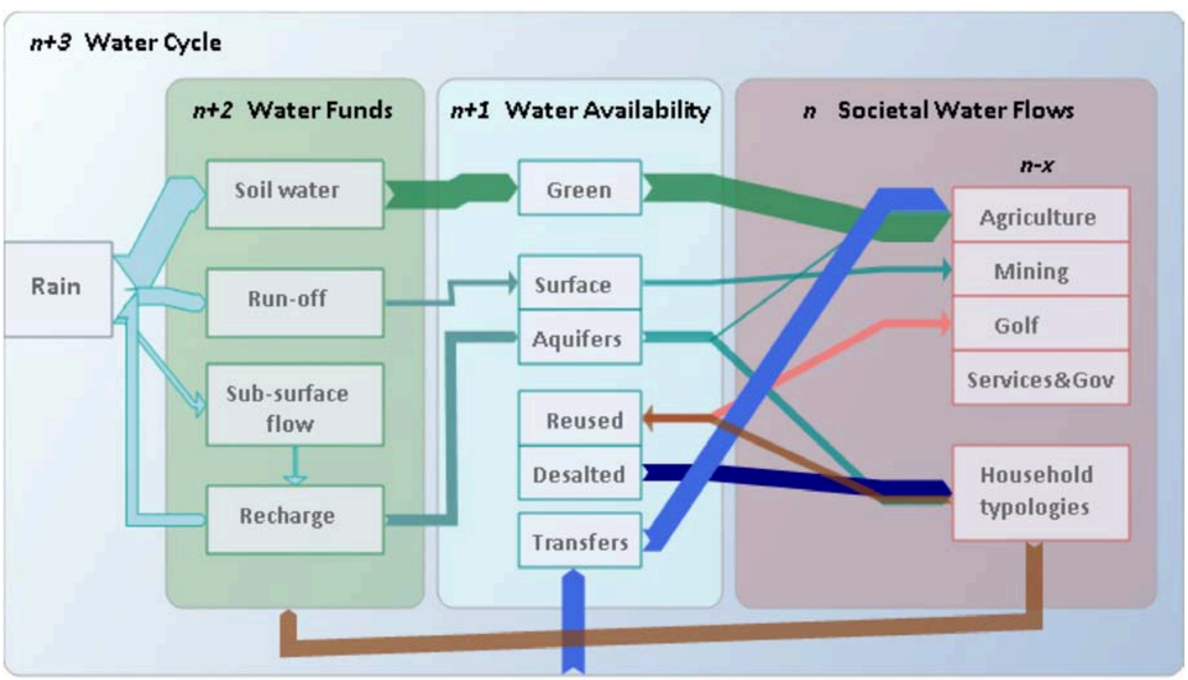

Figure 3. Framework for multi-scale analysis of societal and ecosystems metabolism of water.

3.3.4. The Water Footprint and Virtual Water Trade

The virtual water is defined as the water embedded in agricultural products, which generates a "virtual" flow of water through trade of these products (Allan 1997; 1999). Virtual water trade is seen as a new perspective to achieve an integrated water resource management, particularly for water scarce regions. Authors have claimed that drought effects can be mitigated (Allan, 1999) and the unequal spatial distribution of global water resources can be compensated (Islam *et al.*, 2007) by virtual water trade. Nevertheless, the virtual water trade cannot be used alone as a criterion for selecting optimal trading strategies (Wichelns, 2010). Some authors vindicate that the discourse promoting both the concept of VW and the methodologies used to estimate VW flows is structured according to some underlying ideas that are framed within market logic and the rationality of international trade (Velazquez et al. 2011).

Related to the concept of virtual water, the water footprint (WF) analyses the appropriation of water resources by human societies and computes only the consumptive, or non-reusable, water associated with a specific use or process (Hoekstra et al., 2011). The main strength of this tool is to show the weight of consumption patterns and global dimensions in water governance, although it also requires to be complemented with additional analysis or indicators in order to achieve integrated policy options (Vanham and Bidoglio, 2013). Studies have addressed the WF of a variety of crops and food products such as olive oil (Salmoral et al., 2011a) and sugar-containing water beverages (Ercin et al., 2010), populations within nations (Chapagain and Hoekstra, 2004; van Oel et al., 2009) or other geographical areas such as watershed level (Dummont et al., 2013).

Three water color components are distinguished in the WF assessment: 1) the blue water (surface and groundwater) , 2) the green water (rainwater stored as soil moisture), and 3) the grey water footprint that refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Traditional water planning has been focused on blue water although it has been argued that this conventional approach is incomplete towards more integrated water and land policies (Falkenmark et al., 2006), since green water comprises a critical role in food production and support for terrestrial ecosystems. Beyond water accounting, other authors (Garrido et al., 2010; Salmoral et al., 2011b) provide an "extended" WF calculation including economic indicators for irrigation water (€/m^3) and agricultural land productivity (€/ha), which are in the same line as indicators used in MuSIASEM methodology.

