An integrated assessment of water governance in social-ecological systems

Two case studies: the Andarax basin in Almeria and the Tucson basin in Arizona

Violeta Cabello Villarejo

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A mis abuelas,

Por abrir caminos

A Mari Paz, Rafael, Sabina y Olmo,

Por la primavera

Va el rumor de un río
tras la montaña,
amando hasta inundarla
por el tejado subiendo
ANTONIO VIÑAS

PREFACE

This dissertation is the output of five years of intense personal and professional development. Consistent with the epistemological position of the framework presented here, the research process has been anything but lineal and substantive. On the contrary, the learning path has gone through many cycles and changes in adaptation to the emerging ideas and reflections, to the questions and debates arising along it, and to my own intellectual evolution. This process-oriented research style might not be very orthodox, but I believe it represents a new flexible scientific approach that is necessary when working with complex social-ecological issues and, especially, in transdisciplinary practices.

This adventure started when different coincidences led me to Mario Giampietro and the societal metabolism research group from the ICTA-UAB on one side, and to Leandro del Moral and the GIEST group on the other. Until then, I had not thought about doing a PhD at all, because the academic environments I knew were not as exciting as what I found: two interdisciplinary groups working on sustainability assessment and river basin management from a new scientific paradigm, that of complexity, and from a notably socially and environmentally committed attitude. It was a moment of incredible clarity when I realized that I had to bridge those areas to build my own research interest. And that is what I did.

I spent the first year with Mario in Barcelona learning MuSIASEM, complex systems theory, ecological economics and political ecology. I must admit that it was a challenging task to delve in the MuSIASEM pillars, so diverse and different from my educational background in Environmental Sciences and Hydrology. The collaborative work with Cristina Madrid and the Rural Systems group were an important support that made the process much more productive and fun. I also learnt from this group the 'thinking-learning-reframing by doing' research culture, which sometimes made me feel a bit lost but allowed a much more creative and thoughtful process, developing my own interests through my personal learning on an iterative basis.

By the end of the first year I moved to Sevilla. It was May 2011 and I got involved in the local group of Democracy Real Now and in the organization of the 15M demonstration that led to the indignados movement afterwards. This got me a bit distracted from my research tasks but at the same time gave me a new profound sense of the change I wanted to see in the world that shaped the rest of the development of this thesis. I spent the following years working on the Andarax case study and doing my first teaching on GIS at the University of Sevilla. With Leandro I learnt about water planning and governance, policies and politics, discourses and power. I got a completely new constructivist understanding of social-ecological systems and waterscapes that made me reframe many of my assumptions and questions. I feel it was actually then that this thesis started to get some shape. From the GIEST group I learnt geography, spatial analysis and data management. Juan Manuel Camarillo became my third director in recognition of his support to teach me data modeling and geodatabases management, which as a tipping point in the technical side of this thesis.

In spring 2013 I got an internship at the University of Arizona in Tucson under the frame of the SWAN project. During that time, I got involved in a group of students working on water issues from different disciplines and parts of the world. We spent four months presenting each other approaches and having fruitful theoretical discussions, after which we decided to develop a case study together in the Tucson area as means to move forward to an interdisciplinary effort. This was the beginning of the Tucson basin case study that end up becoming both an important part of this dissertation and a chapter in an upcoming book that will gather our different perspectives. I greatly value the learning experience that I got from my participation in this group regarding the challenges of interdisciplinary research, what I feel will be very useful in my future research endeavors. Furthermore, the research process in Tucson significantly enriched this thesis and was the final drop that propelled the final evolution to what it is now.

Finding connections between the two case-studies made the story I wanted to tell to emerge as a property of the system I had been creating for four years, and once again I had to reframe my objective and questions. I spent half a year of writing seclusion putting all the pieces together, reviewing my past publications, writing unpublished material and adapting and completing the conceptual framework. I hope to have succeeded in making up that story, and that the final reading reflects the long and exciting voyage it required. Foremost, I hope you enjoy and learn with it as much as I did.

Violeta Cabello Villarejo

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Me gustaría empezar diciendo que no creo en la propiedad intelectual y que todas las ideas que se puedan encontrar en este trabajo son de todas las personas con las que he dialogado y compartido durante estos años. De hecho las partes más interesantes son fruto de trabajos colaborativos, los que he procurado desarrollar tanto como he podido dentro del ambiente individualista que es la academia. Son muchas las interacciones que me han traído hasta aquí y que voy a tratar de mencionar, aunque seguro que me dejaré muchas otras.

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En primer lugar tengo que agradecer a los precursores de esta tesis. A Antonio Heredia, por la primera oportunidad y por la trama de la vida que me acercó a esta nueva forma de entender la realidad. A Eduardo Serrano, por catalizar mi gran desterritorialización y alimentar mi insaciable curiosidad, por su generosa sabiduría, su entusiasmo por los demás y, por supuesto, por presentarme a Tarik. A Tarik, por llevarme hasta Mario y ser un buen amigo y compañero de batallas intelectuales. El último precursor que tiene culpa de muchas cosas es Antonio Viñas, por hacerme mirar el agua de muchas otras formas, lo cual fue ya irreversible, y además por presentarme a Leandro.

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participación ciudadana y de la ecología mental como camino necesario para conseguir la social y la ecológica. Espero que nuestros pasos juntas sigan por muchos años y lleguen lejos. Y no puedo dejar de agradecer a Democracia Real Ya y al 15M, por haber soñado con cambiar el mundo y además haberlo hecho.

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ABSTRACT

The emergence of sustainable development as a mainstream issue in the global political agenda defused voices critical of the limits to growth by embracing the discourse of ecological modernization. According to this narrative, environmental problems can and should be dealt with by the promotion of economic growth within existing economic and institutional arrangements. The field of water governance echoed this discourse in the new integration ideas of integrated water resources management, which has gradually become a dominant water management paradigm over the last decades. In the meantime, the western scientific arena has experienced a drastic epistemological shift from mechanicism to complexity. A theoretical basis of complexity underpins the new field of sustainability science, which strives to respond to the challenges associated with retrieving unsustainable patterns through inter- and transdisciplinary research on social-ecological systems. However, water science for governance is slowly mirroring the epistemological implications of complexity, such as the existence of multiple perceptions of nature, the multi-scale organization of living systems, and circular causality as the main type of relationship maintaining this organization. Some research challenges associated with these issues are the following: integrated analysis involving multiple scales and dimensions; mechanisms for quality control over the narratives leading problem-solving; and critical assessments of win-win techno-social fixes. This dissertation attempts to respond to these challenges by offering a complex systems perspective on water resources management that conceptualizes watersheds as social-ecological systems. The research objective is to develop an integrated assessment of the implementation of sustainability objectives in water policies in two semi-arid water basins: the Andarax River basin in Almeria (Spain) and the Tucson basin in Arizona (United States). For this purpose, the dissertation proposes a theoretical framework for the integrated assessment of water governance that combines a series of conceptual devices, such as a complex definition of water use, a holarchic depiction of coupled water-human systems, the water metabolism of social-ecological systems, the semiotic process of water management, and water availability as a boundary object. This conceptual repertoire is operationalized through a methodological framework that bridges quantitative analytical tools, such as a spatial-relational data model and the Multi-Scale Analysis of Societal and Ecosystem Metabolism, and qualitative discourse analysis and assessment of public policies.

The first case study follows the implementation of the first cycle of the Water Framework Directive 2009-2015 in the Andarax River basin. It begins with a thorough characterization of the water metabolism of one sub-basin, linking the analysis of societal and that of ecosystem metabolism on a spatially explicit basis. It is proposed that the analysis of ecosystem metabolism should be carried out through the eco-hydrological processes that control water resource renewability (supply-side sustainability), the impacts caused to ecosystem health (sink-side sustainability), and the boundary concepts of water availability and ecosystem water requirements. The analysis revealed the metabolic pattern of a high mountain rural system with a multi-functional economy striving to deal with exodus and agricultural land abandonment. Centuries of social-ecological evolution shaping waterscapes through traditional water management practices have influenced the eco-hydrological functioning of the basin, enabling the adaptation to aridity. Management challenges posed by the European water regulatory framework as a new driver of social-ecological change are highlighted. In the second analytical chapter, the interplay between agricultural and water policies is assessed on a multi-scale basis by bridging the analysis of management plans and that of societal metabolic patterns. The resulting analysis shows that the integration of these policies is undertaken at regional level through techno-social fixes consisting mainly of new resources and the improvement of irrigation efficiency. Agriculture is the main driver of water use patterns, and a range of which are found in the basin with different associated challenges regarding the meeting of environmental objectives of the Directive. The trade-offs associated with management decisions are uncovered in terms of the rebound effect in water use and the intensification of the energy cost of the water supply. The case study ends with an assessment of the semiotic process of the water management cycle. Discourse analysis shows the existence of multiple contested narratives surrounding the question of how water should be managed. However, the dominant narratives pervading water management decisions prioritize high-cost supply augmentation as a means of coping with environmental objectives. Critical narratives that pinpoint structural problems of metabolic change in rural communities, offer eco-integrative views of economic development, or denounce institutional dysfunction, are disregarded. The analysis shows that management strategies so far have been largely cost-ineffective in a context of financial austerity, and that the management system is notably vulnerable to perturbations. The improvement of information, transparency and accountability arises as a key challenge in the fostering of trust and the improving of adaptive capacity.

The second case study reviews the state of the art of current debates surrounding the sustainability objective in Arizona water policy, focusing on the Tucson basin area. Achieving safe yield for aquifers by 2025 was endorsed in the Groundwater Management Act of 1980, and since then three management cycles have implemented different strategies to pursue this. These combined growth control measures, improved productive efficiency through conservation practices and new resources from the Colorado River and wastewater reclamation. Combining a historical perspective on water use and its drivers with spatial analysis of groundwater management, the analysis of the study area shows how the Central Arizona Project was a tipping point in the water metabolism. The Project allowed continuing fueling economic growth, both through multiplying the sources available and through the infrastructural and institutional complexity involved. The research indicates that growth limitations have only been operative in the agricultural sector, which drives overall demand and overdraft variability. Conservation programs have been effective in the most important segment of the demand, which is the residential use of large urban areas. The recharge and recovery program was the key innovative solution to curbing overdraft, although fiddly accounting and legal mechanisms obscure an uneven progress towards safe yield. The disconnection of recovery from recharge sites entails local impacts on water table levels driven by mines and new developments. While new infrastructures are being negotiated in order to expand the reach of the supply from the canal, vulnerability to potential Colorado water shortages and the high uncertainty over the achievement and maintenance of a distributed safe yield appear as core management issues for the next decade.

Keywords: Andarax basin, water-human systems, Groundwater Management Act, integrated assessment, management paradigms, narratives, science for governance, societal and ecosystem metabolism, social-ecological systems, socio-eco-hydrology, transdisciplinarity, Tucson basin, Water Framework Directive, water governance, water metabolism.

RESUMEN

La aparición del desarrollo sostenible como un tema prioritario en la agenda política global desactivó voces críticas con los límites al crecimiento, abrazando el discurso de la modernidad ecológica. Según este, los problemas ambientales pueden y deben abordarse impulsando el crecimiento económico a través de los modelos existentes de producción y organización institucional. El campo de la gobernanza del agua se hizo eco de este discurso a través de las nuevas ideas de integración en la gestión integrada de los recursos hídricos, que se ha ido constituyendo como un nuevo paradigma de gestión en las últimas décadas. Por su parte, la arena científica occidental ha sufrido un drástico giro epistemológico desde el mecanicismo hacia la complejidad. Las ciencias de la complejidad han servido de base teórica para el nuevo campo de las ciencias de la sostenibilidad, que intenta responder a los retos asociados a la transición hacia de patrones de vida más sostenibles a través de la investigación inter y transdiciplinar en sistemas socio-ecológicos. Sin embargo, la ciencia para la gobernanza del agua apenas ha comenzado a asumir las implicaciones epistemológicas de la complejidad, tales como la existencia de múltiples percepciones sobre la naturaleza, la organización multi-escalar de los sistemas vivos o la causalidad circular como el principal tipo de relación que mantiene dicha organización. Algunos retos de investigación derivados de estas implicaciones son los siguientes: la necesidad de análisis integrados que incorporen diversas escalas y dimensiones, de mecanismos de control de calidad de las narrativas que lideran las estrategias para resolver los problemas ambientales, así como de evaluaciones críticas de los arreglos tecno-sociales tipo gana-gana. Esta disertación intenta responder a estos retos ofreciendo una perspectiva de sistemas complejos sobre la gestión del agua que conceptualiza las cuencas hidrográficas como sistemas socio-ecológicos. El objetivo de investigación es realizar una evaluación integrada de la implementación de objetivos de sostenibilidad en políticas de agua en dos cuencas semi-áridas: la cuenca del Río Andarax en Almería (España) y la cuenca de Tucson en Arizona (Estados Unidos). Para abordar este objetivo, se propone un marco teórico para la evaluación integrada de la gobernanza del agua que combina conceptos como una definición compleja del uso del agua, la representación holárquica de sistemas hidro-sociales, el metabolismo hídrico de sistemas socio-ecológicos, el proceso semiótico de la gestión del agua y la disponibilidad del agua como un objeto frontera. Este repertorio conceptual es operacionalizado a través de un marco metodológico que combina herramientas cuantitativas, como un modelo de datos espacial-relacional y el Análisis Multi-Escalar del Metabolismo Social y Ecológico, con análisis cualitativo del discurso y la evaluación de políticas públicas.

El primer caso de estudio hace un seguimiento de la implementación del primer ciclo de la Directiva Marco del Agua 2009-2015 en la cuenca del Río Andarax. Comienza con una caracterización detallada del metabolismo hídrico en una subcuenca, ligando el análisis del metabolismo social y ecológico de manera espacialmente explícita. Se propone analizar el metabolismo hídrico de los ecosistemas a través de los procesos eco-hidrológicos que controlan la renovación de los recursos hídricos (sostenibilidad del abastecimiento), los impactos generados sobre los ecosistemas (sostenibilidad del sumidero), y los conceptos frontera de disponibilidad y requerimientos hídricos de los ecosistemas. El análisis revela un patrón metabólico de sistema rural de alta montaña con una economía multifuncional que intenta enfrentarse al abandono de la agricultura y el éxodo rural. Siglos de evolución socio-

ecológica modelando los paisajes del agua a través de prácticas tradicionales han influenciado el funcionamiento eco-hidrológico de la cuenca permitiendo la adaptación a la aridez. Los principales retos que plantea la política de aguas europea como nuevo motor de cambio socio-ecológico son señalados. En un segundo capítulo de análisis se aborda la interacción entre las políticas de agua y agrícolas a varios niveles, combinando el análisis de planes y programas de gestión con el de patrones metabólicos. Los resultados muestran que la integración entre estas políticas se realiza a nivel regional a través de arreglos tecno-sociales, que principalmente consisten en la generación de nuevos recursos y la mejora de la eficiencia del regadío. La agricultura es el principal sector consumidor de agua, y en la cuenca existen patrones metabólicos muy diversos enfrentando diferentes retos para alcanzar los objetivos ambientales de la Directiva. Los costes asociados a las decisiones de gestión son discutidos en lo que se refiere al efecto rebote sobre los usos del agua y la intensificación del coste energético del abastecimiento. El caso de estudio termina con una evaluación del proceso semiótico del ciclo de gestión del agua. El análisis de discursos muestra la existencia de diversas narrativas contrastantes sobre cómo se debería gestionar el agua. Sin embargo, las narrativas dominantes que permean en las decisiones priorizan estrategias caras de aumento de la oferta como forma de alcanzar los objetivos ambientales. Otras voces críticas que señalan problemas estructurales de cambio metabólico en las zonas rurales, visiones eco-integradoras del desarrollo económico, o denuncias sobre el mal funcionamiento institucional, son ignoradas o rechazadas. El análisis muestra que las estrategias de gestión han sido bastante ineficientes en el nuevo contexto de austeridad financiera y que el sistema de gestión es notablemente vulnerable a perturbaciones. La mejora de la información, la transparencia y la rendición de cuentas emergen como los retos clave para promover la confianza y la mejora de la capacidad adaptativa.

El segundo caso de estudio revisa el estado del arte de los debates sobre los objetivos de sostenibilidad en la política del agua de Arizona, enfocándose sobre la cuenca del Tucson. El Acta de Gestión del Agua Subterránea de 1980 estableció el objetivo de alcanzar la extracción segura de los acuíferos en el año 2025. Desde entonces, tres ciclos de planificación han implementado diferentes estrategias para alcanzar dicho objetivo. Estas estrategias incluyen medidas de control del crecimiento, mejora de la eficiencia productiva, y la obtención de nuevos recursos provenientes del Río Colorado y de la reutilización de aguas residuales. Combinando una perspectiva histórica sobre los usos del agua y sus principales motores con el análisis espacial de la gestión del agua subterránea, el análisis muestra que el Proyecto de Arizona Central fue el punto de inflexión clave en el metabolismo hídrico de la región. Este proyecto permitió alimentar el crecimiento económico, a través de la multiplicación de las fuentes de agua disponible y del incremento de la complejidad infraestructural e institucional. Los resultados sugieren que las medidas de limitación del crecimiento han sido efectivas en el sector agrícola, principal condicionante de la variabilidad interanual de la demanda y la sobreexplotación. Los programas de conservación han sido efectivos en el segmento más importante de la demanda que son los usos residenciales de las grandes áreas urbanas. El programa de recarga y recuperación de los acuíferos fue la innovación clave para reducir la sobreexplotación, si bien los complejos mecanismos legales y de contabilidad del agua esconden una distribución muy desigual del progreso hacia la extracción segura. La desconexión entre las zonas de recarga y recuperación genera impactos locales importantes sobre los niveles freáticos, causados principalmente por las grandes minas y los nuevos

desarrollos urbanos. Mientras se negocian nuevas infraestructuras para llevar el agua del canal a dichas zonas, la vulnerabilidad a las sequías en el Colorado y la gran incertidumbre sobre cómo alcanzar y mantener una extracción segura espacialmente distribuida aparecen como los mayores retos de la gestión del agua en la próxima década.