The WF of a delimited geographic area (i.e. catchment area) can be studied from different perspectives. The *WF of consumers* in the catchment comprises the internal water consumption from products and services generated in the catchment, plus imported virtual water. Looking only at the imported virtual water, one can determine how dependent on imports a region is, particularly for food, and highlight environmental and economic implications at the production site. The *WF within the catchment* includes the internal water footprint plus related virtual water exports. The analysis can be done with a top-down approach, based on production and trade data, or bottom-up approach according to direct consumption data. A further overview is the integration of the *WF within the catchment* in hydrological modeling (Salmoral, 2011). This procedure allows for distinguishing water storage and consumption with spatial and temporal resolution. An example of summarized results of the WF within the hydrological cycle are shown in Figure 4.

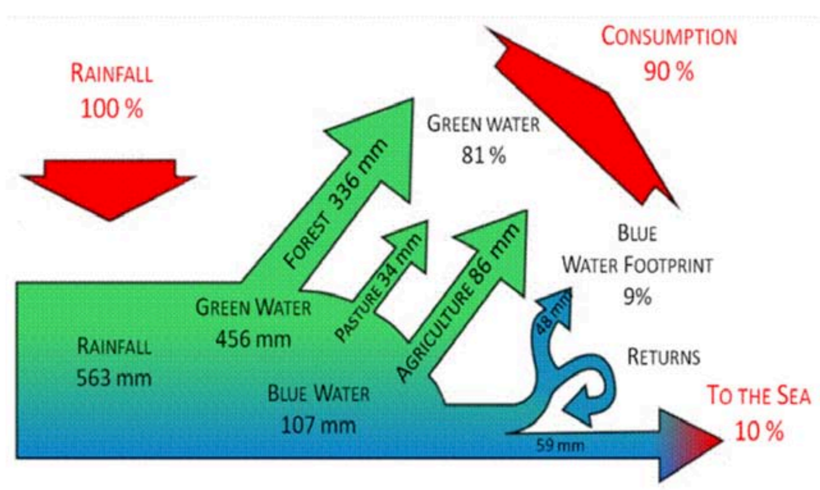

Figure 4. The WF within the hydrologic cycle (inspired by Falkenmark, 2009). Values correspond for a normal climatic year. Source: Salmoral et al. (2011).

At river basin scale, the blue and grey WF components can be called environmentally sustainable when they do not have negative impact on environmental flows and standard water quality of the rivers (Ridoutt and Pfister, 2010; Hoekstra et al., 2011). The Environmental Flow Requirement (EFR), in particular, represents an amount of water that is kept flowing down a river in order to maintain quality, quantity and temporality required for environmental goals, taking into account what local people uses for the river and what river condition is acceptable from them (O'Keefe et al., 2009). This could also be applied on groundwater comparing the actual water abstractions in relation to the natural aquifer recharge. The positive evaluation of the blue WF depends on the reference flows established for the basin or if the blue WF values are less than blue water available for consumptive water use. The assessment of grey WF, in turn, considers the pollution level occasioned by the point/non-point sources, comparing the river dilution capacity, represented by the total river discharge, and the grey WF values estimated for specific water quality standards (Hoekstra et al., 2011).

In this way, spatially and temporally assessment of WF components against environmental indicators allows the identification of hotspots, which refer to a period of the year (e.g. dry period) and a specific sub-basin, when quantitative or qualitative water requirements are violated. Consequently, the hotspots are likely to present problems of water scarcity or conflicts and can be useful for the basin management (Hoekstra et al., 2011, 2012).

4. INITIAL TIPS FOR METHODS INTEGRATION

This section discusses how the effect of human demands can be successively tied to demands on ecosystem services, to water budget components, to hydrologic processes and functions, to climate, and finally to feedbacks between climate and land use cover, which again is strongly influenced by spatial planning and social uses of water. In other words, we describe a potential integration of the previously described approaches in which each methodology poses feedbacks from/to the others, not only between variables and indicators but also between concepts. This integration will help to understand the synergies and overlaps among them. Combining physical and water-centric modeling with social sciences, the goal of a transdisciplinary and integrative methodology the quantitative and qualitative research required for a meta-framework of analysis of water management in socio-ecological systems (Figure 5).

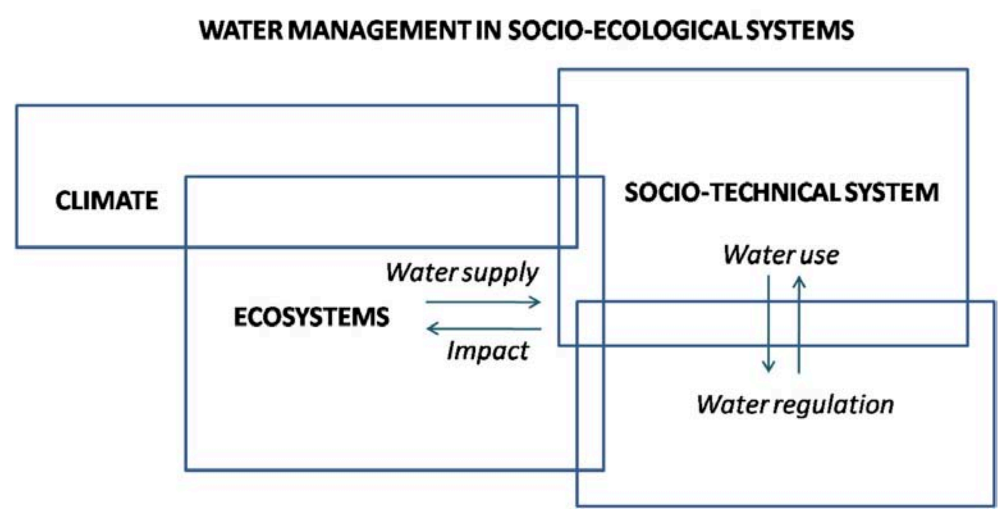

Figure 5. Simplified Conceptual framework for integration of approaches

In this integrative effort, atmospheric and hydrologic modeling provide information regarding the functioning of the physical environment. Atmospheric variables such as precipitation, specific humidity, snow cover, etc. are basic input data to run hydrologic models to generate hydrologic outputs (i.e. actual evapotranspiration, streamflow, groundwater recharge, soil water content). This data is important to relate water availability changes to human well-being. By processing climate change projections through hydrologic models (Rajagopal 2011; Rajagopal et al 2011, Serrat-Capdevila et al. 2007, 2011a, 2013a), future hydrologic states under climate change conditions can be generated. These can be used for water management purposes such as drought planning, development of water supply planning scenarios, connections to agricultural and other use activities, and evaluation of management options that optimize flood protection and water availability.

Hydrological models generate quantitative data with spatial and temporal scale, and in some cases qualitative characteristics of the hydrological attributes and the ability of hydrological systems to supply ecosystem services. Therefore, models can provide detailed hydrological assessments as long as appropriate input data and expertise are available (Vigerstol and Aukema, 2011). The ecosystem services assessment allows managers to have easy access and comprehensive information during decision making about land use and water related services (i.e. visualization of flood control areas by level of flood risk). Comprehensive sets of indicators are needed for integrated assessments, and they need to be selected systematically in order to reflect ecosystem properties, ecosystem functions and ecosystem services, as well as to represent land management as a main driving force for land use change (Burkhard et al., 2012a). Deriving and choosing appropriate indicators from hydrological model results is needed in order to properly quantify water-related ecosystem services. The indicators are chosen depending on the ecosystem services that have been quantified. For example climatic indicators (i.e. precipitation, temperature, albedo, etc.) provide information regarding the ecosystem service *local climate regulation*. Potential indicators for *water flow regulation* are groundwater recharge rate (mm/ha*a), infiltration (mm; m3/km), runoff (mm; m3) and peak flow (mm/hr; m3/s). For *water purification* different water quality indicators: sediment load (g/l), total dissolved solids (mg/l), N (mg/l), P (mg/l), etc. *Provisioning ecosystem service for freshwater* is account with withdrawal of freshwater (l/ha*a, m3/ha*a) (Kandziora et al.,2013).

The approaches for studying the demand for ecosystem services are much less developed than the ones for supply. In this sense, societal metabolism and water footprint assessments provide much better understanding on this side of coupled human-environmental systems. The ecosystem services framework is suitable to connect ecosystems' water-related services to societal metabolic demand of those services. A complete MuSIASEM scheme for water requires the integration of both eco-hydrological and climatic data to describe upper levels of ecosystem metabolism (ecosystems water requirements on the supply side, ecological status of water bodies on the sink side). The different water flows taken from the ecosystems will be followed through the social structure using demographic, labor and economic data in order to assess how these are combined with labor and other resources to produce goods and well being. Water planning scenarios can be used to assess different trade-off solutions for a sustainable balance between human-use and ecosystem health. Institutional configuration of water rights and management plans is essential for a proper definition of the constraints of each scenario.

Green and blue WF figures for agricultural and natural areas will vary based on precipitation and evapotranspiration data gathered from climate models. The water accounting in WF determines the water appropriation of main water users: agriculture, urban, industry and tourism. The assignation of green water for human appropriation is more complicated. In parallel to human activities, land use associated to green water consumption sustains agricultural and natural areas. The repartition between human and ecosystems uses, basis for the WF definition, is even more complex with the ecosystems service concept, since the multiple values for humanity generated by ecosystems could finally be considered also as human appropriation (Dummont et al., 2013). For the integration of the WF analysis in the hydrological cycle, the total available volume of blue water in a watershed comprises the definition of available water resources by the traditional hydrological planning and can be determined as the sum of water yield and deep aquifer recharge. The blue WF accounts for evaporation from reservoirs, irrigation for agriculture and water consumption from urban and industrial areas. Green water storage determines the water availability in soils' root zone, which is a critical component for plant and primary production. The green water storage can be calculated subtracting the blue water from precipitation. The difference between the initial and final soil moisture of each simulated year is considered as the variation of green water storage. The variation of green water and green water storage sums up the total green water consumption of a watershed. This value is equivalent to the evapotranspiration.