Palabras clave: Acta de Gestión del Agua Subterránea, cuenca del Andarax, cuenca de Tucson, Directiva Marco del Agua, ciencia para la gobernanza, evaluación integrada, gobernanza del agua, metabolismo hídrico, metabolismo social y ecológico, narrativas, paradigmas de gestión, sistemas hidro-sociales, sistemas socio-ecológicos, socio-eco-hidrología, transdisciplinariedad.

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Acronyms and abbreviations

AIA – Andalusian Irrigation Agenda

ADWR – Arizona Department of Water Resources

AMA – Active Management Area

APRD – Andalusian Program for Rural Development

AWBA – Arizona Water Banking Authority

AWS – Assured Water Supply

EO – Environmental Objectives

GMA – Groundwater Management Act

CAGP – Common Agricultural Policy

CAP – Central Arizona Project

CAWCD - Central Arizona Water Conservation District

CAGRD – Central Arizona Groundwater Replenishment District

GUAC – Groundwater Users Advisory Councils

HA – Human Activity

IPAG – Institutional and Policy Advisory Group

IWRM – Integrated Water Resources Management

LSO – Less Stringent Objectives

LU / LULC – Land Use / Land Use Land Cover

MP – Management Plan

MuSIASEM – Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

PoM – Programme of Measures

SE-hydrology – Socio-Eco-hydrology

SES – Social-Ecological System

SGWA – Shallow Groundwater Areas

SYTF – Safe Yield Task Force

RBAs – River Basin Authorities

RBD – River Basin District

RBMP - River Basin Management Plan

WFD – Water Framework Directive

WHS – Water-Human System

WMSES – Water Metabolism of Social-Ecological Systems

INTRODUCTION

The last fifty years have witnessed a drastic scientific and governance shift in the environmental field in general and in water resources management in particular. The emergence of environmentalism as the reflection of a collective awareness of human impacts on ecosystems, and sustainability as a mainstream issue in the global political agenda, raised a whole new range of scientific questions. In trying to answer those questions, the scientific community realized that, on the one hand, traditional means of knowledge production were insufficient and, on the other, existing natural resource management regimes were indeed a problem (Ostrom 2005, Young et al. 2006). Since the eighties, new analytical frameworks, computing capacity and the global internet are driving a new era of knowledge focused on understanding interconnectedness, relationships and processes. Complexity as an emerging scientific paradigm is superseding Newtonian mechanics, and science for the governance of sustainability has opened the debate on the epistemological implications of the transfer of scientific knowledge to policy making (Funtowicz and Ravetz 1990, Mayumi and Giampietro 2006). However, as increasingly complex lenses were looking at environmental problems, the initially concerted political efforts invested in global sustainability strategies progressively waned or stagnated, captured in a win-win rhetoric of eco-efficiency and market-based problem solving (Leach et al. 2010, Gomez-Baggethum and Naredo 2015). As a result, the science-policy gap in environmental governance continues to widen, with relevant mismatches pinpointed regarding spatial and temporal scales of action, professional priorities and institutional pressures, the difficulty of accessing rapidly evolving knowledge, or the insufficient contemplation of politics, power relations and the power of judgement in scientific assessments (Faber 2008, Klauer et al. 2013, Jarvis et al. 2015).

The world of water very soon began to echo the sustainability debates. Water scientists questioned sanctioned knowledge and management models, and proposed the ambitious Integrated Water Resources Management (IWRM), which has gradually become a new management paradigm (Koudstaal et al. 1992). The many experiences of IWRM around the globe are uneven and in constant evolution. However, they all have two things in common: they have institutionalized the watershed as the standard management scale and they have incorporated sustainability objectives into water policies. Sustainability objectives are a form of normative constraint on the impacts on water bodies and/or their dependent social-ecological systems caused by human quantitative or qualitative appropriation of water.

As the ideas of IWRM spread throughout the world, water science also went global. The burgeoning literature on the *global water system* or *global water governance* (Vörösmarty et al. 2010, Gupta and Pahl-Wostl 2013, Vörösmarty et al. 2013 a and b), mirroring the field of global environmental change, is commonly cited by water scientists to frame research problems. The connections of local processes to global drivers and between human and water systems have become key research issues, as has the question of how to effectively operationalize the overarching concept of *integration* (Madrid 2014 p. 41). These challenges raised the question of interdisciplinarity in water research, where different scientific communities stem from very diverse educational, cultural, and discursive backgrounds (Vogel et al. 2015). While hydrologists worry about how to integrate social sciences into their models (Braden et al. 2009), water governance researchers focus on appraising institutional arrangements and introducing politics into scientific debates (Mollinga 2008, Molle et al. 2009, Hernandez-Mora et al. 2015). Madrid (2014 p. 22) argues that "assuming that we acknowledge the epistemological challenge associated with the complexity of water, 'coping with it' means finding means of effective communication between different narratives". Although the languages of social and natural scientists still encounter many barriers to dialogue that hamper the generation of collaborative knowledge, new endeavors are moving towards integrated studies of socio-ecohydrology (Pataki et al. 2011, Savenije et al. 2013, Madrid and Giampietro 2015). However, these recent leaps in water science that are propelled by ideas of complexity are not so rapidly permeating the water governance arena, which is still caught between old hydraulic practices and heterogeneous experiences of IWRM. In this sense, there are not many analytical frameworks specifically envisaged for the integrated assessment of water policies striving to bridge science-policy gaps (Pahl-Wostl et al., 2011).

This thesis is based on a complex systems perspective on water resources management that can be summarized in three points:

- There are multiple legitimate perceptions about what water is and how it should be managed; these perceptions derive from different constructions of 'nature' and the relationships between social and environmental systems.
- Water systems dynamics is multi-dimensional and multi-scale, and links ecological and social processes; its analysis requires integrated frameworks for social-ecological systems.
- Water is an inherently political resource; its management requires assessments that go beyond the rhetoric of win-win solutions.

Multiple, legitimate and contrasting views on water problem-solving coexist at both the level of scientific knowledge (where different disciplines study water through different framings) and that of decision making (where different groups defend contested interests in the same pool of finite resources). This raises an important epistemological issue in science for water governance: water management strategies respond to dominant constructions about water that are in essence constructions about nature and its relationship to humans. The question then arises as to how to perform a quality control of the relationship between the construction underlying management strategies and the outcomes obtained from these strategies (Kovacic and Giampietro 2015). This appraisal is usually a weak stage in the water management cycle because, as a deeply normative action, it requires the individuation of an external story-teller to perform this check.

As water flows through the water cycle, it links different systems with different operational scales and analytical dimensions (ecological, hydrological, economic, technological, institutional, cultural, etc.) that have usually remained within separated disciplinary domains. Water management involves all these dimensions and thus its assessment requires integrated analytical methodologies capable of escaping disciplinary reductionism and addressing the multi-dimensional impacts and tradeoffs associated with management decisions (Madrid et al. 2013). In relation to this, a plethora of analytical frameworks for social-ecological systems (SES) has emerged during the last decade with different aims and scopes (Binder et al. 2013). The Water Metabolism of Socio-Ecosystems (WMSES) is one of these frameworks and has been specifically proposed for the quantitative integrated assessment of sustainability (Madrid 2014, Madrid and Giampietro 2015). Building on the Multi-Scale Analysis of Societal and Ecosystem

Metabolism (MuSIASEM, Giampietro et al. 2009, 2012, 2014), it constitutes a determined effort to propose a language for the integration of disciplines within water research. The main advantage of the water metabolism approach over other frameworks for SES is that it is specifically designed to deal with multiple scales and dimensions, and thus with the challenges of complexity. In addition, it is semantically open to adaptation to particular analytical objectives and contexts, offering the possibility of creating batteries of meaningful indicators for each of them. However, a remaining challenge in this framework is the conceptual incorporation of institutional and political dimensions, which are essential in other frameworks that address reciprocity between social and ecological systems (Schultz and Binder 2003, Pahl-Wost 2009). On a methodological level, a second challenge is the integration of eco-hydrological modeling with societal metabolism accounting.

If water management strategies are shaped by dominant perceptions, and these are expressed through narratives, the analysis of dominant narratives in management plans and reports can shed light on the bias behind policy implementation and the "'how and why'" of observed social-ecological patterns. Decisions on water management are usually justified through win-win rhetoric advocating the benefits of large infrastructures and technologies, and are usually accompanied by poor assessments of those benefits that lack biophysical and ecological economic perspectives. The WMSES provides a comprehensive framework with which to move forward towards a more complex assessment beyond the reductionism of the monetary dimension. Moreover, I argue that bridging integrated analysis of water metabolism and qualitative policy and discourse analysis is a robust conceptual and methodological framework for the integrated assessment of the implementation of water policies.

Research objectives and questions

The research objective of this dissertation is to assess the implementation of sustainability objectives in water policies in two semi-arid watersheds—the Andarax river basin in Almeria (Spain) and the Tucson basin in Arizona (United States of America)—using a complex systems approach capable of coping with the above-mentioned research challenges. To do so, I aim to bridge qualitative analysis of water governance and quantitative analysis of societal and ecosystem metabolism of water. Thereby, I hope to contribute to the opening of doors for dialogue between social and natural scientists about water management challenges and our role as researchers in working on them.

Besides the specific research questions posed for the two case studies, the following general questions are raised:

- What are the current limitations and challenges for the implementation of sustainability objectives in water policies in the two case studies?
- How does the conceptualization of watersheds as social-ecological systems contribute to the detection of those limitations?
- How can water governance and water metabolism analysis be bridged? Is this bridging a robust methodological approach with which to assess the implementation of water policies? How can the WMSES framework be operationalized in order to link societal and ecosystem metabolism of water at the scale of watersheds?

- What lessons can be drawn from the analysis of two semi-arid watersheds in Arizona and Spain regarding the effectiveness of water management strategies and the discourses and paradigms in which they are framed?

This research therefore pays special attention to the following issues:

- Theory. The WMSES is essentially a conceptual and methodological framework grounded in complexity theory and several related research fields. Understanding, appropriating and changing it, in its own evolution through the work of other researchers, has been an incredible and ongoing intellectual exercise.
- Methods. I propose concrete analytical tools (concepts, grammars, data models and models) with which to operationalize the framework in order to respond to my research questions. In addition, I endeavor to integrate quantitative and qualitative analytical methods.
- Applications. Two practical case studies are presented that respond to specific contextual questions and serve as a basis for the acquisition of some less context-dependent abstractions about water management challenges in semi-arid areas.

Reasons for the selection of these case studies

This dissertation is situated in a constructivist scientific perspective known as *post-normal science* (Ravetz and Funtowicz 1993). I consider that sustainability science must pay special attention to the question "Who reframes scientific questions?" (Filardi 2015). Post-normal science requires that problem structuring and assessment of scientific outcomes should not be developed by the analyst alone but in cooperation with an extended peer community of stakeholders who are affected by the environmental problems under analysis.

The two study areas looked at in this dissertation share a similar semi-arid climate and sun-driven models of economic growth that shape similar situations of social water scarcity. They also share traditional water management ideologies of hydraulic mission (Sauri and del Moral 2001, Molle et al. 2006). Furthermore, they share a background of participatory processes in the last five to seven years that have diagnosed water problems and management challenges. Because these processes had either finished or were ongoing when I started this research, the development of a whole post-normal science cycle was unfeasible. However, the outcomes of those processes allowed a prior understanding of relevant issues and existing perspectives, about which I tried to raise scientific questions and to propose some form of collaboration with stakeholders within my research time constraints.

Locating the observer in the observed: who is the story-teller?

“The problem does not lie within the complexity of what is observed in the external world, rather complexity lies within the decisions of the story-teller about what to observe”. This quote from Giampietro et al. (2006a) raises the question of the transparency of the construct behind any scientific exploration, that is to say, the explicit acknowledgment of the values of the analyst, or the values of the story-teller behind the narratives used by the analyst (i.e. whom the analyst is working for). Kovacic and Giampietro (2015) continue the discussion by arguing that in order for science for governance to become reflexive, this is an essential pre-analytical step.

Barbas-Baptista (2010) proposed that when analyzing environmental conflicts, the story-teller should use the narrative of the victims in order to address power imbalances. However, my focus is not on water conflicts but on water policies. There is no funding institution requiring the adoption of any particular narrative, but I have cooperated with groups that have a stake in water decision-making processes. These stakes generally align with those of environmental protection and/or of improving the democratic quality of water governance. My bachelor's degree is in Environmental Sciences and I am thus a daughter of the environmentalism era. I am also becoming an adult after the financial crisis of 2008 wrecked the aspirations of many of my generation; therefore equity, social justice and real democracy are part of the values I personally pursue. That said, I endeavored to understand all the perspectives that were on the table concerning water management problems in order to be able to look at those realities through complex lenses. I hope to have succeeded in balancing my personal bias and the strong methodological commitment I had when developing this research.

A final note on my values is that I am a faithful advocate of open-source software, open access in science and open ideology in general. It is my belief that scientists should adopt a decisive attitude in making our research accessible to any person on this planet. Moreover, I think that not sharing all the rewards of our research is a source of inefficiency and a hindrance to the progress of knowledge. Joining the current for open and reproducible science, I have organized all the data sets and scripts in a downloadable reusable format that can be found in my Research Gate account and in the following links:

Chapter 2 (see Appendix 2):

https://www.dropbox.com/sh/45za6hqmnjelqoi/AAD-ObuilYtGzFwVKyJ_WzQ5a?dl=0

Chapters 3-5 (see Section 1.3.4):

https://www.dropbox.com/sh/a58jb6vahvsfs2j/AAAdKspBs4dXquwvTisRv2EBa?dl=0

Dissertation structure and chapter summary

The dissertation is structured in four parts. The format presented is a hybrid of sorts between a monography and a compilation of articles, since three of the analytical chapters (2, 3 and 5) are edited versions of existing publications. The decision not to submit a compilation of articles stems from the fact that the conceptual and methodological framework is based on a paper of which I am the second author. The original framework was further developed by the first author, Dr. Cristina Madrid, for her dissertation, and I have in turn adapted it to the objectives of this research.

Part I consists of only Chapter 1, encompassing the theoretical background and the conceptual and methodological frameworks. The first section presents a discussion about the coevolution of scientific and governance paradigms in the environmental and water realms, highlighting the epistemological implications of complexity and some relevant conceptual developments within the field of sustainability science regarding the relationships between human societies and their environments. The second section describes the conceptual framework of the water metabolism of social-ecological systems, and its conceptual bridge to the analysis of water governance. The third section of this chapter proposes a general methodological framework, including the operationalization of the MuSIASEM system of accounting for water use, qualitative methods of discourse analysis and public policy assessment, and a data model for the structuring of geodatabases in water metabolism analysis.

Part II is the first analytical part and focuses on the implementation of the European Water Framework Directive (WFD) in the Andarax basin (Spain). It begins with an introduction to the case study that includes the institutional framework for water management in Europe and Spain, and an overview of the study area and the water management problems identified by regional stakeholders. Following this introduction there are three analytical chapters.

Chapter 2 operationalizes the WMSES in a sub-basin of the Andarax, linking ecosystem and societal water metabolism, as well as the conceptual bridge to water governance within the general analytical framework. A MuSIASEM grammar is formalized, connecting water flows and funds, land uses, human activity, monetary flows and water quality variables. Four types of interaction are explored: between societal organization and water uses/demands, between ecosystem organization and its water requirements/supplies, between societal metabolism and aquatic ecosystem health, and between water demand and water availability.

Chapter 3 analyzes the interplay between water and agricultural policies in the Andarax basin. It starts with a discussion about how the incoherence in European policies is attempted to be resolved at regional level in Andalusia. Then, the water metabolism of the basin is depicted for 2005, the baseline date of the EU Water Framework Directive. In a third step, an integrated characterization of the different agricultural metabolic patterns in the basin is presented. Finally, some trade-offs associated with management decisions are quantified through a scenario exercise that compares official water-demand scenarios of the River Basin Management Plan (RBMP) with alternative scenarios defined through different normative assumptions.

Chapter 4 focuses on the evaluation of the first management cycle of the WFD 2009-2015. Building on the concept of the semiotic process of water management, the appraisal is performed through the criteria of efficacy, effectiveness, efficiency and pertinence, all of these operationalized through the three checks of Hajer (1995): social accommodation, problem closure and discursive closure. Discourse analysis is the main analytical tool used to first of all characterize non-equivalent narratives about water in the Andarax basin, and then identify dominant narratives permeating management decisions. The quantitative analysis presents an update of the water metabolism accounting for 2015, looking at the evolution of societal funds from 2005 to 2011 as well. Based on the previous analysis, the last part discusses the semantic closure of the management cycle through the mentioned criteria.

Part III is the second analytical part and focuses on the implementation of the Arizona Groundwater Management Act (GMA) in the Tucson basin (USA). Similar to Part II, it presents an introduction to the case study that comprises the institutional framework for water management in Arizona, a discussion of the concept of safe yield, and a description of the study area and the perspectives of stakeholders regarding water management challenges. The analysis is presented in Chapter 5 and reviews sustainability debates in the area surrounding water management goals. First, the research looks at the effects on the metabolic pattern of water induced by infrastructural and institutional changes during the last decades. Next, the impact of conservation programs on municipal and agricultural water demand is discussed. Last of all, an assessment of the current spatial management of groundwater (recharge, users, storage and water levels) is developed. The discussion section pinpoints the main challenges of current water management strategies in terms of the achievement of safe yield sustainability goal.

Finally, Part IV contains the conclusions, which are divided into four sections. I first of all summarize the main conceptual and methodological contributions of this dissertation to the field of water metabolism. I then draw conclusions from the two case studies regarding challenges in water governance. I also include some reflections on the interdisciplinary and transdisciplinary experiences in which I was involved in the course of writing this dissertation. The conclusions end with an outlook for future research in the fields of the water metabolism of social-ecological systems and water governance.

Related publications

Peer review journals

Cabello, V. Willaarts, B., Aguilar, M., and del Moral, L. 2015. River basins as socio-ecological systems: Linking levels of Societal and Ecosystems Metabolism of Water in a semiarid watershed. *Ecology and Society* 20(3):20.