Ecosytem Services, Social Metabolism and Water Footprint are three approaches developed to respond to the same scientific challenge: understand how human activities interact with ecosystems, thus have many overlaps. Nevertheless, the conceptual metaphors behind are different and thus each of them highlight some perspectives and objects of analysis while hide others, and their combination and comparison will support their further development as frameworks. While ecosystems services focus on the benefits obtained by society from ecosystems (Raymond et al 2013), societal metabolism is based on systems autopoiesis (Maturana and Varela 1971) (i.e. societal requirements to maintain and reproduce itself and which ecological thresholds can't be surpassed to guarantee this reproduction). Similarly to the ecological and carbon footprints (Rees, 1992; Wiedmann and Minx, 2007), the WF addresses the appropriation of water resources by humanity. It represents an innovative approach introducing the metaphor of virtual water (water embedded in a product) leading to analysis of water equity and food security through virtual water trade, as well as the impacts created on ecosystems by consumers choices.

The institutional analysis of common pool resource management developed by Ostrom can help to understand how human groups organize themselves to face resource management problems and to arrange collective responses (Ostrom 1990, 2009). By studying which are the specific rules of organization, different management systems can be compared towards their success in guaranteeing a sustainable resource exploitation. The conflict dimension is a transversal one to the institutional issues, emphasizing how these magnify/ameliorate inequalities in resources access/conservation and which are society's responses to them. Water and land planning integration are a further institutional analysis at a higher scale of organization, which feeds from all the approaches and at the same time constitutes their normative frame, in continuous updating and adaptation. Water management plans provide information regarding management goals, future scenarios of water use, measures to meet new water demands etc. Land planning is the main driver of land use change, core feedback for the rest of the quantitative approaches. Therefore, building realistic scenarios and assessing their social viability and their biophysical feasibility requires detailed analysis of both water and land planning.

In order to further embed the scientific process within the broader exercise of water management, proper participatory processes should be arranged with decision-makers of the issues being researched. There are many participatory planning and research approaches that can provide guidance to define and structure the problems to be analyzed, to identify relevant stakeholders to engage, and to establish a collaborative process for a fruitful post-normal science practice. Scientific questions should be validated by a stakeholder community from the very beginning and continuous dialogue and feedbacks maintained until the final assessment of scientific results.

5. CONCLUSIONS

This paper proposes an integration of human-centric approaches that look at human water demand, use and impact, with physico-centric approaches that provide understanding of climate, hydrologic and environmental processes. The presented approach provides: i)a new way of assessing feedbacks and linkages between fields of research that have been disconnected until now , ii) a comprehensive planning and, iii) water governance processes. In summary, we presented a meta-framework that can relate (a) human behavior and the way water is used, governed and organized with (b) specific water budget components and footprints, ecosystem functions, environmental impacts, climate, land use change, and social parameters.

This integrated approach is a first step that provides theoretical outlines for a new integrated framework. A second step would consist in defining not only relations between disciplines or paradigms but also key questions and specific methodologies. Furthermore, this transdisciplinary approach should be articulated with case studies and collaborations with stakeholders. To this end, it will be necessary to define new scientific practices on water issues, as the debates initiated by post-normal science have encouraged them. The added value of such a framework might be constituted by another way of understanding and practicing water management beside today's top-down decision-making processes and the current institutionalized but somewhat limited "participation" in water management and planning. It would be a way to provide the bottom-up feedbacks from changes in the way people decide to change their water footprint, their imposed needs on ecosystem services and functions, their needs on water resources and their influence in climatic feedbacks through their choices on land and energy use.

While technology has pushed societies forward in terms of extracting resources, processing and combining them to produce wealth, the same science that enabled such technology has constantly struggled to advance our understanding of how new technological tools would impact relationships with the environment and how to manage such interaction. Acknowledging the need for an evolving science with new schools of thought to analyze environmental issues, this paper is an effort to provide an integrative analysis to keep up with observed growing levels of complexity in social-ecological dynamics. More effective strategies are needed to deal with present and soon to come ecological problems.

6. REFERENCES

AhValerl Ie, Allen T. F. H. (1996) *Hierarchy Theory: A Vision, Vocabulary, and Epistemology*. Columbia University Press.

Allan, T., 1997. Virtual water: a long term solution for water short Middle East economies? British Association Festival of Science. In: water and development session, University of Leeds, United Kingdom.

Allan, J. A. (1999). Global systems ameliorate local droughts: water, food and trade. Occasional Paper No. 10, Water Issues Study Group, School of Oriental and African Studies, University of London, UK.

American Planning Association (2002) *Growing Smart Legislative Guidebook 3: Model Statutes for Planning and the Management of Change.* (S. Meck, Ed.). American Planning Association Planners Press.

Arizpe N., Giampietro M., Ramos-Martin J. (2011) Food Security and Fossil Energy Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003). *Critical Reviews in Plant Sciences*, 30 (1-2): 45-63. doi:10.1080/07352689.2011.554352.

Bakker K. (2011) *Privatizing Water. Governance Failure and the World's Urban Water Crisis*, Ithacca and London, Cornell University Press.

Brookshire D, Gupta H., Matthews P. (Eds) (2012), *Improving New Mexico Water Policy And Management by Coupling Science, Modeling and Institutions*, RFF Press, Resources for the Future Book Series: Issues in Water Resources Policy Series.

Burkhard B., Groot R. de, Costanza R., Seppelt S. E., Potschin M., (2012a) Solutions for sustaining natural capital and ecosystem services. *Ecological Indicators* 21: 1-6.

Burkhard B., Kroll F., Nedkov S., Müller F. (2012b) Mapping of ecosystem service supply, demand and budgets. *Ecological Indicators* 21: 17-29.

Burkhard B., Kroll F., Müller F., Windhorst W., 2009. Landscapes capacities to provide ecosystem services – a concept for land-cover based assessments. *Landscape Online* 15: 1–22.

Carter, J. G. (2007) Spatial planning, water and the Water Framework Directive: insights from theory and practice. *Geographical Journal*, 173(4): 330–342. doi:10.1111/j.1475-4959.2007.00257.x

Changnon S.A., Semonin R.G., Auer A.H., Braham R.R., Hales J., 1981. *METROMEX: A review and summary*. Meteor. Monogr. 40, Amer. Meteor. Soc., 81 pp.

Chapagain A. K., Hoekstra A. Y. (2004). *Water Footprints of Nations*. Vol. 1. (Value of W.). UNESCO-IHE.

Chapagain A.K., Hoekstra A.Y., Savenije H.H.G. (2006) Water saving through international trade of agricultural products. *Hydrol Earth Syst Sci* 10, 455-468.

Crutzen Paul J., Stoermer, Eugene F., (2000) « The "Anthropocene" », *Global Change, NewsLetter*, n° 41, p. 17-18.

Groot R. S. de, Alkemade, R., Braat, L., Hein, L., Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7: 260-272.

Diaz-Maurin F., Giampietro M. (2013) A "Grammar" for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy. *Energy* 49: 162-177. doi:10.1016/j.energy.2012.11.014.

Diem J. E., Brown D.P. (2003). Anthropogenic impacts on summer precipitation in central Arizona, U.S.A., *Prof. Geogr*. 55: 343–355.

Dumont, A., Salmoral, G., & Llamas, M. R. (2013). The water footprint of a river basin with a special focus on groundwater: The case of Guadalquivir basin (Spain). Water Resources and Industry, 1-2, 60–76. doi:10.1016/j.wri.2013.04.001

Ercin A.E., Aldaya M.M., Hoekstra A.Y. (2010) Corporate Water Footprint Accounting and Impact Assessment: The Case of the Water Footprint of a Sugar-Containing Carbonated Beverage. *Water Resources Management*. 25: 721–741.

Espeland W. N. (1998) *The Struggle for Water. Politics, Rationality and Identity in the American Southwest*, Chicago & London, University of Chicago Press.

Environment Agency, *Spatial planning and the Water Framework Directive* http://www.environment-agency.gov.uk/research/planning/40195.aspx

European Environment Agency (EEA) (2012): *Territorial cohesion and water management in Europe: the spatial perspective.* Luxemburgo: Publications Office of the European Union. Retrieved from: http://www.eea.europa.eu/publications/territorial-cohesion-and-water-management

Falkenmark, M., Rockström, J. (2006) The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management* 132: 129–132.

Falkenmark M. (2009) Water for a Starving world: time to grasp the 1977 war-ning. Presentación 4º Seminario de Aguas: Seguridad hídrica y alimentaria. Seminarios internacionales del Observatorio del agua de la FMB.

FAO/UNEP: Choudhury K., Jansen J.M. (Eds.). (1998) *Terminology for integrated resources planning and management.* Food and Agriculture Organization of the United Nations.

FAO (2009). How to Feed the World in 2050. FAO.

FAO (2011). *The state of the world´s land and water resources for food and agriculture (SOLAW) - Managing systems at risks*. Food and Agriculture Organization of the United Nations, Rome and Earthscan. London.

Foley J.A., Ramankutty N., Brauman K.A., Cassidy E.S., Gerber J.S., Johnston M., Mueller N.D., O'Connell C., Ray D.K., West P.C., Balzer C., Bennett E.M., Carpenter S.R., Hill J., Monfreda C., Polasky S., Rockström J., Sheehan J., Siebert S., Tilman G.D., Zaks D.P.M., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342

Funtowicz, S.O. and Ravetz, J.R. (1991). "A New Scientific Methodology for Global Environmental Issues." In *Ecological Economics: The Science and Management of Sustainability*. Ed. Robert Costanza. New York: Columbia University Press: 137–152.

Funtowicz, S. O., and Ravetz, J. R. (1993). Uncertainty and quality in science for policy, Dordrecht: Kluwer.

Funtowicz, S., Ravetz, J.R. (1994) The worth of a songbird: ecological economicsas a post-normal science. Ecological Economics 10 (1994) 197-207

Garrido A., Llamas M. R., Varela-Ortega C., Novo P., Rodríguez-Casado R., Aldaya M. M. (2010) *Water Footprint and Virtual Water Trade in Spain*, Springer.