Cabello Villarejo, V., and Madrid Lopez, C. 2014. Water use in arid rural systems and the integration of water and agricultural policies in Europe: the case of Andarax river basin. *Environment, Development and Sustainability* 16(4):957–975.

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

Book chapters

Cabello V., Hernandez-Mora N., Serrat-Capdevila A., and del Moral L. 2016. Water use and sustainability in the Tucson basin: implications of a spatially neutral approach to groundwater management. In Gupta H., Gupta M., Poupeau F., Serrat-Capdevila A., (Eds) *Water in the Desert. A transatlantic transdisciplinary dialogue.*

Working papers

Serrat-Capdevilla A., Cabello-Villarejo, V., Boyanova K., Poupeau F., Rodriguez, D., Salmoral, G., Segura, S., Yang, Z. 2014. *Analyzing new challenges for water management: a review of existing conceptual frameworks and outlines for a trans-disciplinary approach*. Deliverable 5, Supplement 1. Sustainable Water Action –SWAN- EU Incolab FP7 project. http://swanproject.arizona.edu/sites/default/files/Deliverable_5_Supplement1_web.pdf

Madrid, C. & Cabello, V., 2011. *Re-opening the black box in Societal Metabolism: the application of MuSIASEM to water.* ICTA Working Paper. http://www.recercat.cat//handle/2072/172087

PART I

The framework

Chapter 1. Theoretical, conceptual and methodological framework

1.1. Background

1.1.1. Paradigms, narratives and management models: the loop between science and policy making

Saying that scientific knowledge is socially produced might sound a truism, but it has been a long way from realism to post-structuralism and constructivism perspectives. However, in words of Naredo (2006), not everything is a construct, and environmental degradation continues despite our tangled and diverse interpretations of ‘the problem’. Khun (1962) notion of paradigm is used to condense the set of ontological and epistemological assumptions that are socially acceptable in successive historical periods. It refers to existing scientific consensus around i) what has to be observed, ii) what type of questions can be asked, iii) how these questions can be structured and iv) how research results can be interpreted (Pahl-Wostl et al. 2011). Therefore, paradigms delimit problem structuring, methods to be used and the criteria through which scientific outputs are legitimized and become useful for society. The emergence of a new paradigm is usually opposed to a pre-existing one that is deemed incapable of dealing with problem-solving. However, paradigms are not immutable pyramids applying homogeneously around the world. Rather, they represent the main scientific consensus in specific contexts and given timeframes. On one hand, multiple paradigms coexist and strive to supersede each other over decades or centuries (Pahl-Wostl et al. 2011). On the other hand, political cultures act as filters of sanctioned scientific paradigms (Jasanoff 2005 p. 21). The concept of paradigm relates to that of scientific narratives or intentional expressions of the point of view of different framings of a reality (Allen and Giampietro 2006, Leach et al. 2010). Advocates of a paradigm develop their own new narratives to dialectically compete with the other and create shared meaning. After all, scientific progress is also about rhetorical battles.

Madrid (2014 pp. 33) defines the water discourse as the sanctioned narrative about how water shall be studied and managed that result from the entanglement of the multiple scientific, social and political co-existing narratives. Obviously, not all narratives have the same influencing capacity and the social life of one particular concept or narrative very much depends on whose interests decide to appropriate it (Molle 2008a). Pahl-Wost et al. 2011 and del Moral et al. 2014 apply the paradigm concept to the realm of water management to designate “the set of basic assumptions about the nature of the system to be managed, the management goals and the procedures through which these goals are pursued”. The paradigm is shared by an *epistemic community* of actors (academics, practitioners, decision-makers) in charge of the generation of the relevant legitimate knowledge (Haas 1992). Management paradigms are expressed in form of the different devices used for management: type of infrastructures, planning approaches, regulations, engineering practices, models, etc. Molle 2008a differentiates between nirvana concepts (or overarching management frameworks), narratives (or story-lines expressing causal or explanatory beliefs) and models (or practical policy implementations). Management models and strategies are therefore concomitant to the dominant paradigm in each context, in constant re-working and re-framing through the multiple narratives contesting it.

Narratives shape paradigms and paradigms shape narratives. By now we have learnt to live with chicken-eggs dilemmas through the only linearity of time. Thus one can assert that: i) The relation between knowledge generation and political practices is a loop without one sole linear entailment direction, thus ii) one can analyze the interplay between scientific narratives and management models and vice versa, deployed within nirvana concepts or paradigms. This section is devoted to review the evolution of relevant scientific and governance paradigms in the water and environmental realms of the last decades, the influences and mismatches between them that are relevant to the purposes of this research.

1.1.2. Evolving governance paradigms

Water management

Several authors have proposed a historical perspective on the evolution of water management discourses. Savenije et al. 2013 summarize it as "until the 1970s, the field of water management was known by the term 'water resources development'. In the 1980s, it became more popular to speak about 'water resources management' and in the 1990s about 'integrated water resources management'". Turton 1999 distinguishes four phases he accurately named 'getting more', 'end-use efficiency', 'allocative efficiency', and 'adapting to absolute scarcity'.

Allan (2006) discusses five water management paradigms that have superseded in semi-arid western countries during three historical periods (Figure 1.1). According to him, the first paradigm was that of pre-modern societies that developed water management systems with the limited available power capacity but that were sustainable for long periods of history, especially in semi-arid areas. The second paradigm of industrial modernity was enabled by the steam engine and reinforced concrete, coupled to the development of hydrological sciences and engineering (Savenije et al. 2013). This paradigm is usually referred to as the hydraulic mission or hydraulic paradigm and has been described in many arid and semi-arid regions of the world in different periods (see Reisner 1993, Allan 1999, Faggi 1996, Feitelson 1996, del Moral and Sauri 1999, Swyngedouw 1999, Molle 2006, Hutchinson et al. 2010, del Moral et al. 2014). This dominant paradigm from the late nineteenth century to the sixties in western countries was later exported to impoverished countries. The discourse underpinning this paradigm is that of nature as something to be tamed in order to pursue progress and development, by modernizing barren landscapes and incrementing water availability through large engineering works. Both the United States, with the Tennessee Valley Authority in the Roosvelt mandate, and Spain, with the *Regeneracionismo* movement, were pioneers of this management model (del Moral and Sauri 1999, Molle 2006). They were also primary experiments of institutionalization of the river basin as water management scale. Two distinctive characteristics of the hydraulic mission are the centralized organization through state bureaucracies and hydraulic engineers as prominent public figures of modernization (Molle et al. 2009). The win-win-win rhetoric of flood control, rural poverty override and cheap hydroelectricity prompted powerful epistemic communities (big land owners, engineers and building and energy companies, under the umbrella of acquiescent political leaders) that have been reproduced as dominating elites in water decision-making until our time (Hernandez-Mora et al. 2015).

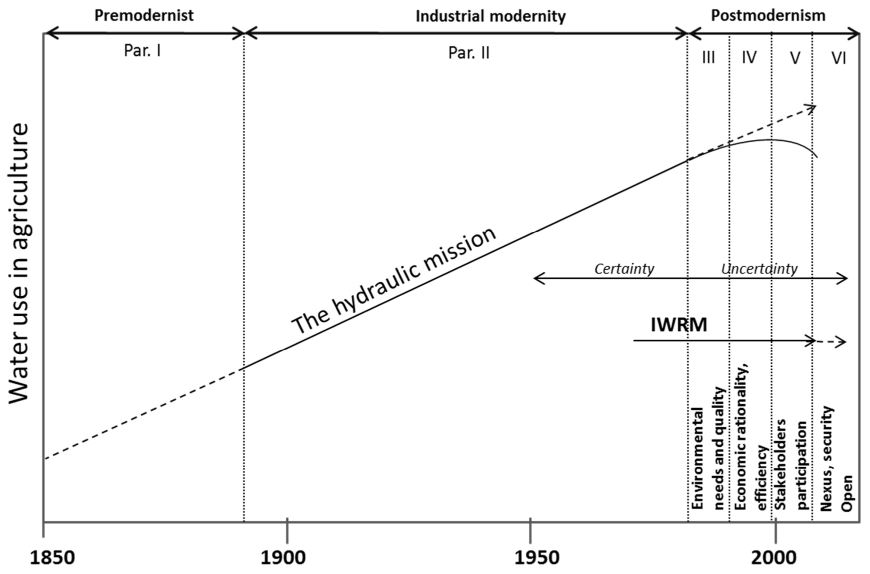

Figure 1.1 - Water management paradigms. Adapted from Allan 2006 and Madrid 2014

Around midcentury, the effects of the industrial revolution over the environment and public health triggered the emergence of a new social narrative, environmentalism. The green movements rising in the sixties and seventies in the United States, but also the European May 68, and their ensuing worldwide influence, fostered a new cultural epoch that Giddens et al. 1994 termed 'reflexive modernity'. This concept served as a basis to reassess sociology as a science of the present (moving beyond the early 20thC conceptual framework). In addition, it provided a counterbalance to the post-modernist paradigm offering a re-constructive view alongside deconstruction. The awareness over the global risks induced by environmental problems (Beck 1998) begot a detachment of social perception over scientific certainty and 'truth' as something that is scientifically demonstrable. Relativism or constructivist epistemologies were the most impactful outcome of those movements on science (Pahl-Wost 2011).

Reflexive is a good term to refer to the rapid incorporation of new concerns into the water discourse during the last forty years. Allan considered three phases (Figure 1.1): III- the raise of environmental awareness that permeated the policy realm during the 80s; IV- the consideration of economic concerns and the value of water for economic productivity; and V- the incorporation of participatory approaches in water planning. He discusses this last shift as the acknowledgement of water management as a political process in which contrasting interests need to be balanced. To this purpose, inclusive consensual-seeking participatory processes have to be arranged in water planning and management as means to gain legitimacy and give voice to underrepresented groups.

Even though their linearity is a bit faulty, these cumulative concerns underpin the IWRM paradigm that emerged after the approval of the Dublin Statement on Water and Sustainable Development (Dublin Principles) at the 1992 International Conference on Water. Koudstaal, Rijsberman and Savenije 1992 wrote the first description of the framework around the core concept of *integration*. Under its umbrella, they pinpointed a series of aspects like the consideration of both water quantity and quality of both surface and groundwater, the inclusion environmental water requirements, the combination of public and private management models and the take on participation of stakeholders. One of the most significant changes was the emphasis on water-demand control incentives like pricing and efficiency in combination with standard water-supply increment. Cooperation between public and private entities was clearly embraced, considering central state planning a source of corruption and inefficiency. The post-Cold War mistrust to public interventions on the economy is evident in their narrative, so it is the emerging neo-liberal advocacy for market solutions to environmental problems.

Nowadays, IWRM is considered the dominant paradigm for water management (Pahl-Wost et al. 2011, del Moral et al. 2014, Mancilla-García 2015), albeit implementations are as heterogeneous as the debates around their effectiveness, and the continuous reinterpretations of the framework. The lack of a clear definition, consistent enforcement strategies and evaluation procedures has resulted in a myriad of contextual-adaptations which results are yet to be assessed (Stefano 2010). Some well anchored experiences are the South-African National Water Act in 1998, the European Water Framework Directive 2000 or the 2004 Intergovernmental Agreement on a National Water Initiative in Australia. In the United States there is another more extended narrative that focuses on ecosystems management rather than on separated resources: adaptive management (Williams 2011). Rather than an overarching framework, it is a practical proposal to handling uncertainty through iterative cycles of planning, action and evaluation that enable social learning and adaptation in each of the iterations. More recently in 2013 the United States Army Corps of Engineers launched an on-line Federal Support Toolbox to provide Integrated Water Resources Management information (del Moral et al. 2014).

Discussions around the ideas and the practice of IWRM have raised some important critics:

- The ambiguity of concept of integration allows its appropriation by many types of players emphasizing those aspects that align with their interests while disregarding others. For this reason, Molle 2008a labels IWRM a nirvana concept, also known as boundary objects in sociology, concepts that resist disambiguation (Jasanoff 2005 p. 27). While this malleability is necessary for context-adaptation of a 'panacea', it has also enabled the maintenance of old elites and coalitions with a renovated, but not embodied, discourse (Biswas 2004).
- The maintenance of a win-win-win rhetoric associated with new challenges of social equity, economic efficiency and environmental sustainability, fostered through the inclusiveness of integration. The problem is that the three Es are commonly antagonistic under the current economic system, but the conflict among them is avoided through techno-social fixes and managerial strategies (Loris 2008, March et al. 2013). This is related to an insufficient recognition of the political dimension of water management that keeps on being reduced to technical procedures and right knowledge. Associated to this rhetoric is the maintenance of a techno-managerial vision, with the figure of the 'expert' extoled as well as the role of the scientist as certainty providers (Pahl-Wost et al. 2011).
- The lack of consideration of inequality and power dynamics has yielded unsuccessful participatory approaches used to legitimize pre-existing power structures (Hernandez-Mora et al. 2015). This is what Swyngedow 2011 refers as post-political regimes where

water decisions are reduce to management, that is, to decisions located at the level of 'policies', where problems and courses of action have been pre-framed, and not in the realm of the 'political', where the antagonistic struggle among contesting views challenges power dynamics.

- The embeddedness in a general economic context of neoliberal globalization, that found in IWRM a favorable narrative to pursue privatization processes under monetary reductionism (del Moral et al. 2014). These processes enabled the formation of a new epistemic community by multinational corporations and global institutional partnerships colonizing the previously state-public infrastructures with the logic of decentralization, de-regulation and private marketization.
- The maintenance of the pre-eminence of the river basin scale in detriment of other relevant geographies, disregarding the debates around its appropriateness (Budds and Hinojosa 2012, Del Moral and D'O 2014).

Despite all these debates, IWRM is recognized to have brought new issues to the discussion table, such as environmental requirements or the plea for good governance, and given voice to new players (Molle 2008a). In addition, it is a clear manifestation of new forms of understanding the relations between social and environmental systems and the need of new scientific holistic frameworks to operationalize the concept of integration (Pita et al. 2014, Madrid 2014). New scientific narratives rooted in visions of complexity, such as the security and nexus approaches (Muller 2015), and the burgeoning concept of SES (discussed in next section), open new avenues for another reflective screw turn to IWRM. The global movement against privatization of public services, claiming for remunicipalization of urban water supply, the critics around post-political governance regimes (Swyngedow 2011, 2012) or the claims for more open democracies and accountable governments (Pedregal et al. 2005), are emerging social phenomena that will influence next decade of water narratives. How collaborative decision-making approaches can improve the efficacy and legitimacy of water policies, or their environmental and equity outcomes is still a question open to debate (Newig and Fritsch 2009, Parés 2011, Hernandez-Mora et al. 2015).

Sustainable development

Sustainable development and sustainability are the boundary objects par excellence in the environmental realm hitherto. They paved the way for the emergence of IWRM, and they epitomize the question of science for governance in the challenging task of producing relevant scientific knowledge to advice policies capable of diminishing environmental damage (Martens 2006). Gómez-Baggetum and Naredo (2015) pinpoint three main factors underpinning the rise of environmental social movements during the 70's: the impacts of pollution over public health, the rapid population growth and the peak in oil prices in 1973 that brought back concerns over resources scarcity. Mirroring these processes, a radical critique to mainstream economics launched the debate about the impossibility of infinite growth in a finite planet, setting the ground for the new heterodox fields of bioeconomics and ecological economics (Georgescu-Roegen 1971, Odum 1971, Commoner 1971, Daly 1973).

According to Gómez-Baggetum and Naredo (2015), first debates in the political arena echoed these critiques to economic growth as unequivocal political objective, and aimed at opening avenues for a reorientation of economic models to face challenges such as equality and well-being with a strong emphasis on the role of public regulation. Examples of these where the Club of Rome report Limits to growth (Meadows et al. 1972), the first Earth Summit held in Stockholm in 1972 that prompted the creation of the United Nations Environmental Program (UNEP), and the Cocoyoc Declaration[1] promoted by UNEP and the United Nations Commission on Trade and Development (UNCTAD) in 1974. The declaration points at colonial control, inequality and wealth distributional aspects across countries, as well as to the exclusive pursuit of GDP growth and free market, as key underlying forces for environmental degradation.

However, these initial radical claims were soon overridden by a new more inclusive narrative: sustainable development came into scene in 1987, bringing back the bond between economic growth and environmental protection. The report Our Common Future was released by a new institution, the World Commission on Environment and Development, independent of United Nations and commissioned by the Prime Minister of Norway Gro Harlem Brundtland. The discursive strategy in the report shifted the crux of the matter from wealth and inequality to poverty, from growth as the cause to growth and international trade as the solution, and from public regulation to private entities and decentralized governance (Tovey 2009, Gómez-Baggetum and Naredo 2015). This discursive shift is what Hajer (1995) termed 'ecological modernization', a discourse that poses economic growth and free trading as absolute political objectives to pursue social equity and environmental protection, under the sole supervision of existing international organizations and agreements.

This narrative became hegemonic in environmental governance, gaining support throughout the subsequent Earth Summits Rio 92 and Rio+20, the UNEP proposal for a green economy (UNEP 2011) and the recent draft of United Nations Sustainable Development Goals 2015-2030 (UNSDKP 2015). Sustainability has been translated into a matter of technical innovation for eco-efficiency or more value for less environmental impact, and market-based mechanisms to cope with distributional issues (Ehrenfeld 2012, Curran 2009, Leach et al. 2010, Gómez-Baggethum and Naredo 2015). The purportedly win-win-win among the dimensions of sustainability should be fostered through innovative business, decoupling of resources extraction from production and stewardship (Shellenberger and Nordhaus 2007, Hecht et al. 2012). Under this 'for the sake of economy and the environment' statement, millions devices are being produced without much planning or assessment, usually with public research funds. A good example are the CO2 capturing techno-machinery that has no modeled connection with climate change, just the hope that at some point of the entanglement of non-linear processes, an expected outcome of reduced CO2 concentration will be observed in the atmosphere. Sustainability is promoted at the levels of production, whole supply chains, urban planning, building, without connecting the different scales into comprehensive socio-economic planning (Curran 2009). Thereby, innovation focuses on life-cycle design, incrementing the efficiency of production processes (demand-side), or on reducing discharges to the environment (sink-side) (Stutz 2012). Moreover, sustainable solutions are designed for only one type of resource or problem without addressing effects on others (energy, waste, transport, food) (Kemp and Martens 2007). Innovation for social sustainability is commonly downplayed to changing consumption patterns while aspects like equity, social justice or public

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[1] UNEP/UNCTAD (United Nations Development Programme/United Nations Commission on Trade and Development) (1974) Patterns of resource use, environment and development strategies. Cocoyoc. Mexico, October 8–12, 1974. Available at: http://www.mauricestrong.net/index.php/cocoyoc-declaration

participation are disregarded (Leach et al. 2010, Boström 2012, O'Riordan 2012, Murphy 2012).