Georgescu-Roegen N. (1971) The Entropy Law and the Economic Process. in Giampietro, M. (2003) *Multi-Scale Integrated Analysis of Agroecosystems*. 1.a ed. CRC Press.

Giampietro M., Mayumi K., (2000) Multiple-scale integrated assessment of societal metabolism: Introducing the approach. *Population and Environment* 22 (2): 109-153.

Giampietro, M., Mayumi K., Munda G. (2006) Integrated assessment and energy analysis: Quality assurance in multi-criteria analysis of sustainability. *Energy* 31 (1): 59-86. doi:doi: DOI: 10.1016/j.energy.2005.03.005.

Giampietro M., Mayumi K., Ramos-Martin J. (2009). Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy* 34 (3): 313-322. doi:doi: DOI: 10.1016/j.energy.2008.07.020.

Giampietro M., Mayumi K. Sorman A. (2011) *The Metabolic Pattern of Societies: Where Economists Fall Short*. Routledge.

Giampietro M., Mayumi K., Sorman A. (2013) *Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism*. (1^{st} Edition) Routledge.

Gloor M. *et al.* (2012). The carbon balance of South America: a review of the status, decadal trends and main determinants. *Biogeosciences*, 9 (12), 5407–5430.

Grossman-Clarke S. *et al*., (2010) Contribution of Land Use Changes to Near-Surface Air Temperatures during Recent Summer Extreme Heat Events in the Phoenix Metropolitan *Area. Journal Of Applied Meteorology And Climatology* V: 49, I: 8: 1649-1664. DOI: 10.1175/2010JAMC2362.1

Global Water Partnership (2000) Towards Water Security: A Framework for Action. Stockholm, Sweden and London, United Kingdom. ISBN 91-630-9202-6.

(http://www.gwp.org/Global/ToolBox/References/Towards water security. A framework for action. Mobilising political will to act (GWP, 2000).pdf)

Hartfield, K., Schneier-Madanes, G., Marsh, S., Curley, E. (2014) Remote Sensing of Urban Change: Water and Urban Growth in the Sun Corridor of the US Southwest. Sustainable Water ActioN (SWAN) Report - Working Paper.

Hoekstra A.Y., Chapagain A.K., 2008. Globalization of water: sharing the planet's freshwater resources. Blackwell Publ, Oxford, UK.

Hoekstra A. *et al.* (2011). *The Water Footprint Assessment Manual: setting the global standard*, London: Earthscan.

Hoekstra A. Y., Mekonnen M. M., Chapagain A. K., Mathews R. E., Richter B. D. (2012), Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability, *PLoS ONE* 7(2), e32688, doi:10.1371/journal.pone.0032688.

Hughes Th., 1985. *Networks of Power. Electrification in Western Society (1880-1930)*. Baltimore and London, Johns Hopkins University Press.

IMECHE (2013). *Global food waste not, want not*. Institution of Mechanical Engineering. London, UK.

Islam M.D., Oki T., Kanae S., Hanasaki N., Agata Y., Yoshimura K. (2007) A grid-based assessment of global water scarcity including virtual water trading. *Water Resources Management* 21, 19-33.

Jasanoff S. (2007) *Designs on Nature. Science and Democracy in Europe and the United States*, Princeton & Oxford, Princeton University Press.

Kandziora M., Burkhard B., Müller F. (2013). Interaction of ecosystem properties, ecosystem integrity and ecosystem service indicators – A theoretical matrix exercise. *Ecological Indicators* 38: 54-78.

Kelly E.D. (2010) *Community Planning: An Introduction to the Comprehensive Plan.* 2nd Edition. Island Press.

Kroll F., Müllera F., Haaseb D., Fohrera N. (2012). Rural–urban gradient analysis of ecosystem services supply and demand dynamics. *Land Use Policy* 29: 521– 535.

Lafont B. (2009) *Eau, pouvoir et société dans l'Orient ancien : approches théoriques, travaux de terrain et documentation écrite* In : *Stratégies d'acquisition de l'eau et société au Moyen-Orient depuis l'Antiquité*. Beyrouth : Presses de l'Ifpo: http://books.openedition.org/ifpo/1256

Lansing J. S, de Vet, T. (2012) The Functional Role of Balinese Water Temples: A Response to Critics. *Human Ecology*, 40 (3): 453-467

Liu Y., Gupta H., Springer E., Wagener T. (2008). Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling & Software* 23 (7): 846-858.

Madrid C., Cabello V. (2011). Re-opening the Black Box in Societal Metabolism: The Application of MuSIASEM to Water. Working Paper. Nov.4. http://www.recercat.net/handle/2072/172087.

Madrid C., Cabello V., Giampietro M. (2013) Water-Use Sustainability in Socioecological Systems: A Multiscale Integrated Approach. *Bioscience* 63 (1): 14-24.

Martinez-Alier, J., Schlüpmann, K. (1987) *Ecological economics: energy, environment, and society*. Basil Blackwell.

Martinez-Alier, J. (2008) Conflictos ecologicos y justicia ambiental, *Papeles*, 103: 11-27. http://www.fuhem.es/media/ecosocial/file/Analisis/enero 2009/Conflictos ecologicos_J. MARTINEZ ALIER.pdf

Koïchiro M. (2007) *Signons la paix avec la Terre*, Paris, Unesco.