Despite the hegemony of the sustainable development discourse, there are also multiple contesting narratives. Since the 70s, ecological economics advocates have focused on unveiling the existence of trade-offs in sustainability decisions, promoting new understandings of the relationships between humans and their environments, and reclaiming a normative view of sustainability (Mishan 1993, Giampietro et al. 2006b, Leach et al. 2010, Becker 2012). Giampietro (1994) shows how the narrowness of scientific analysis adopting one sole scale of analysis leads to the illusion of near-decomposability (Simon 1962). That is, one can ensure to find the positive linkages between sustainability dimensions at one scale by ignoring their trade-offs at other scales. However, what appears sustainable at one scale usually drives unsustainable patterns at another (Martens 2006, Giampietro 1994, Giampietro et al. 2012). This is what happens with most technical innovations that focus on just one scale (for instance improving energy efficiency of specific products), without looking at the wider picture (rebound effects on overall consumption or social change induced by new technologies). The non-linearity of cross-scale interactions makes it very difficult to demonstrate the linkages between technological innovation and outcomes on the environment. Moreover, the high uncertainty of the temporary scales of benefits (the coming generations), liaised to reductionist methods to calculate current costs (monetary costs-benefit analysis), hamper the social desirability for sustainability policies (Giampietro 1994). Political ecologists meanwhile have maintained the critique to the limits of growth proposing new counter-narratives around degrowth (D'Alisa et al. 2014), and centering the attention on conflicts around distributional aspects, access and control to natural resources (Martínez-Alier and Elguea 2005).

Sustainability has thus become a rhetoric category, an 'essentially contested concept', that cannot be agreed upon but still emerges from our observations of the world (Ehrenfeld 2008). Global statistics and aggregated indicators show that resources extraction and inequality soared in the last decades (Rockström et al. 2009, OECD 2011). However, rigorous evaluations of the outcomes of sustainability policies in the governance arena are still missing, and the science-policy gap keeps widening (Klauer et al. 2013). The scientific community has endeavored in addressing new challenges derived from measuring, testing and assessing a strong definition of sustainability[2] that embraces dynamics far from equilibrium, incomplete knowledge and multiple contesting narratives (Leach et al. 2010). These are the challenges that the field -or fields- of Sustainability Science is trying to respond to, under the canopy of a new scientific paradigm.

1.1.3. Evolving research paradigms

Complexity

If there is an epistemic concept that moved the ground of western scientific mindsets in the last forty years is that of complexity. Opposing to the mechanicistic or Newtonean paradigm, complexity anchored systems thinking in multiple scientific fields, from physics (Schrödinger 1983, Nicolis and Prigogine 1989), cybernetics (Wiener 1948, Von Foerster 1981) and ecology

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[2] Strong sustainability refers to the opposition to R. Solow idea of full substitutability of natural capital for human or technological capital, i.e. weak sustainability. There are many ecosystem services that cannot be replaced with human-made processes and therefore their conservation should be a constraint to the expansion of impactful human activities. In addition to the need for an eco-integrative economy (Naredo 2006), a strong definition of sustainability should clearly state equity as another main criterion.

(Maturana and Varela 1980, Odum 1983, Ulanowicz 1986); to sociology (Morin 1994, Giampietro 2003), linguistics (Luhmann 1990) or anthropology (Bateson 2000). Complexity has been defined[3] as the multiple interactions between multiple instances or complicatedness (Holland 1996, Ulanowicz 1997, Wolfram 2002); as the whole being more than the sum of the parts or emergence (Simon 1962, Odum 1971); as the ability to self-organize and maintain itself or autopoiesis (Prigogine and Stengers 1985, Maturana and Varela 1980); or as a dialectical process determined by the characteristics of the interaction between the observer and the observed or complexity à la Rosen (Rosen 1985, 1991, 2000). Each of these definitions pose important epistemological issues that demand a serious paradigm shift if one wants to look at a reality as a complex system.

Living with dualities is one the main lessons from complexity, something common in eastern philosophy but that can be overwhelming for western scientific linear thought. This is one of the great contributions of Rosen's modeling theory distinguishing between the observer and the external world or 'the self' and 'the other' and between 'the observed' reality and 'its ambience'. In order to model a complex system, one must be able to recognize a reality as an external identity that can be distinguished from its context. Another dualism was introduced by Mayumi and Giampietro 2006 between the real world 'observed' and our individual 'observations' and representations of it, what they described as the TAO and the NAMED using the words of the Tao Te Ching. Because each representation of the TAO derives from the perception of an observer (based on education, culture, and personal background), another important distinction is between values or meaning (semantics) and models (syntaxes) (Rosen 1991 p. 43, Giampietro et al. 2006a). Values and analytical purposes shape the necessary pre-analytical assumptions of the observer when starting a scientific inquiry. These assumptions include what is the reality that is relevant to observe, which are the expected causal relations between the elements of that reality, what is the relevant scale for observation, which are the narratives underlying the analysis and the later interpretation of the scientific outputs in order to guide action (Kovacic and Giampietro 2015).

Impredicativity refers to the dependency between a system and its context (Giampietro et al. 2011). Impredicative models are context-dependent, meaning that the relevance of the values of variables used to describe the system depend on the context. For instance, one can describe the price of a liter of water as 1.5 euros (context-independent or predicative) or as expensive according to the standard of living of the population (context-dependent). This concept is related to that of autocatalytic loops or positive feedback relations because impredicative relations are closed loops of self-entailment between different levels of a complex system (Rosen 1991 p. 46). The core point with the recognition of feedback loops as the main type of relationship in complex systems is that it forces the analyst to scape linear causality and address chicken-egg dilemmas (Chemero and Turvey 2008). In addition, it uncovers the existence of multiple directions of causality depending on the chosen scale of observation, as has been shown in ecological prey-predator models (Giampietro and Mayumi 2003).

Incommensurability refers to the co-existence of multiple non-equivalent identities of the same system depending on the scale of observation and of the co-existence of different perceptions among the observers. That is, an identity of an observed system is determined by

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[3] Good conceptual reviews of complexity and complex systems can be found in Giampietro 2003 and Gomiero 2004.

an agreement about a relevant perception of the investigated system considered as an entity distinct from its background, and from other systems with which it is interacting (Giampietro 2003:26). Non-equivalent means that the spatial or temporal scales used to represent the different identities cannot be reduced to each other without losing relevant information. For instance if one splits a sugar lump into its molecular components you lose the emergent property of its flavor. Munda (2004) describes two types of incommensurability. Technical incommensurability refers to the existence of non-equivalent models in different scientific disciplines to describe the same reality and it is the challenge of interdisciplinary approaches. For instance the observations by an ecologist will never be framed in the same way than a sociologist or an engineer; a pond will never look the same if you model its phytoplankton or its hydrological regime. Social incommensurability refers to the existence of different story-tellers interpreting the outputs of a scientific inquiry according to their perceptions, translating them into non-equivalent narratives to guide courses of action.

So the question turns into which type of representation is the analyst developing, under which type of assumptions, and which narratives do the outputs reinforce. The explicit acknowledgement of the key role of normative choices in both the encoding and decoding modeling phases is what Kovacic and Giampietro (2015) name reflexivity. They argue that in science for governance "the focus should shift from the quest for truth to the quality check of scientific information with respect to social and political goals". These issues are rarely found in most scientific literature that assumes modeling activity as the generation of objective knowledge. Indeed some types of simple observations under certain type of conditions are difficult to refute. But when dealing with problems in which science attempts to trigger action in society, we enter a very fuzzy area between descriptive and normative practices. According to these authors, "objectivity can only be understood as a validation of the underlying narrative assumed to be valid by within a given social setting". This is illustrated by the concept of civic epistemologies of Jasanoff (2005 pp. 255-271), which shows the dependence of the pathways to building objectivity, validating scientific knowledge and making collective choices on historical and political cultures.

Uncertainty is another essential characteristic of modeling complex systems. According to van Asselt (2000), there are two main sources of uncertainty: variability of the external world and insufficient knowledge. In addition, there are some forms of uncertainty that can be measured somehow, while there are others that are incommensurable (structural uncertainty). Leach et al. (2010) differentiate four type of situations in uncertainty: i) risk as a situation in which we know the possible outcomes of an action and their probability distribution; ii) uncertainty as situations in which the probability distribution is unknown; iii) ambiguity, referring to situations in which there is disagreement characterization of the outcomes because of different perceptions about them; and iv) ignorance, when both outcomes and probabilities are unknown, or when we ignore what we don't know. In their analysis, the two first types - risks and a strict definition of uncertainty- are measurable. For instance, uncertainty in hydrology is related to the lack of data series and the reliability of hydrological models (Montanari 2011). This is a measurable uncertainty of the model development process. A myriad of quantitative and qualitative methods have been developed to deal with it (see for instance Liu and Gupta 2007). The other two are sorts of structural uncertainty.

Knight 1964 distinguished four sources of structural uncertainty associated to i) perception (we cannot fully represent the TAO); ii) anticipation (we only have the past to anticipate the future); iii) effect (we cannot know the consequences of our actions) and iv) implementation (we cannot know what will be the outcomes of the implementation of policies and regulations). Mayumi and Giampietro (2006) deemed the perception uncertainty as the most important source because it is at the beginning of any form of inquiry about the external world. In addition, they pose another type of uncertainty specific to self-modifying or reflexive systems, i.e. human societies, which is the uncertainty associated to goal selection and to problem structuring. This is especially relevant in sustainability issues were different stakeholders pursue different goals (Giampietro 1994).

Structural uncertainties are those related to incommensurability and the point of departure of post-normal science for situations where “facts are uncertain, values in dispute, stakes high and decisions urgent” (Funtowicz and Ravetz 1993 p. 744). In this type of situations, Kovacic and Giampietro (2015) argue, “scientific rigor does not guarantee that the assessment carried out is relevant”. Science for governance of sustainability falls in this type of situations for which Funtowicz and Ravetz propose a different approach to the scientific process. The crux of the matter is that the peer community should be extended beyond the scientist community to relevant stakeholders. This extended community undertakes problem structuring, selection of alternatives to be modeled and the appraisal over modeling outcomes to decide which of the alternatives is ‘more sustainable’.

Sustainability science and the relations between humans and natures

As sustainable development moved into mainstream politics and business, new research fields like ecological economics or industrial ecology flourished within the scope of sustainability science(s) (Kates 2001, Martens 2006, Clark 2007, Kemp and Martens 2007). Rooted in complex systems theory, energetics, thermodynamics, bioeconomics and ecology, sustainability science shifted the center of attention of scientific queries to the relationships between societies and their environments. For over a decade, conceptual and analytical tools striving to cope with the issues of uncertainty, multiple contested perceptions, scales and analytical dimensions have emerged. Some prominent examples are concepts like social-ecological systems (Berkes and Folke 1998), society‘s metabolism (Fischer-Kowalski 1998), ecosystem services (de Groot et al. 2002), or planetary boundaries (Rockström et al. 2009). As epistemic concepts, they have galvanized interdisciplinary and transdisciplinary work and continue to be revisited and reinterpreted (Becker 2012). In what follows, I introduced three of them that are relevant for this dissertation.

Soci(et)al and ecosystem metabolism

Building on the concepts of self-organizing dissipative systems (Prigogine 1968), autopoiesis (Maturana and Varela 1980), and evolutionary theory (Weber et al. 1989, Brooks et al. 1989), pioneers of theoretical ecology (Margalef 1968, Odum 1983, Ulanowicz 1997) have developed various methodological approaches to the quantitative analysis of the patterns exchange of matter and energy within ecosystems. The rationale of self-organization is useful for establishing a set of expected relationships between the various parts of ecosystems at multiple organizational levels, what is known as integrity or metabolic patterns of ecosystems (Müller et al. 2000, Lomas and Giampietro 2014).

In an analogy, the concept of societal metabolism refers to the processes of appropriation, transformation and disposal of materials and energy of societies in order to maintain and reproduce human activities (Marx 1970, Martínez-Alier and Schlüpmann 1987, Fischer-Kowalski 1998, Swyngedouw 2006, Giampietro et al. 2011). The applications of the concept of metabolism to societies can be traced back to the field of energetics (Ostwald 1907, Lotka 1922, 1956, Zipf 1941, White 1943, Cottrell 1955) and materialism (Liebig et al. 1843, Marx 1970, Swyngedow 2006). However, it reemerged as a strong metaphor for the study of the biophysical needs of human societies with the concerns around sustainability (Martinez-Alier and Schlüpmann 1987, Fischer-Kowalski 1998, Giampietro et al. 2011). The boom of metabolism studies in sustainability science has driven some turmoil around its terminology and definition. Madrid 2014 differentiates between social metabolism as an interdisciplinary research field dealing with sustainability analysis (like ecological economics or industrial ecology) and societal metabolism as a property of societal systems using biophysical flows to organize themselves. In this sense, both society and ecosystems can be interpreted as complex, self-organizing, dissipative systems capable of stabilizing their own identity by reproducing defined metabolic patterns (Giampietro et al. 2011). Recent works are complementing the analysis of societal metabolism with that of ecosystem metabolism (Lomas y Giampietro 2014, Serrano-Tovar and Giampietro 2014) or directly propose hybridized social-ecological metabolism studies (Madrid 2014).

Social-ecological systems

SES, or coupled human-natural systems, are a specific case of complex systems focused on the interactions between humans and natures[4] (Berkes and Folke 1998, Ostrom 2007, Liu et al. 2007). The concept was propelled onto scientific stardom after Elinor Ostrom published her framework in Science in 2007. Descriptions and analytical frameworks have flourished since then without epistemological consensus (Farhad 2012). Common definitions include characteristics such as open, self-organized and adaptive systems (Resillience Alliance 2010, Walker et al. 2002), with none-linear dynamics and thresholds of transition between states (Liu et al. 2007, Berkes et al. 2003) and with emergent properties as a consequence of their multi-level organization (Holling 2001, Müller and Nielsen 2008). Some aspects of divergence concern the consideration of some form of conceptual separation between societies and ecosystems (thus implying interfaces between them) or as completely intertwined hybrids (Swyngedow 2006), their formalization as hierarchies (Giampietro 2003, Madrid and Giampietro 2015) or as networks (Janssen et al. 2006), and their modeling aims as exploratory (Ulanowicz 1997) or predictive (Walker et al. 2002).

In an effort for systematization and guidance for researchers, Binder et al. (2013) develop a comparative review of ten well-established SES analytical frameworks (Figure 1.2). They depart from a classification based on three criteria: the direction in which the interaction between social and ecological systems occurs; the perspective from which the ecological system is conceptualized; and whether it is an analysis oriented or an action oriented framework.

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[4] The plural is intentionally used to reject the idea of one sole ontological category of nature to which a plurality of humans relates.

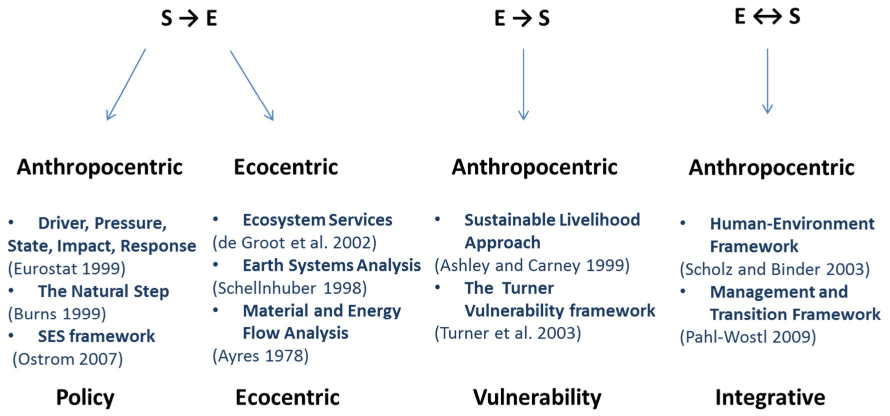

Figure 1.2 - Binder et al. (2013) classification of SES analytical frameworks. Ecocentric and policy frameworks analyze the effects of the social system over the ecological system (S→E); vulnerability frames face how the ecological system affects human systems (E→S); integrative frameworks consider the reciprocity of interactions (E↔S). The three latter categories include anthropocentric frameworks that observe the ecological system from the social system perspective.

According to the authors, from all the compared frameworks only two of them deal with the reciprocity between social and ecological systems. They do so by explicitly addressing some form of feedback relations. These are the Human-Environment Systems framework (Scholz and Binder 2003, Scholz and Binder 2011) and the Management and Transition Framework (Pahl-Wostl 2009, Pahl-Wostl et al. 2010, Pahl-Wostl et al. 2011). Both of them address the interface between social and ecological systems through institutional and policy analysis.

The Human-Environment Systems framework bridges interesting elements from psychology and political sciences, considering a mutualist relation between social and ecological systems, which are observed from the human perspective. It establishes a hierarchy of the human system organization, whereas the scales of the ecological system are set according to problem perception. Society is considered as composed by four subsystems: economic, legal, political and cultural, all of which are regulated by institutions at different hierarchical levels. Institutional settings are deemed the boundary conditions for social organization, and regulatory mechanisms are the cross-scale interactions in the social hierarchy. Feedbacks are characterized as interactions between short term (first order) and long term (second order) impacts on the ecological system and the decision-making process (described as a process of goal set, strategy selection, action implementation and evaluation). 'Environmental awareness' is designated as the linking category shaping these loops. Once a whole decision-making process has been implemented, if there is evaluation of impacts there is learning and feedback of first order occur. Secondary loops appear whenever long-term monitoring systems are established to measure slow moving response.

The Management and Transition Framework was specifically envisaged for the appraisal of water governance regimes. It builds on three thematic areas: adaptive management, social learning/regime transitions and the Ostrom (2005) institutional analysis framework. The 'water system' it composed by ecological, social and technological subsystems. The relations of the ecological systems to the social systems are characterized by environmental services and hazards. The feedback loop is related to the social learning cycle, characterized through several elements and mechanisms (actors, action arena and action situations). The 'operational outcomes' of this cycle are regulations on the use of ecosystem services and on hazards prevention. In this case, the linking concept is the 'change in the perception of the system state' and includes sustainability assessment as a specific element of this change. The framework does not consider a hierarchical organization of SES and its emphasis is on governance arrangements and understanding formal and informal political processes.

Socio-Eco-Hydrology

Mirroring the research field of global environmental change (Buttel et al. 1990, Price 1990), and the scientific and managerial development of IWRM, water governance research has gone global in the last years (Vörösmarty et al. 2010, Hoekstra et al. 2012, Pahl-Wostl et al. 2013, Vörösmarty et al. 2013 a and b). In addition to the consideration of the connections of wider scales to the traditional watershed, hydrologist started to acknowledge the need for more holistic approaches to coupled water-human systems (WHS) (Braden et al. 2009). Discussions around how to operationalize interdisciplinarity in water research are bourgeoning (Braden et al. 2009, Serrat-Capdevila et al. 2014, Vogel et al. 2015): how can we bridge social and natural sciences to address water problems? Should human-footprints be integrated in hydrological models and decision support systems? Can we integrate different disciplinary frameworks, or the best we can expect is to have open disciplinary discussions? How can we foster collaboration when educational backgrounds restraint common language for dialogue?

There are two important currents facing these questions. On one side, eco-hydrology is a well-developed research area focused on the interactions between hydrological and ecological processes (Smettem 2008, Gill 2011, D'Odorico et al. 2012). On the other side, recent proposals of socio-hydrology are sitting together social scientists and hydrologist to work on a common understanding of the societal drivers of water resources degradation (Sivapalan et al. 2012, 2014, Sivakuma 2012)[5]. A logical merge of these trends comes in hand of the overarching socio-eco-hydrology (SE-hydrology) (Pataki et al. 2011, Savenije et al. 2013, Madrid and Giampietro 2015). Madrid 2014 develops a theoretical dissertation on the need to integrate social metabolism studies and SE-hydrology, providing a conceptualization of SES that eases integration for IWRM (Madrid 2014 p. 78). To do so, the author depicts the WMSES bridging a definition of coupled water-human systems as complex systems, and virtual water theory. This framework is the point of departure of this dissertation and is further presented in the next section along with its adaptation to my research objectives.

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[5] The American Geosciences Union Annual meeting is holding interdisciplinary sessions about socio-hydrology https://agu.confex.com/agu/fm14/meetingapp.cgi#Session/4928
http://fallmeeting.agu.org/2014/events/sociohydrology-modeling-and-synthesis/

1.2. Conceptual framework

1.2.1. A complex look to water use

Water resources degradation is a complex environmental problem that involves multiple analytical dimensions, scales and perceptions. As explained, water science is evolving towards more interdisciplinary approaches in the recognition of the human alteration of the global water cycle (Vörösmarty et al. 2010), yet there are not many comprehensive frameworks designed to cope with the multiple interwoven magnitudes of such problems. Quantitative methods that strive to link the analysis of water uses to their impacts on ecosystems have usually focused on (i) physical flows associated to specific production activities or geographic scales (water footprint); (ii) combination of physical flows with monetary flows (extended water footprint); (iii) analysis of the relation between physical and economic flows contextualized by trade and markets (virtual water)[6]. However, none of these approaches deal with two sources of complexity that are specific to water as resource. First, water has different meanings for different actors in different context, and also for different scientists from different disciplines. Second, water systems operate at several interconnected levels, in which they express different identities that cannot be reduced to each other.

The multiple definitions of water as a resource

Water is defined as a public good, a heritage, a human right or an economic asset, just to name a few. These definitions depend on the narrative of the story-tellers, on their values, interests and goals; therefore they are non-equivalent. The definition of 'what water is' and 'what is useful water' is a prior source of uncertainty in water research. In fact, different understandings – i.e. perceptions and representations - of the 'element water' will lead to the adoption of different assessing methodologies, with different quantitative results and ensuing diverse advices to water management options. Most of the methods for water use analysis employ fixed definitions of water, for instance the well-known blue and green water footprint. The problem with *semantically closed* definitions is that they cannot address the shifting identity of water among contexts. Does green water mean something relevant everywhere? Closed definitions are also too rigid to be adapted to different scientific or governance goals. For instance if one wants to address the interaction between surface and groundwater flows, the blue water footprint that aggregates both of them together is of little utility.

There are some flexible definitions of water such as a 'multi-functional' resource, referring to the fact that water can be "used in different sectors and within these sectors it can be used for different purposes and for different functions" (Allan 2001); or as an 'eco-social asset' (Aguilera Klink 1995) emphasizing the idea that water provides many benefits for ecological, economic and social systems at the same time. These definitions embrace the idea of multidimensionality derived from the cyclic nature of water as compared to other resources like energy (Madrid 2014 p. 66). That is, water does not change its chemical composition but just its characteristics as it flows through the water cycle from one use to the next one. What changes are its attributes that make it a resource for specific end-uses.

This idea is connected to the definition of what a resource is. Zimmermann coined the famous sentence 'resources are not, they become' (Zimmermann 1951 p. 15), meaning that they

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[6] A review of water accounting methodologies can be found in Madrid 2014.

cannot be defined in substantive terms but only as a function of their utility. Thereby, a certain volume of water becomes a resource if it can provide a service to an end use (Madrid and Cabello 2011). To qualify as 'useful to provide a service', water must have a certain set of attributes regarding its quantity, purity, pH, temperature, temporal and geographical reference or cultural meaning. What is useful for some purpose at some scale and in some context will not be in another. For this reason *semantically open* definitions of water resources are more useful in integrated analysis.

The dimensions and levels of water systems

Water systems have been represented using multiple analytical lenses: hydrological, ecological, institutional, cultural or socio-economic, among others. Each of these dimensions is a criterion for observation that draws a descriptive domain; this is 'the domain of reality delimited by interactions of interest' (Kampis 1991). Complex systems are commonly depicted as organized in nested hierarchies, in which different identities are expressed at different levels of observation. Hierarchies have been described for ecosystems (Allen and Hoeckstra 1992, Jørgensen and Nielsen 2013), hydrological systems (MacLachlan and Moulton 2006, Li and Ren 2010), institutions (Gupta and Pahl-Wostl 2013), agro-ecosystems (Giampietro 2003, Ewert et al. 2011) and social systems (Scholz and Binder 2003, Giampietro et al. 2014).

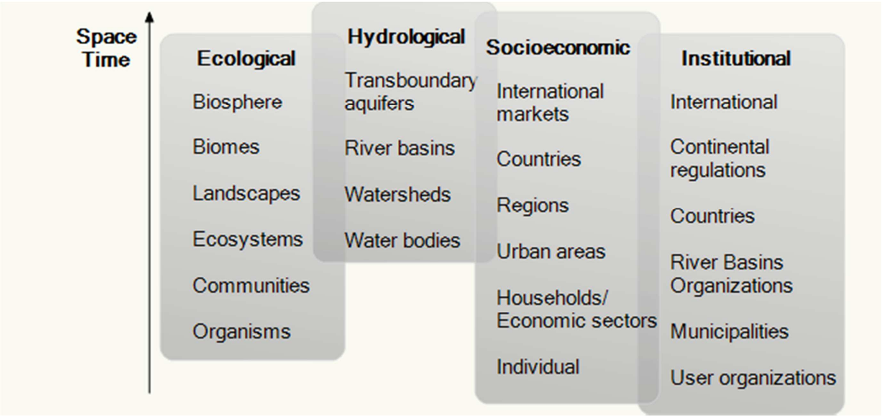

Figure 1.3 - Hierarchies in different descriptive domains of water systems. Adapted from Ewert et al. 2011

Choosing a descriptive domain means choosing a narrative and a story-teller and allows recognizing an identity of the water system (dimensions and levels to analyze) and determining corresponding observation scales. From the multiple understandings of scale, here scale is defined in a geographical sense by the extent of the temporal or spatial boundaries of the description (the extent) and its resolution (or grain) (Turner et al. 2001). On the other hand, levels refer to the criteria chosen to depict a complex system as a hierarchy (Allen and Hoeckstra 2000 p. 8). Levels result from the composition between the observed system and the observer interests. It is the analyst who sets these criteria according to decisions about i) which are the relevant parts of the system whose interactions generate emerging patterns in the system as a whole (lower levels in the hierarchy); and ii) which are the relevant contexts stabilizing boundary conditions of the system (upper levels in the hierarchy). There is a tendency to augment the size of the system, and thus its scale, with the level, but hierarchical levels can be analyzed at any temporal and spatial scale (we can study a rock holding it with our hand or looking through a microscope) (Allen and Hoeckstra 2000 p. 53).

Madrid (2014 p. 65) proposes the integration of at least three descriptive domains, or story-telling, in the analysis of water metabolism. In turn, the individuation of different story-tellers enables the definition of analytical scales as the extents and grains required to generate useful representations for guiding action:

- The Earth metabolism of water refers to the global water cycle, a system that metabolizes energy in order to maintain the boundary conditions for life in this planet. This is the descriptive domain of climatology and atmospheric sciences. This story telling is relevant to study the processes guaranteeing the stability of boundary conditions in the biosphere.
- The ecosystems metabolism of water is studied at intermediate levels, bridging the very large scale of the global water cycle to the local scales of social water use. This is the *watershed* descriptive domain, studied hydrology and ecology, dealing with the reproducibility of water resources in the interface of the water cycle and eco-hydrological processes. At these levels, water is a structural part of ecosystems, a determining factor for their distribution on Earth. This story telling can require the use of more than one scale, depending on the nature of the problem to be considered.
- The societal metabolism of water studies the use of water resources for the maintenance of human societies. This is the *problemshed* descriptive domain of social sciences and water use accounting methods (Allan 1998). At these levels, water is a metabolite, a substance that is used and transformed in order to maintain socioeconomic processes, and which appropriation transforms the hydrological system impacting living systems depending on it. Also in this case, several scales can be required to characterize problemsheds of different sizes.

Distinguishing descriptive domains does not mean that social and ecological processes are separated. What it means is that the story-telling and analytical scales for generating useful representations of their functioning are different. This is why they have been compartmentalized in scientific disciplines and why SES frameworks that strive to bridge them together require interdisciplinary approaches.

A metabolic definition of water use

Taking into account the multiple dimensions, definitions of water as a resource and analytical levels, *water use* would allude to the services that a given volume of water provides for the maintenance of metabolic patterns at each domain of a water system. This definition aligns with that of water ecosystem services from Aylward et al. (2005) that Madrid (2014 p. 77) arranges on a multi-scale basis: the water cycle functions provides services to ecosystems, which functions provide services to societies, which functions provide services to individuals. Water flows ‘down’ from the water cycle through ecosystems improving its qualitative attributes in a way that increases its value for human end uses, thus becoming a resource (Brauman et al. 2007). Once it is used by humans, water useful attributes are degraded, returning to the water cycle that recycles them again and again.

A metabolic analysis of water use at the interface society/ecosystem should look at both internal constraints (how and why water is used inside the society) and external constraints (how ecosystems generate useful water and societal water uses impact ecological processes) of a metabolic pattern. This means that it is necessary to deal with feedback relationships between societal and ecosystem processes.

1.2.2. Water Metabolism of Social-Ecological Systems

Linking the analysis of societal and ecosystem metabolism

Saying that water use analysis should deal with loop interactions society/ecosystems opens the question about how to bridge the disciplines dealing with the different descriptive domains of water systems. This is where the concepts of SES and WHS, is useful to advance towards integrated analytical approaches. As discussed in section 1.1.3 there are a few frameworks for SES with different aims and scopes, and at least two of them deal with reciprocal relationships (Binder et al. 2013). These are addressed on a qualitative basis, by analyzing governance cycles and evolution of social perceptions.

Madrid and Giampietro (2015) propose to bridge the two classical descriptive domains discussed in hydrology, the *watershed* and the *problemshed*, through a definition of SES as holarchical, open and autopoietic. The term holon was coined by Koestler (1970) in order to capture the dual fuzzy identity of levels in hierarchically organized complex system, which are at the same time parts and wholes, structural compartments (a water mass) and functional types (a typology of water bodies), a material rate-dependent thing and an informational rate-independent one.

The conceptualization of SES as holarchies (Allen and Hoeckstra 1992, Giampietro 2003, Serrano-Tovar and Giampietro 2014) enables dealing with the transfer of information and cross scale feedbacks within and between holons. Each level of organization operates and adapts to changes according to the information received from the levels above (context) and the levels below (parts). This type of organization of living systems as a set of feedback processes of transformation of products and information which final aim is to reproduce the network itself has been termed autopoiesis (Maturana and Varela 1971). Moreover, as living systems, SES are open to the exchange of matter and dissipation of energy with their contexts in order to maintain their functioning (Prigogine 1968). Therefore, emerging patterns of resources use are observed at each holon as a result of the interaction between its parts at lower levels and the contextual constrains at upper levels.

Figure 1.4 depicts the watershed (e±x) and the problemshed domains (s±x) as holarchies intersecting in the focal level (chosen analytical extent) (Madrid 2014 p. 94). In this dissertation, the focal level of observation is the water management scale. This level connects eco-hydrological and socioeconomic processes through a normative input: the water management plan, which sets water allocations, acceptable type of water resources and acceptable levels of impact on ecosystems. Public policies, as a mirror of social values, are an essential element shaping relations between societies and ecosystems. Which are the water policy goals, which strategies do they deploy and how these strategies are decided, implemented and evaluated are key questions when analyzing water basins as SES. I represent an additional third axis with the *infoshed*, referring to public policies produced at multiple levels that shape societal metabolic patterns and their interactions with their contextual environment. This is not a physical holarchy, but represents the information side of any holon, as will be later explained.

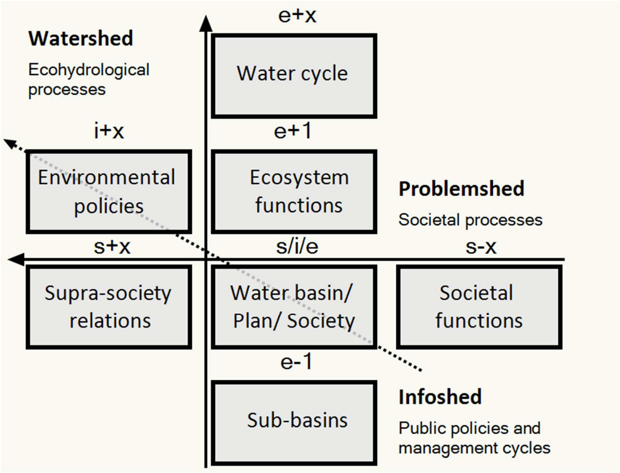

Figure 1.4 – Multiple axes representation of multi-level descriptive domains for a WHS. Adapted from Madrid and Giampietro 2015

A comprehensive framework based on hierarchy theory

The WMSES is proposed by Madrid (2014) as a comprehensive framework capable of dealing with complexity issues about water use by building on the previously described definition of SES. As observed in Figure 1.5, the framework bridges the three descriptive domains of water systems, each of which is analyzed at different levels, and depicts different interfaces with relationships crossing them (Box 1.1). There relationships can be formalized through relational quantitative indicators. Moving up and down in the crux of holarchies (Figure 1.4), one can set different focal analytical extents and address social-ecological processes through their observed organizational structures and their water exchange, alongside the external (upper scales) and internal (lower scales) constraints to those processes. MuSIASEM, a heuristic methodological framework specifically developed to deal with the analysis of metabolic patterns in SES (Giampietro et al. 2009, 2012, 2014), is proposed as a common language for the operationalization of this framework (Section 1.3).

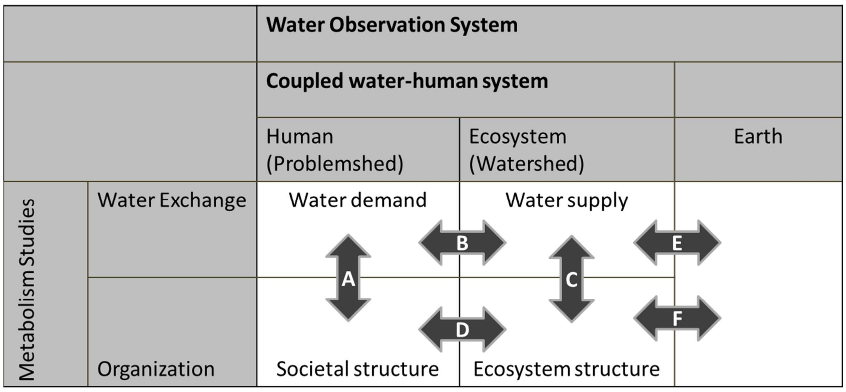

Figure 1.5 - Conceptual framework for Water Metabolism of Socio-Ecosystems

According to Madrid (2014), the *problemshed* domain has been largely developed by the virtual water theory (Allan 1998, 2003). Virtual water enables the differentiation between direct and indirect water uses related to the two main economic functions of production and consumption, both of which are responsible for environmental impacts, either on their context or somewhere else. Virtual water is thus a useful tool to connect international trade and regulations to the distribution of the impacts associated to consumption patterns. Advocates for management strategies based on virtual water defend the idea that water scarce regions avoid political conflicts by importing water-intense commodities instead of producing them (Allan 1999). Nevertheless, this is rarely the case, and very intensive water use patterns are frequently found in arid and semi-arid areas. This is an indication that virtual water theory alone is insufficient to respond to the question of *how and why societies use water* in the way they do. Indeed, relations A-D are shaped by existing technologies and infrastructures, social perceptions about water and 'nature', sanctioned discourses, conflicts around access to water, expectations and imaginaries, power relations and political cultures.