Manning J. (2002) Irrigation et État en Égypte antique, *Annales. Histoire, Sciences Sociales* 3: 611-623.

Ministry of Housing, Spatial Planning and the Environment, Ministry of Transport, Public Works and Water Management, Ministry of Agriculture, Nature and Food Quality, and Ministry of Education, Culture and Science (Netherlands) 2009. *Designing on the interface between water and spatial planning. Guide and Examples*. The Hague, Netherlands: The Ministry of Housing, Spatial Planning and the Environment with the Ministry of Transport, Public Works and Water

Management, the Ministry of Agriculture, Nature and Food Quality and the Ministry of Education, Culture and Science. http://www.rijksoverheid.nl/documenten-en-publicaties/rapporten/2009/02/01/designing-on-the-interface-between-water-and-spatial-planning.html

Munda G. (1995) *Multicriteria Evaluation in a Fuzzy Environment: Theory and Applications in Ecological Economics*, Physical Verlag, Heidelgberg.

Nedkov, S., Burkhard B. (2012) Flood regulating ecosystem services – mapping supply and demand, in the Etropole municipality, Bulgaria. *Ecological Indicators* 21: 67–79.

Nilsson M., Persson Å. (2012). Can Earth system interactions be governed? Governance functions for linking climate change mitigation with land use, freshwater and biodiversity protection. *Ecological Economics*, 75: 61–71.

NRC (National Research Council) (2011) *Climate stabilization targets*, Washington, DC: The National Academies Press, 286 p.

NRC (National Research Council) (2012) *NRC Report on Urban Meteorology: Forecasting, Monitoring, and Meeting Users' Needs.* National Academies Press. Authors: Snow, J.T., X. Zeng, P. Klein, S.E. Sarnat, J.M. Shepherd, and E.M. Stanley, Washington, D.C., 190 pp.

O'Keeffe J. (2009), Sustaining river ecosystems: balancing use and protection. *Progress in Physical Geography*, 33(3): 339–357, doi:10.1177/0309133309342645.

Ostrom E. (1990) *Governing the commons. The Evolution of Institutions for Collective Action*, Cambridge, Cambridge University Press.

Ostrom Elinor (2009) A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325: 419-421.

Palerm A. & Wolf E. (1955) El Desarrollo del área clave del imperio texcocano, *Revista Mexicana de Estudios Antropológicos*, 14: 337-349.

Pincetl S. (2011) Urban water conflicts in Western US, in Barraqué Bernard (ed.), *Urban Water Conflicts*, Paris, Unesco.

Rajagopal, S. (2011). Impacts of Climate Change on Water Supply for the City of Phoenix, Arizona, Ph.D Dissertation, University of Arizona.

Rajagopal, S., Gupta H., Dominguez F., Troch P. (2011). Assessing Climate Change Impacts on Water Supply for the City of Phoenix, Arizona, Water Resources Research (in press).

Ramos-Martin, J. (2001) Historical Analysis of Energy Intensity of Spain: From a "Conventional View" to an "Integrated Assessment". *Population and Environment* 22 (3): 218-313.

Ramos-Martín J., Cañellas-Boltà S., Giampietro M., Gamboa S. (2009) Catalonia's energy metabolism: Using the MuSIASEM approach at different scales. *Energy Policy* 37 (11): 4658 - 4671. doi:DOI: 10.1016/j.enpol.2009.06.028.

Rees W.E. (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out, *Environment and Urbanization* 4: 121–130.

Reisner M. (1986) *Cadillac Desert. The American West and its Disappearing Water*, Penguin Books.

Andrew R. (1992) *Global Warming : Understanding the Forecast*, American Museum of Natural History, Environmental Defense Fund, New York, Abbeville Press.

Riddoutt B. G., Pfister, S. (2010) A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Glob. Environ. Change*, v.20, p.113–120.

Rockström J., *et al.* (2009) A safe operating space for humanity. *Nature* 472-475.

Rosenfield, P.L. (1992) The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 1992;35:1343–57.

Salmoral, G. (2011) Green, blue and grey water analysis of the bottom part of the Turia River Basin. Dissertation for the Master in Environmental Technology for Sustainable Agriculture. Technical University of Madrid

Salmoral, G., Aldaya, M. M., Chico, D., Garrido, a., & Llamas, R. (2011). The water footprint of olives and olive oil in Spain. Spanish Journal of Agricultural Research, 9(4). doi:10.5424/http://dx.doi.org/10.5424/sjar/20110904-035-11

Salmoral G., Dumont A., Aldaya M.M., Rodríguez-Casado R., Garrido A., Llamas R. (2011b) Extended Water Footprint Analysis of the Guadalquivir basin. *SHAN nº 1. Observatorio del Agua*. Fundación Marcelino Botín. Available at: http://www.huellahidrica.org

Scheidel A. (2013a) Flows, funds and the complexity of deprivation: Using concepts from ecological economics for the study of poverty. *Ecological Economics* 86: 28-36. doi:10.1016/j.ecolecon.2012.10.019.

Scherr S.J., McNeely J. A. (2008) Biodiversity conservation and agricultural sustainability: towards a new paradigm of "ecoagriculture" landscapes. *Philosophical transactions of the Royal Society of London, Series B, Biological sciences* 363: 477–94.

Serrano T., Giampietro M. (2009) A multi-purpose grammar generating a multi-scale integrated analysis of Laos, *ICTA Working Paper*. http://ddd.uab.cat/pub/estudis/2009/hdl_2072_40519/ICTATechnicalReport_2009-3.pdf

Serrat-Capdevila A., Browning-Aiken A., Lansey K., Finan T., Valdés J.B. (2009) Increasing Socio-Ecological Resilience by placing science at the decision table: The role of the San Pedro Basin Decision Support System Model (Arizona). *Ecology and Society* 14(1): 37.

Serrat-Capdevila A., Dominguez F., Valdes J.B., Rajgopal S., Gupta H. (2013) Characterizing the Droughts of the new century in the US Southwest: A comprehensive assessment from state-of-the-art climate model projections, *International Journal of Water Resources Development*, 29:2, 152-171, http://dx.doi.org/10.1080/07900627.2012.721717

Serrat-Capdevila, A., Scott, R. L., Shuttleworth, W.J. and J.B. Valdés (2011a) Estimating ET under warmer climates: Insights from a semi-arid watershed, *Journal of Hydrology*, 399: 1–11.

Serrat-Capdevila A., Valdes J.B., Gupta H. (2011b) Decision Support Systems in Water Resources Planning and Management: Stakeholder participation and the sustainable path to science-based decision making. In: *Efficient Decision Support Systems: Practice and*

Challenges – From Current to Future / Book 1", ISBN 978-953-307-165-7. InTech - Open Access Publisher.

Serrat-Capdevila A., Valdes J.B., Gupta H., Schneier-Madanes, G. (2014) Water Governance Tools: The role of Science, Decision Support Systems and Stakeholder Participation. In Schneier-Madanes, G. (ed.) *Globalized Water*, Springer, ch.17: 241-259. ISBN 978-94-007-7323-3

Serrat-Capdevila A., Valdes J. B., Gonzalez J., Baird K., Mata L.J., Maddock T. (2007) Modeling climate change impacts - and uncertainty - on the hydrology of a riparian system: the San Pedro Basin (Arizona/Sonora), *Journal of Hydrology*, 347: 48-66.

Shepherd J., Pierce H., Negri A. (2002). Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *J Appl Meteorol*. 41, 689–701.

Shepherd, J.M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions*, 9 (12), 1-27.

Sorman A. H., Giampietro M. (2013). The energetic metabolism of societies and the degrowth paradigm: analyzing biophysical constraints and realities. *Journal of Cleaner Production* 38: 80-93. doi:10.1016/j.jclepro.2011.11.059.

Steffen W., Crutzen J., McNeill J.R. (2007). The Anthropocene: are humans now overwhelming the great forces of Nature? *Ambio* 36: 614–21.

Stokols D., Hall K.L., Taylor B.K., Moser R.P. (2008) The science of team science: overview of the field and introduction to the supplement. *Am J Prevent Med*. 35: S77-S89.

Tilman D., Balzer C., Hill J, Befort B.L. (2011) Global food demand and the sustainable Intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America* 108: 20260-4.

United Nations (2007) World Urbanization Prospects: The 2007 Revision [Available online at http://esa.un.org/unup].

UNPD (United Nations Population Division) (2010). *World urbanization prospects, the 2009 revision*. Available from http://esa.un.org/unpd/wup/doc_highlights.htm. Accessed on 12/26/2011.

Van Oel P.R., Mekonnen M., Hoekstra A. (2009). The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment, *Ecological Economics* 69: 82–92.

Vanham D., Bidoglio G. (2013). A review on the water footprint indicator for the EU28. *Ecological Indicators* 26: 61-75.

Velázquez E., Madrid C., Beltrán, M. (2011), Rethinking concepts of virtual water and water footprint in relation to the production–consumption binomial and the water–energy nexus. *Water Resources Management* 25: 743-761.

Vigerstol K. L., Aukema J. E. (2011) A comparison of tools for modeling freshwater ecosystem services. *Journal of Environmental Management* 92: 2403-2409.

Wichelns D. (2010) Virtual water: a helpful perspective, but not a sufficient policy criterion. *Water Resources Management* 24: 2203-2219.

Wiedmann T., Minx, J. (2007) *A Definition of Carbon Footprint*, ISA Research & Consulting, Durham, United Kingdom.

Woltjer J., Niels A. (2007) Integrating Water Management and Spatial Planning. *Journal of the American Planning Association*, 73(2): 211-222.

Worster D. (1985), *Rivers of Empire. Water, Aridity and the Growth of the American West*, Oxford, Oxford University Press.

Directives:

Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy

Directive 2007/60/EC on the assessment and management of flood risks

European Union Biodiversity Strategy to 2020, Target 2, Action 2