Relation A indicates the dependence of the social organization on water for its functioning, this is, the water end use.

Relation B encompasses the water exchange between societies and ecosystems, conceptually equivalent to the water appropriation in quantitative and qualitative terms.

Relation C indicates the dependence of the ecosystem organization on water for its own functioning and reproduction. In the following, the results of the appropriation of water are observed by the changes in this relation.

Relation D deals with the structural organization of WHS as hierarchical systems.

Relation E Indicates the water recharge of the water bodies in the ecosystem as a result of the precipitation processes of the water cycle.

Relation F deals with the structural organization of a Water Observation System combining processes of the water cycle with the social and ecosystem processes.

Box 1.1 - Relations on the interphases of a WHS. Source: Madrid 2014 p. 79

Water basins as social-ecological systems: mismatches and implications

Water basins are always middle scales, between the social and the hydrological, between the local and the regional, between the rural and the urban. Allen and Hoekstra (1992 p. 64) shed light on the problematic with middle scales: "these have too many parts to model each one separately, but not enough to allow averages that fully subsume the individuality of the part. Questions that cannot be answered imply a middle number system specification. They are unpredictable because the constraint structure is unreliable. […] At middle scales, each part of the landscape has its own individual explanation". The multi-axes holarchic representation (Figure 1.4) is an attempt to escape this middle scales dialectic, by tailoring holons that embody these dualities to specific analytical objectives. The co-existence of non-equivalent relevant holons within different story-telling explains this unavoidable epistemological predicament.

Madrid 2014 deems water basins as the traditional focal level in the eco-hydrology holarchy because they are the main analytical extent for hydrological modeling. Nevertheless, they are not in societal metabolism studies. One of the main reasons is the mismatch between boundaries and associated available data. The axes in Figure 1.4 can be moved up and down, setting different focal analytical levels in which different boundaries will intersect and thus different mismatches will be generated. Economic variables are crucial to study the self-organization of social systems. These are not usually available at the exact boundaries of a catchment and have either to be aggregated from lower administrative divisions (municipalities or similar), or disaggregated from upper ones. In addition, water basins have evolved from a biophysical modeling unit to a governance tool for water decision-making in many countries (Cohen and Davison 2011, Del Moral and Do Ó 2014). As such, institutional performance and governance structures are drivers of change as much as biophysical and socioeconomic processes. Focusing on the watershed level one gains connection with eco-hydrological processes and water governance but loses the capacity to delve into the economic relations within the social system. To this purpose, administrative units as focal level are more appropriate. Therefore, the criteria to define coupled WHS will vary according to analytical objectives and the trade-offs on relevant information loss associated to each type of intersection between eco-hydrological and socio-economic criteria.

WMSES as a framework for social-ecological systems

In order to contextualize the presented framework among the multiple existing frameworks for SES, Appendix 1 presents its characterization according to the contextual and structural criteria proposed by Binder et al. 2013.

1.2.3. Bridging water governance and water metabolism

Rogers and Hall 2003:16 defined water governance as "the range of political, social, economic and administrative systems that are in place to regulate development and management of water resources and provisions of water services at different levels of society'. Pahl-Wost et al. (2010) differentiates the term governance to that of water management referring to "the activities of analyzing and monitoring, developing and implementing measures to keep the state of a resource within desirable bounds". The term governance emerged in opposition to that of government or state-based policy making (del Moral et al. 2014). It alludes specifically to the decentralization and diversification of actors taking part in decision-making. The anchoring of governance has been particularly relevant in the field of water resources with the popularization of IWRM as main management paradigm, resulting in new networks of actors with different capacity of influencing decisions and their outcomes.

In practice, water governance can be considered the application of water policies through specific management regimes. Water policies are regulations endorsed at upper institutional levels than the basin that stand for a long periods of –human- time (usually decades). As public policies, they respond to specific problems arising from the situation of water systems, which is deemed somehow unsustainable. In order to deal with these situations, policy goals are laydown and guidelines provided for regional planning, implementation agendas and evaluation protocols (Subirats et al. 2008 p. 113). However, it is at the management scale (river basins, water bodies boundaries, etc.) where the specific management strategies are drawn, where debates between public and private actors take place and where final actions are implemented in planning cycles of shorter frequency (usually less than a decade). A loop is therefore established between the cycles of policy and management, through the political-administrative agreement about how policy implementation shall be done, and through the feedback about the effects produced on the manifestation of the problem at the basin level. Another characteristic of water policy is the fuzzy differentiation between beneficiary and target groups, since water problems are usually many, intertwined and with multiple types of actors involved, including non-human actors such as water bodies. For this reason, there is a lot of non-linearity in the processes triggered by the implementation of water policies, with social groups causing impacts and suffering consequences usually overlapping.

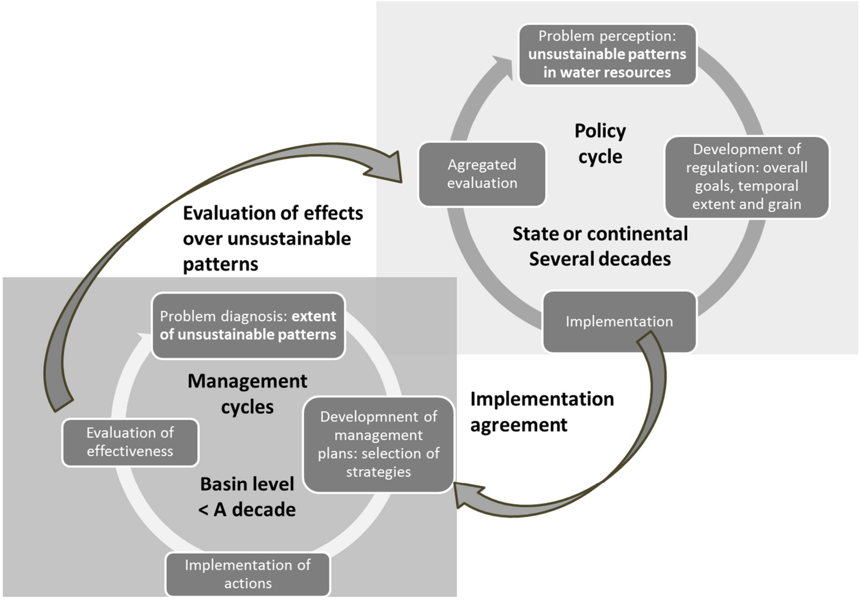

Figure 1.6 - Connection of water policy and management cycles. Adapted from Subirats et al. 2008:114

The water management cycle should be able to i) diagnose unsustainable metabolic patterns in water systems at the basin level; ii) develop a plan to change those patterns according to overall policy goal by selecting specific strategies; iii) implement actions according to those strategies and iv) evaluate its effects over metabolic patterns and outcomes regarding progress towards policy objectives. As described in the introduction, two hypotheses of this dissertation are that:

i) The selection of water management strategies responds to a great extent to dominant water management paradigms and political cultures.

ii) The evaluation phase in water management is the weakest part of the cycle because it is a political action and requires the individuation of an external story-teller to perform a quality control over the relevance of the information used for retrieving the degradation of water resources.

Regarding these premises, the WMSES framework can contribute to the crucial step of evaluation of biophysical outcomes of water management decisions through the integrated analysis of metabolic patterns in SES. In addition, in what follows I discuss two concepts that I deem useful to bridge quantitative and qualitative analytical tools.

The semiotic process of water management

The concept of holon has received a special attention in recent developments dealing with the dual nature of a system as material thing that can be observed and is subjected to thermodynamic laws and a coded part that handles information and creates meaning using the rules of linguistics (Allen and Giampietro 2014, Diaz-Maurin and Kovacic 2015). This conceptualization of a holon is related to the distinction between perceptions and representations as discussed in section 1.1.3. Perceptions are determined by values and expressed through narratives. There are narratives before and after a representation: models encode variables according to the values of the observer, and resulting outcomes are decoded according to the narratives of story-tellers. The analyst can take one or the two roles. The semiotic process is that of observing-encoding-inferencing-decoding for guiding action proposed in Rosen modeling theory (Rosen 1985, 2000). A model is said to achieve “semantic closure” (Pattee 1973) if the predictions are consistent with the observed behavior of the observed system. In other words, the pre-analytical choices determined by the story-teller when choosing narratives (causality) are consistent with the results of the formal model created by the observer (encoding–inference–decoding). Following Hajer (1995), we can split semantic closure in three types of checks: discursive closure (does the definition of the problem lead to adequate policy goals?), social accommodation (how are contrasting and conflictive narratives included in the process of problem-solving?) and problem closure (do the final actions taken solve the perceived problem?).

These concepts are particularly useful in environmental governance in order to analyze the process of validation of specific management strategies. They also help to frame the analysis of the feedbacks between the information side of the managed system (management plans, scientific models, public discourses) with the biophysical realization of the system (metabolic patterns arising from the meaning created by information processing). For instance, Diaz-Maurin and Kovacic (2015) show that there is a strong inconsistency between expectations and experience in the realm of nuclear energy. Indeed, the representation of nuclear power as a viable alternative energy source is not validated through empirical experience but responds to strong beliefs in the pre-analytical assumptions that lead to a situation of technological lock-in.

Allen and Giampietro (2014) propose a general scheme of the semiotic process in a biosocial system. Figure 1.7 shows an adaptation for the representation of a hydro-social system as a holon. As explained, water metabolism requires an additional level of analysis than those of energy because it depends on the favorable gradients from ecosystem functions but also from the water cycle –favorable climatic conditions. These three levels are represented through two surfaces in the figure, one delimiting the bio-social system and the second one demarks the hydro-social system from its climatic context.

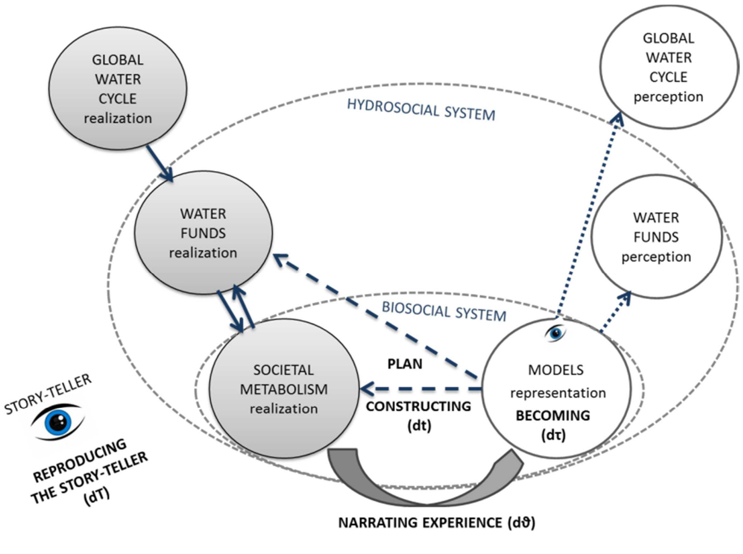

Figure 1.7 - General functioning of the semiotic process of the holon of a hydro-social system.

Source: adapted from Allen and Giampietro, 2014 and Diaz-Maurin and Kovacic 2014.

The left side of the figure represents the biophysical part consisting of a social system using water for its maintenance, which depend on its availability (hydro-social border) but also on the perception over water resources on the right side. This perception of the water system shapes management goals, the assumptions behind hydrological models and the type of information used when developing a plan. For instance, depending on whether you consider climate change projections or not, the scenarios used for water planning will vary and so they will the measures foreseen to modify both societal and ecosystem water metabolism. When water management goals are imposed by upper level policies, as in the case studies that are presented in this thesis, the whole system needs to readjust in order to pursue them. The actions implemented in the plan modify the managed system, *constructing* it in interaction with multiple other plans from other political realms. The experience of these actions provokes responses from multiple actors *narrating* their experience, feeding back to decision-makers. They assess the outcomes of the plan in terms of their prior expectations and the multiple inputs from different narratives. This evaluation should lead to an update of the management strategy, depending on whether goals have been achieved and information employed was sufficient (*becoming*). Diaz-Maurin and Kovacic 2014 depict different time-scales for the subprocesses of the semiotic process described using a much larger time differential dT – reproducing the story-teller, dt - constructing, $d\theta$ – narrating and $d\tau$ – becoming of the representation. The following constraints in relation key characteristics of the system are posed:

(1) its ‘plasticity’: $dt < d\tau$ – the system must be able to change according to the new plan;

(2) its ‘responsiveness’: $d\theta < dT$ – the system must be able to give a feedback within the time horizon of reproduction of the story-teller;

(3) its ‘adaptation capability’: $d\tau < d\theta$ – the system must be able to change according to the new narratives generated after the plan.

This means that for the system to achieve semantic closure the time of implementing a plan < time of adapting < time of validity of narratives < time of reproduction of story-teller. In the case of participatory governance, as for instance the WFD in Europe, there is a quality control over the representation of the system undertaken in a preliminary version of the plan. This adds an internal shorter loop in which decision-makers collect inputs from different stakeholders and accommodate them in the plan. These narratives will later monitor whether or not the final plan achieves discursive closure according to what they proposed and expect to be change. Therefore one could add another condition that is:

(4) *its ´reflexivity’:* $d\alpha<d\Omega<d\theta$ – the system must be able to improve the representation, the information used for the plan, according to the feedback obtained in the first narrating loop.

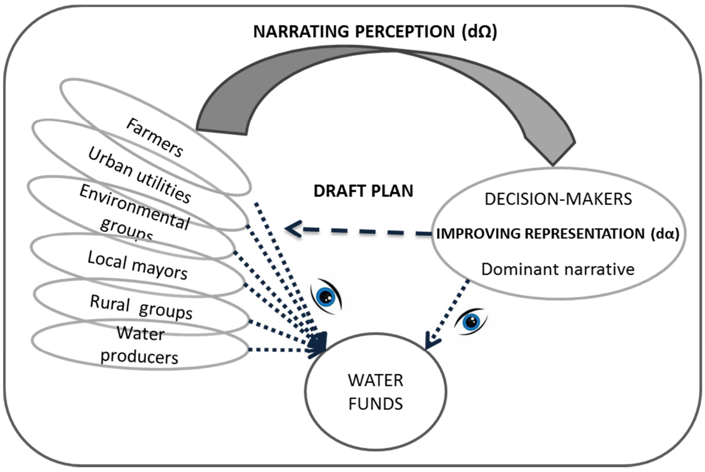

Figure 1.8 - Internal prior loop of the semiotic process in participatory water management. Own elaboration

If the system is reflexive at this stage, narratives during the second loop after the plan implementation should evolved regarding the first narratives about plan perception. The problem is then who are these intermediate observers of the system, who are the multiple story-tellers generating meaning and how these meanings permeate the dominant narrative that pervades the final plan. Using Hajer's checks one can ask: Who defined the problems? Which narratives underlay the models used and the foreseen management strategies? (discursive closure); Do the different actors agree with the plan? Which is their capacity to influence the public opinion? (social accommodation); Does the observed experience of applied actions solve perceived problems? Do the models need to be re-adjusted? Do we need additional information for the readjustment? (problem closure). The answers to these questions enable a discussion about the validation of the information and models used to make decisions, about the effectiveness and legitimization of management strategies and of the narratives behind them.

Water availability as a boundary concept

Water availability is a concept approached from multiple definitions and perspectives (Table 1.1). The most common one alludes to the long-term average freshwater volume yearly supplied by the hydrological cycle, including runoff and aquifer recharge (see for instance Parish et al. 2012, Post et al. 2012, Menzel and Matovelle 2010). In this sense, it equates to the Falkenmark and Rockström 2004 concept of blue water. Other approaches encompass the environmental flows (e-flows) as a prior allocation to what is available for humans (Poff et al. 2010, Hoekstra et al. 2012) or focus on the reproducibility of specific end uses (Henriques et al. 2008, Molden et al. 2011, Padowski and Jawitz 2012).

Availability, in a social-ecological sense, is a dynamic boundary concept between societal water uses, expectations on additional water requirements (demand), technical capital to regulate water bodies and desired ecosystem integrity. Defining availability is the process of determining what is considered a resource for a specific, usually human end-use, and what is not. For instance, on confined aquifers water *becomes available* when technological advances and energy prices allow deeper pumping, as long as there are no adverse effects that the social system using that groundwater are not willing to accept (del Moral 2005 p. 16, Zhou 2009). As a normative category, water availability depends on which are the accepted trade-offs between water extraction and environmental, economic and social consequences of this extraction. Because narratives on availability might differ depending on whom you ask, especially when water allocation implies uncertainties and high stakes, a normative definition of availability is usually set as a compromise to avoid conflicts, or as an imposition of a party, in the frequent case of existence of unbalanced power relations. Despite formal commitments or authoritarian impositions, the implementation of the resulting standards are often subjected to infringements, a not incidental but structural atmosphere of deviance or non-compliance with legal norms. This is the case of the region where the Andarax is located (Sampedro and Del Moral 2014). Nonetheless, what is allocated as available at one scale for an end-use it will entails trade-offs, and thus, creating winners and losers. Therefore, a further negotiation with those affected is usually required. For instance e-flows established in European river basins are calculated first and negotiated afterwards (see for instance section 4.3.6 of the Spanish water legislation (http://www.magrama.gob.es/es/agua/legislacion/iph_tcm7-207591.pdf).

When moving from semantic to formal categories of water metabolism analysis, we need to make explicit the definition of water availability being considered. This definition is at the core of any water use sustainability assessment and introduces a value judgment into the scientific analysis, a pre-analytical decision made by the analyst. Molle and Mollinga (2003) define water scarcity in terms of scarcity of what and for what. When using normative concepts such as sustainability, scarcity or availability, these questions become relevant: availability of which type of resource, for what type of end use, at what costs and for whom. In the interface of society and ecosystem, the definition of available water (Box. 1.2) deals with the trade-offs between allocation of water for productive uses (provisioning ecosystem services) and impacts over water bodies (and thus their regulatory services).

Table 1.2- Water availability definitions for different systems

System	Water availability	Trade-offs
Whole SES	Total water inflow to the river basin including precipitation (minus evapotranspiration), inflow from other aquifers and from external transfers	With other river basins
Land subsystem	Soil water that can be used for plant transpiration	Between productive and non-productive uses
Aquatic subsystem	Ecosystem requirements of surface and groundwater (normatively established)	With societal appropriation
Human subsystem	Total water available for human direct appropriation from different sources	Between provisioning and regulatory ecosystem services
End users	Water that can be used by each end user according to institutional regulation	Between end users

Water Availability for Society= ∑ (Surface + Groundwater + Produced + Transferred + Soil) Available Water

Surface Available Water= Compromised diversion from the river and reservoirs within established environmental flow regime for aquatic ecosystems
Groundwater Available Water= Compromised pumping rate within an established sustainable yield
Reclaimed Available Water= Wastewater reuse + Desalination capacity
Transferred Available Water= Transfers from other basins
Soil Available Water= Soil moisture appropriated for human use for plant growth and food production

Box 1.2 -Water availability at the ecosystems/society interface

1.3. Methodological framework

1.3.1. MuSIASEM: a ‘quantLitative‘ framework for sustainability assessment

MuSIASEM is a heuristic methodological framework designed for the integration of the various dimensions, scales and disciplines required for holistic quantitative analysis of metabolic patterns in SES. It bridges the analysis of energy and material resources required for societal activities to that of the ecosystem functions providing services. First applications of MuSIASEM focused on agroecosystems (Giampietro 1994, Gomiero 2004) and energy use (Ramos-Martin et al. 2007, Giampietro et al. 2012). Food and water systems were later added (Madrid et al. 2013, Cadillo-Benalcazar et al. 2014) and recent applications evolved to the integrated analysis of energy-water-food-land nexus (Giampietro et al. 2014). The analysis of ecosystems metabolism so far has received less attention than that of societal processes (Lomas and Giampietro 2014). This dissertation aims to contribute in this sense with the analysis of water metabolism at the scale of watersheds conceptualized as SES.

MuSIASEM stems from multiple fields and concepts in complexity theory, but there are two in particular that make it unique for complex analysis of water use. First, hierarchy theory, that is the branch of complexity dealing with scale issues and the multi-scale organization of complex systems as discussed in section 1.2 (Pattee 1973, Allen and Starr 1988, Giampietro 2004). Second, bioeconomics and the work of Georgescu-Roegen that paved the ground for a new epistemology of the biophysical roots of the economic process (Georgescu-Roegen 1971, Mayumi 1995, Funtowicz and O’Connor 1999).

Madrid 2014:112 labels MuSIASEM as a *quantLitative assessment* because it is a quantitative method based on a pre-analytical qualitative process comprising the definition of (i) the relevant analytical levels and dimensions of the system, (ii) the functional compartments of the system at each level and (iii) the relevant attributes delimiting useful resources for those compartments. These choices lead to the development of *grammars* that are the core *semantically open* quantLitative tool of MuSIASEM. A thorough description of these steps can be found in Giampietro and Bukkens (2014). In this section I introduce its application to the analysis of water use.

Water as a flow and a fund

The quantitative ground of MuSIASEM is the flow-fund model of Georgescu-Roegen (1971 pp. 211-275). The author proposed the model to escape the reductionism of the mainstream debate between the stock model and the flows model, neither of which considered the qualitative nature of the source of resources (Giampietro and Lomas 2014). Thereby, he distinguished three types of elements:

- *Flow* variables are quantities appearing or disappearing (resources used or products generated) over the duration of the analysis. They indicate quantities that are either consumed or produced in the expression of a metabolic pattern. Examples are energy, food or waste used or generated by social processes.
- *Fund* variables are those remaining the same during the time frame of the analysis, or those we want to conserve. They indicate quantities of organized structure that are used (their presence is required) in the expression of the metabolic pattern, requiring

flows for their maintenance. Common funds are human beings and technical capital for societies and biomass for ecosystems. Land is an especial case of coupled societal-ecosystem fund (Aspinall 2014).

- *Stocks* refer to buffers of flows which change during the analysis (they are depleted or filled) because of the flows. At difference of the fund elements that, during the analysis, maintain their identity because of the flows, stocks change their identity because of the flows during the analysis. Examples include fossil fuels reservoirs, minerals or fossil water.

While most environmental accounting schemes consider natural resources as stocks (see for instance the definition of water bodies as stocks in Falkenmark and Rockström 2004 p. 37), the difference between funds and stocks is fundamental in MuSIASEM (Giampietro and Lomas 2014). Stocks are non-renewable resources at the time scale of the representation, like reservoirs or aquifer overdraft, which consumptive use diminishes availability for ecosystems or for future needs. Funds are resources consumed at slower pace than their renewability rate during the representation, like aquifer sustainable yield or soil moisture. Ecosystems live on funds limits. Flows consumed by humans can thus come from funds or stocks, as we can create artificial stocks to increase available flows or overdraft remaining stocks. This model is employed in MuSIASEM to provide i) a semantic criterion to define the structural organization of systems across scales through fund elements; ii) a formal criterion to address the biophysical exchange among scales through flow elements (Giampietro et al. 2011, Madrid 2014) and iii) a sematic criterion to distinguish between renewable and non-renewable resources from within the system boundaries through fund-flows or stock-flows (Giampietro and Lomas 2014).

Given that the distinction between fund and flow is semantic, the same water volume can be perceived as a fund or as a flow depending on the temporal scale considered. Once the temporal extent of the focal analytical level is fixed, when the required attributes of a given volume of water are compromised during the time scale of the analysis by its use, it is considered a flow; otherwise, it is a fund. Most social uses of water belong to the category flow because each use modifies one or more of the attributes that make water a resource. That is, even when the volume of water remains the same after a given use, that water has lost the original capacity to provide the same service again because of the use. For instance when water falls generating electricity it has no more power generation capacity unless it is pumped up again, or wastewater reclamation that needs energy-intense treatments. In the same way, a liter of water used for cleaning loses its capacity to be used for drinking. Attributes defining water as a resource are progressively lost depending on the uses unless an energy input restores that attribute. Because temporal patterns of ecosystems are usually longer than societal ones, water is normally considered a fund in them (Madrid et al. 2013). Indeed water is a structural part of ecosystems (in soils and water bodies) which seasonal pattern determines the distribution of ecosystem types on Earth and regulates their functions. The predictable flow regime of water in a river is a fund for the ecosystem that requires a regulation of the input (e.g., affluents) in relation to the output (e.g., effluents). There are also important human uses of water funds, like recreational and cultural uses, also known as water-related cultural ecosystem services. However, in this dissertation only societal water uses as a flow are addressed.

Steps to build a MuSIASEM of water

a. Defining relevant levels

The first step is laying down the dendrogram presented in Figure 1.9 for the system under study. This is done by choosing the relevant elements that will be included in the analysis and arranging them on a multi-level basis according to specific criteria. Implicitly, it also requires setting the spatial-temporal scales in which the processes at each level will be studied. According to hierarchy theory, to study the organizational structure of complex system one has to consider at least three contiguous analytical levels: the whole (*n*), its parts (*n-1*) and its context (*n+1*). Within the problemshed domain in Figure 1.4, the whole society will be level *s*, divided in levels *s-i* describing its internal functional compartments, for instance production and consumption, and contextualized by markets and regulations at supra-societal levels *s+i*. Regarding the watershed domain, Madrid 2014 p. 95 distinguishes at least four levels: the water cycle (*e+i*), the ecosystems (*e+1*), the water bodies as a structural part of ecosystems (*e*) and the basin level at (*e-i*). Note that this is not a substantive structure; rather it should be anchored according to analytical purposes. The chosen levels will depend on the taxonomical relations between the parts of the system depicted in dendrograms that disaggregate compartments of each level in the level below.

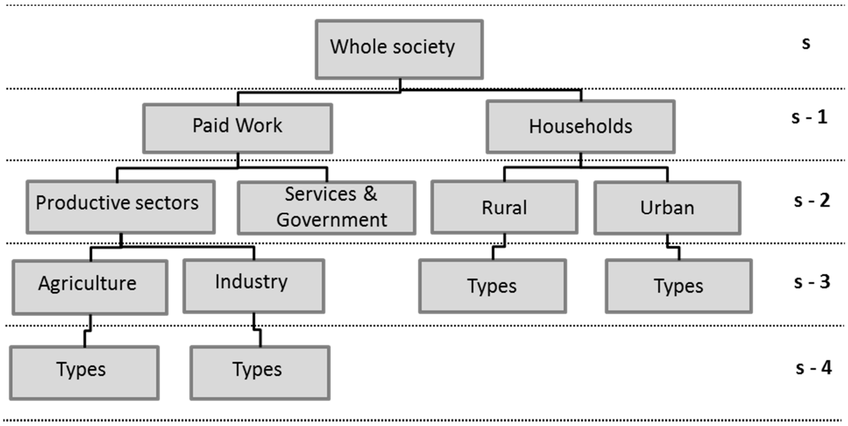

Figure 1.9 - Dendrogram of internal societal functional compartments. Adapted from Giampietro and Bukkens 2014

b. Defining grammars

A grammar is a formal system of rules for accounting metabolic processes, given a set of expected relationships between semantic categories of what we want to indicate (for instance water use) and formal categories (indicators, data and rules for calculation). Building on the flow-fund model, MuSIASEM uses different interrelated grammars for water, energy, land and food (see Giampietro et al. 2014). To this purpose, each chosen level in step *a* is semantically defined and then formalized into quantitative variables through data and calculation rules. These variables are the relevant funds describing structural size for each compartment, and the relevant flows required to maintain those funds. Because flows are fund-specific, they need to be defined in both qualitative (type of flows admissible for a specific end-use) and quantitative terms (admissible ranges of flows per unit of fund). Flows and funds are quantified in absolute terms (extensive variables) in multi-level matrices cross-checking bottom-up and top-down information. The relations between them provide intensity flow:fund, flow:flow and fund:fund ratios that are used to establish typologies of metabolic systems. Data can come from direct measurements, statistics or estimations when neither measuring is possible nor statistics are available for the required analytical levels. The quantitative formalization of flows and funds requires the implementation of different models from different disciplines, like hydrological models for *e+i* levels or land-time budget analysis at *s-i*.

The water grammar provides a set of semantic categories for multi-level accounting of water metabolism in ecosystem (*e±i*) and social systems (*s±i*) (Madrid and Giampietro 2014 p. 120). Water resources are classified as flows, funds or stocks according to the chosen temporary scale of the processes analyzed at each level. In order to make grammars comparable, a common taxonomy (general levels & services provided by water) is proposed by Madrid (2014 p. 105) (Table 1.2). Water types are openly defined at each level according to analytical purposes. Thereby, water can be green and blue water at one level and direct and indirect water at another level. This is opposite to other type of water use accounting methods that apply the same definitions of water regardless the context. The main constraint to create types is usually data availability.

Table 1.2 - Taxonomy for water grammars. Source: Madrid 2014:101

Role	Holons	Services provided	Water types examples
FUND	Water cycle (e+2)	Water supply	Rain Snow
	Ecosystem functions (e+1)	Water recharge	Runoff Recharge Infiltration
FUND/ STOCK	Water bodies (e)	Appropriation / Availability (capacity to use water attributes by changing water bodies or generating other water resources)	Surface Groundwater Soil water Desalinated Transferred
FLOW	Society (s)	Extraction	Withdrawn Soil
	Social functions (end uses) (s-i)	Direct use Indirect use (virtual water)	Human right Economy water Food production

The water grammar allows the operationalization of the WMSES conceptual framework depicted in Figure 1.5. By referring water flows to societal funds and water funds to other ecosystem funds we obtain relations type A and C. The trade-offs on the water exchange between ecosystems-society are characterized by linking the roles of water as flow and fund (or stock) for each of them in relation B which are typical water extraction indices (for instance how much groundwater is withdrawn regarding recharge). Finally, relation D refers to the structural competition between societies and ecosystem and is quantified through their respective funds or land as a connecting societal-ecosystem fund.

c. *Integrated representation of metabolic patterns*

A metabolic *type* is a set of expected relations between flows and funds, which is labeled for instance as highly or low intense or efficient. Metabolic types are necessary as benchmarks to refer to once we obtain *instances* of metabolic patterns in our studies, enabling comparisons. To this end, visualization tools for integrated sets of relevant indicators are an essential part of the analytical process. A nice review of integrated representations can be found in Gomiero and Giampietro (2005). Those used in this dissertation are explained within each analytical chapter.

d. Assessment of scenarios through mosaic-effect

What has been described so far is MuSIASEM as a diagnostic tool for a thorough characterization of metabolic patterns (as it is applied in Chapter 2). In addition, MuSIASEM can be used as a simulation tool for integrated assessment of different scenarios (Giampietro et al. 2006b, Giampietro and Bukkens 2014). Integrated assessment is defined as the simultaneous appraisal of indicators of performance referring either to several dimensions of analysis and/or scales (Mayumi and Giampietro 2006). This type of assessment can inform discussions about sustainability of management options. For this reason MuSIASEM has been entitled a ‘discussion support system’ (Barbas Baptista 2010 p. 126).

Sustainability of water metabolism in SES refers to the maintenance of a set of relations A, B, C and D (Figure 1.5, Box 1) within admissible ranges (Madrid 2014 p. 114). Once these relationships are quantified through funds and flows, a loop of interconnectivity between the organization and the biophysical exchange of societies and ecosystems is established. This is what is known as mosaic or Sudoku effect in MuSIASEM (Giampietro and Bukkens 2015) , i.e. you cannot change any element or relation in the system without affecting the rest. Each quadrant in Figure 1.5 contains functional compartment from one or several levels of the holarchies (Figure 1.4), therefore cross-scale interactions can also be checked. For instance, if the social system expands by urban development (*s-1*), vegetation cover is necessarily reduced (*e+1*) and with it the eco-hydrological functions like infiltration (*e+1/e*). As a result, the pattern of water availability is altered (*e/s*), the water that was previously infiltrated will now runoff (*e+1/e*), what affects the services provided to the social system (*s*). This type of loop can start anywhere either with a change in funds or in flow:fund ratios (modified for instance by new technologies or infrastructures) and every time one is altered, a space of options about how to re-arrange the rest is opened. This enables the analysis of trade-offs required in a discussion about management alternatives. It is important to note that heuristics does not imply causality. The set of rules generating the Sudoku game provide a nice example of a set of expected relations over numbers that are not deterministic in defining their location in the grid. The set of constraints defines the rules within the pattern, but the actual final pattern cannot be predicted because it depends on the specific process followed when filling the cells. As explained, each descriptive domain is quantified through different methods. One can only establish direct relations of congruence once we have a connected multi-level accounting of all flows and funds.

The discussion about sustainability is proposed through three checks:

- *Desirability* is a qualitative check at the level of end-users and it is related to their perceptions about the performance of water uses in the metabolic pattern. Therefore, a metabolic pattern is desirable if the individual members of a society agree with their supplies.

- *Viability* refers to the ability of processes under human control to stabilize water flows in the metabolic pattern. At this level we can observe the emergent behavior of the relationships between individuals at lower levels, often entailing trade-offs (what is good at the individual level, for instance paying less taxes, is not necessarily good at an upper collective level, for instance providing social services). This check connects relations A and B of the framework in that the social organization depends on the capacity of ecosystems to supply the required water.
- *Feasibility* refers to the ability of processes outside human control to stabilize water funds in the metabolic pattern (both on the supply side, relations C, and the sink side, relations D).

A note on the adaptation of MuSIASEM to the assessment of water policies

The problem with the last step in MuSIASEM is that, as an assessment, it requires a normative input (deciding what is more or less desirable or viable) while an analysis (previous steps) deals only with the description of the system. According to post-normal science, this normative input shall be obtained through a participatory process in which stakeholders are involved in a deliberative process. In this case, research has to be carried out on an iterative basis with the aim of arriving at a final compromised solution among the appraised alternatives. However, this requires: i) a group of stakeholders willing to participate (concerned and pro-active social actors) and ii) decision-makers willing to accept and implement the outputs of the process (empowered social actors). In the water realm, where participatory governance was institutionalized with IWRM, practical experiences have elicited very feeble results (Ballester and Parés 2013, Hernandez-Mora et al. 2015). The main reason for this is that decisions about management alternatives are essentially political, not technical. Therefore they are rarely based on scientific information uniquely, but rather shaped through networks of actors with uneven power positions, among which consensus is commonly not very plausible. Indeed, practical applications of integrated assessment frameworks in real decision-making processes about water are almost inexistent.

In this dissertation, I propose to apply the presented conceptual and analytical framework to follow up the implementation of water policies at the basin level, taking into account the multiple non-equivalent narratives about water problems. As explained in section 1.2.3, management plans lay down specific problems to be solved and establish strategies that can aim at the three types of sustainability checks: over *desirability* by affecting behavior of target-groups (individuals, irrigation communities, utilities); over *viability* by for instance improving efficiency or modifying water availability; over *feasibility* by preventing impacts on ecosystems or restoring them when they are degraded. These strategies are combined according to a prior hypothesis of causality, expecting that the emerging outcome will be progress towards management objectives and the overall policy goal. In their implementation, funds and/or flow:fund relations are modified, triggering changes through their connections with other parts of the system (internal system dynamics).

I argue that the WMSES framework operationalized through MuSIASEM is a useful method to understand the trade-offs associated to water management strategies that modify flows or funds, and therefore their effectiveness and/or limitations towards achieving specific goals. Moreover, building on the discussed concepts of semiotic process, holon and water availability (section 1.2.3), the combination of MuSIASEM with qualitative policy and discourse analyses is a robust toolkit for integrated assessment of the implementation of water policies.

Although I did not have the opportunity of arranging an ex-ante participatory process, I endeavored in simulating iterative research processes with different forms of stakeholders' participation. To this purpose, I undertook stakeholder mapping, thorough reviews of legislation, management plans and reports, field interviews and meetings with local stakeholders. In the Andarax case-study I stem from an on-going participatory process arranged for another research project (Participatory Search for Water Management Alternatives – ALTAGUAX). I could attend some participatory workshops, quantify the indicators chosen by stakeholders, and present them in a focus group two years after the project ended. In the Tucson basin, a wider research project (Sustainable Water Action – SWAN) allowed me to arrange a deeper iterative collaborative process of problem diagnosis, scientific questions validation, decision over sustainability indicators and results devolution. Both processes are described in the case-studies.

1.3.2. Qualitative methods

Discourse analysis

Hajer (1995) defines a discourse as 'an ensemble of ideas, concepts and categories through which meaning is given to physical and social realities and that are produced, reproduced and transformed in a particular set of practices'. Discourses shape and are shaped by social constructions of problems and power relations. At all steps of the policy cycle, discourses emerge, are anchored or disregarded. Underlying these processes is the creation of shared meanings and capacity of influence. Meanings delimit policy options and thus their outcomes (Hajer and Versteeg 2005).

Environmental problems are essentially-contested for the reason that there are multiple constructions of nature, or natures, despite mainstream politics strives to reduce them to one sole ontological category (Swyngedouw 2010). These multiple contested views of environmental problems result in a wide variety of actors struggling in discussions about how to solve them with those in better positions actively trying to impose their discourse over those underrepresented. Discourse analysis is therefore useful to understand why a particular understanding of the environmental problems at some point gains dominance while others are discredited. It also allows tracing power struggles and shifting meanings underlying environmental policies (Hajer and Versteeg 2005). A discourse is said to become hegemonic, (or weaker labels such as dominant or sanctioned), if it is *institutionalized* and if the credibility of actors requires them to draw on the ideas, concepts and categories of the given discourse (*discourse structuration*).

Hajer (1995) uses the term story-lines in a similar way that narratives has been defined here (section 1.1.1), as some sort of narration that allows 'clustering' the different discursive categories about a phenomena. Actors might use the same story-lines but interpret them differently or even not understand each other at all, especially when they are inclusive or ambiguous. Story-lines are useful analytical tools to understand the positioning of actors and the creation of discourse coalitions amongst them. The analysis of dominant story-lines or narratives in official documents, reports and management plans can shed light over the bias behind policies development and implementation, the discussion about water management paradigms, and the 'how and why' of observed social-ecological patterns.

Public policy assessment

Subirats et al. (2008 p. 35) define a public policy as the set of decisions and actions that result in repetitive interactions between public and private actors which behavior is constrained by the resources they own and the existing institutional rules. The authors propose an analytical framework that focusses on the outputs at each phase of the policy cycle and their derived impacts and outcomes over the problem to be resolved. They pinpoint five criteria to assess a public policy, four of which are gathered in Table 1.3. Building on the concept of semiotic process and the criteria for policy discourse analysis of Hajer (1995), the questions for the analysis of semantic closure exposed in section 1.2.3 are used in order to operationalize the policy evaluation criteria.

Table 1.3 - Criteria for the assessment of public policies.
Own elaboration based on Subirats et al. 2008 and Hajer 1995

Criteria	Definition	Type of check	Questions in water policy
Efficacy	Impact on behavior of target groups	Social accommodation	Did the different actors agree with the plan? Which is their capacity to influence the public opinion? Did they carry out suggested actions by the water administration?
Effectiveness	Progress toward objectives and solving the problem	Problem closure	Did the implemented actions solve perceived problems? Is the information considered sufficient to make decisions? Do the models need to be readjusted?
Efficiency	Costs-effectiveness of actions implemented	Problem closure	Were the actions implemented the most effective ones regarding available resources?
Pertinence	Adequacy of policy objectives to solve perceived problems	Discursive closure	Who defined the problems? Which narratives underlay decisions and chosen management strategies? Is the local perception of problems reflected in policy goals?

As explained in section 1.2.3, the public problem that triggers the development of a new water policy is the observation of patterns of degradation of water resources and their dependent ecosystems. I focus on the implementation phase of the policy cycle; this is, the management cycle at basin level, where strategies are chosen and actions implemented. Although I considered all the criteria as a general framework along the analysis, not all are discussed in the same depth in the two case studies. I mainly focus on the effectiveness of water management, in terms of how the specific set of chosen management strategies has contributed to the achievement of policy goals and problem-solving. In addition, Chapter 5 adds on the concept of semiotic process in order to assess the first cycle of implementation of the WFD in the Andarax through the four criteria.

1.3.3. A spatial-relational data model for water metabolism analysis at basin scale

GIS and MuSIASEM

The integration of Geographic Information Systems (GIS) in MuSIASEM has recently received especial attention in what regards the connection between societal and ecosystems metabolic patterns (Serrano-Tovar and Giampietro 2014, Aspinall and Serrano-Tovar 2014, Serrano-Tovar 2014). This integration has mainly explored GIS as analytical tools. Because land is the main social-ecological fund in MuSIASEM analysis, GIS techniques are required to deal with its accounting and that of the different flows of energy, food and water per land use type unit. In addition, the feasibility check over environmental impacts of social metabolism makes sense only when applied on a geo-referenced basis (Guan and Moore 1996). As discussed, water is also a social-ecological resource, an eco-social asset, and its geographical reference is fundamental in order to understand patterns of relationships between socio-economic and environmental variables. GIS are the core tool for eco-hydrological modeling relating water funds and land covers (for instance the Soil and Water Assessment Tool, SWAT model, already operates as an ArcGIS extension), enabling the aggregation of funds according to their geographical reference.

As an integrated accounting scheme, MuSIASEM combines different types of data from different sources, with different formats and spatial-temporal references. These raw data are processed into multi-level tables that are the basis for the analysis. However, data storing and management has usually been done in different formats, like Excel sheets or Access databases in combination with GIS shapefiles. On the other hand, relational geodatabases have climbed during the last years as data management systems for geographic information, due to their reliability, scalability, available tools, and performance (Connolly and Begg 2009). This dissertation contributes to step forward in the integration of GIS and MuSIASEM by designing a relational-spatial data model for water metabolism that serves as a semantic definition to develop repositories for open data structuring, management and analysis in geodatabases. Precisely the property of scalability of relational databases makes them particularly useful to the multi-scale analysis in MuSIASEM, since data can be adapted and scaled through specific SQL queries according to analytical purposes without ‘closing’ them into for instance a multi-level matrix. In this section few relevant concepts of data modeling are introduced and the conceptual model is presented.

Data modeling and geodatabases

The International Water Association defines data modeling as the process of defining and analyzing data requirements needed for specific purposes[7]. Data requirements are structured in conceptual models defining the entities from which data is required and the relationships amongst entities. In a second step, conceptual models are further developed into logical data models that describe specific tables for each entity, their univocal keys and attributes, which are used to specify relationships (what is known as cardinality). Logical models adapt the conceptual model to the specificities of each case study and enable the implementation into relational databases. These are employed for storing data in a consistent, atomic and none redundant manner that allows consultation, analysis and replication. Data modeling has become very popular in environmental monitoring as the main technique to standardize collection procedures and share data generated by sparse data producers (Horsburgh et al.

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[7] http://www.iwawaterwiki.org/xwiki/bin/view/Articles/Data-drivenmodellingandmanagement#H

2008).

Geodatabases are a particular type of relational database capable of storing geographic information. While none geographic information has only thematic attributes, geographic information has a twofold nature defined through both thematic and topological attributes. Entities in a geodatabase can therefore be a geographic unit (point, line or polygon) stored in a GIS layer or thematic characteristics of those or other none-geographic entities stored in tables. Relationships amongst entities in a geodatabase can also be topological (spatial relations) or thematic (none spatial relations). The advantage of geodatabases regarding shapefiles or other GIS layers is that they provide querying (and therefore data relating) capability as well as an open connection between calculation and spatial analysis software (Figure 1.10). In addition, they enable the integration of multiple types of geographic and none-geographic data from different formats with their corresponding metadata in a structured format. This provides the capacity to track changes and reproduce data and information, improving transparency and efficiency of the research process.

Figure 1.10 - Data management and analysis tools used in this dissertation

In this dissertation I implemented geodatabases in the Microsoft Access format provided by ArcGIS 10.0/1, which was the main software for spatial analysis and visualizations. Variables calculation has been done in an R programing language interface, R-studio, or Microsoft Excel sheets for simpler operations. This enables an open connection between variables calculation and spatial analysis.

Conceptual data model

Figure 1.11 shows the conceptual model for data structuring in water metabolism analysis at water basin scales. The model differentiates between geographical entities (white background), referring to physical spatial units represented in GIS layers, and thematic entities (grey background), which are tables containing attributes related to geographic entities. Second, it shows the relationships among entities classified in topological or thematic and three types of cardinality. This design is not a fix picture but rather an open format that can be adapted and complemented with additional entities and relationships.

At the center of the model there are two geographical entities that are the focal levels of the water metabolism analysis (Figure 1.4): the watershed and the problemshed. While the former is given by physiographic characteristics of the terrain, the latter can be formed by aggregation or disaggregation of different administrative boundaries (agricultural, municipal, etc.) Relationships in the model are defined for watershed as focal level. When the problemshed is the main focal level, cardinality between water bodies and watersheds reverses for some variables. There are also two key thematic entities when building the water grammar: water sources (types defined according to the repertoire of water resources) and water services (types defined according the end uses).

Water bodies are geographical entities that have different types of related attributes: hydrological regime, environmental impacts, management goals and indicators employed for assessing progress towards policy goals. Other water sources can be desalination, wastewater and transfers. Recharge sites are added because they are an important water source connected to an external transfer and reclamation plants in the Tucson basin. They can also be connected to soft-infrastructures for rainwater retention, a common management technique in semiarid areas.

Land uses and covers are usually found in GIS layers with a hierarchical classification. This is an important element linking water bodies and land covers throughout topological relations that enable for instance the aggregation of eco-hydrological variables into average hydrological regimes of water bodies (as shown in Chapter 2). In addition, land uses can be connected with related data on human activity, agricultural production or energy and water use per land unit. Water use variables are referred to end-users that are geographical entities (urban areas, agricultural units, industrial areas, etc.), each of which has an associated technical capital (irrigation and supply systems) and qualitative attributes of the required water flows. A complicated issue is the difficulty in breaking down urban areas into residential and non-residential, hindering the establishment of holonic relations land:human activity in other many economic sectors (Serrano-Tovar and Giampietro 2014). This is one of the main mismatches when working at water basin scale, for instance the services sector clearly overlaps with households, and other economic sectors located in urban areas.

Three main types of economic variables are included: added value of economic sectors, income and similar indicators of equality (usually referred to households), and the costs and price of water sources (key variable in water management). Other variables like the price and costs of other resources, like energy or food, could also be added if they are relevant to the case study. Finally, energy & food nexus is included through the variables of energy use per water source, food production in agricultural areas and energy produced by the industrial sector. Hydropower is not included because it is inexistent in the analyzed case studies but if added it would imply additional relations between reservoirs data and energy production and consumption entities.

The spatial-temporal extents, data sources, metadata and explicit attributes and entities will depend on the case studies and need to be further specified through logical models. For the analytical chapters, two logical models have been developed one for the Andarax basin and another for the Tucson basin, with corresponding geodatabases implemented that can be downloaded here:

https://www.dropbox.com/sh/a58jb6vahvsfs2j/AAAdKspBs4dXquwvTisRv2EBa?dl=0

In addition, Chapter 2 geodatabases and R scripts can be found here (see Appendix 2 for detailed description):

https://www.dropbox.com/sh/45za6hqmnjelqoi/AAD-ObuilYtGzFwVKyJ_WzQ5a?dl=0

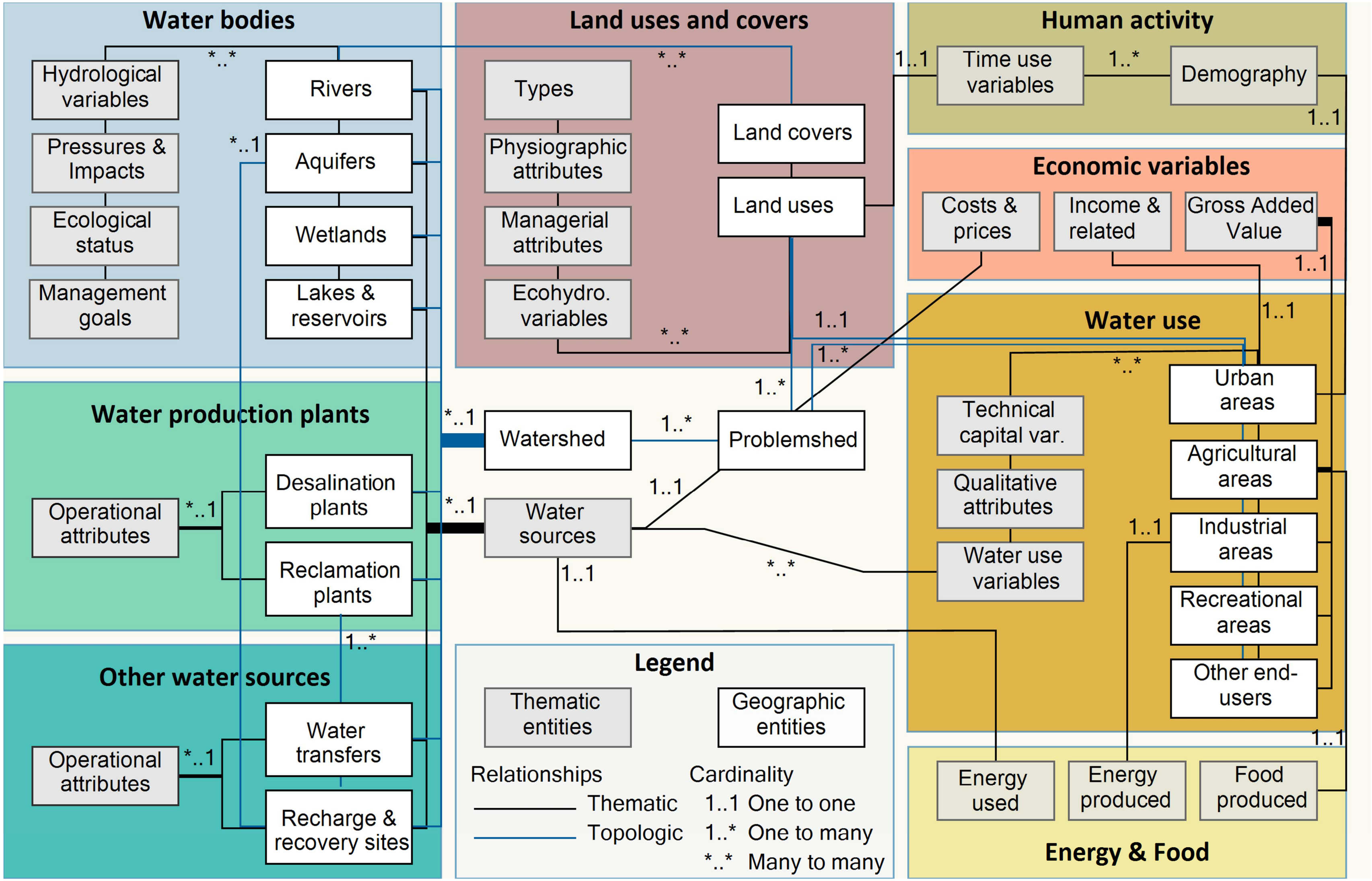

Figure 1.11 – Conceptual data model for the analysis water metabolism of social-ecological systems at water basin scale

PART II

The Andarax basin

Introduction to case study: the Water Framework Directive in the Andarax River basin

The Water Framework Directive (WFD) is the European water regulation since the year 2000. As exemplary application of IWRM, it brought an important reconfiguration of relevant scales, procedures and actors involved in water decision-making (Kaika 2003). First of all, it is a formidable effort towards the homogenization of water management models for all twenty-eight European countries. Second, it is a revolutionary policy in environmental terms because its main goal is the achievement of the good status for all water bodies in Europe, defined through ecological and chemical quality goals for surface waters, and through quantitative and chemical quality objectives for groundwater bodies. However, key concepts of the directive are ambiguous, embracing a deep-ecology narrative through an ecological modernization discourse that reconciles environmental conservation and economic growth without questioning political regimes driving environmental problems (Hajer 1995). The directive introduces two main innovative management devices: on one hand, economic instruments as means to control demand and prioritize courses of action; on the other hand, public participation in the planning process.

This case-study follows up the implementation of the so-called environmental objectives of the WFD in the Andarax river basin, a semi-arid south-eastern watershed in Spain, during the first management cycle 2009-2015. The hypothesis I attempt to test is that the win-win rhetoric of the WFD, implemented through ill-defined economic and participatory governance mechanisms, in a country like Spain where the traditional hydraulic paradigm had been anchored for more than a century, leads to ineffective management strategies and poor semantic closure of the management process. I argue that, among others, there are three relevant aspects of this water policy hampering its capability to achieve an improved quality of ecosystems in the Mediterranean Spain:

- An excessive emphasis on ecosystems in detriment of the human dimension. This new perspective strongly contrast with the tradition of Spanish river basin authorities that had a nearly exclusive focus on attending a ‘structural deficit’ through increasing water supply (Sampedro and Del Moral 2014). I argue that a more holistic perspective on SES would perform better in diagnosing the multiple entangled causes of water resources degradation.

- The lack of rigorous integration with other European policies driving structural metabolic change, especially agriculture and rural development, leads to contested policy objectives and discourses at lower governance levels, opening avenues for biased win-win strategical bridges through techno-social fixes (Swyngedouw 2013).

- A weak definition of public participation through mere consultation of documents. The application of this feeble form of participation in a country with a poor democratic and deliberation tradition results in a meager discursive and problem closure, because perceived problems at local level are not duly attended within formal water planning (Hernandez-Mora et al. 2015).

The following three analytical chapters focus on these issues in the Andarax river basin. Chapter 2 deals with the definition and analysis of watersheds as SES, operationalizing the WMSES framework in a sub-basin. Chapter 3 presents a multi-level analysis of the interplay between water and agricultural policies, and how this shapes metabolic patterns at the basin level, addressing some trade-offs associated to management priorities. Chapter 4 is devoted to the identification of the multiple narratives about water problems existing in the Andarax basin, assessing the first policy cycle in terms of its semantic closure (Table 1.3). This introduction presents the institutional context for water management at European and national Spanish levels, an overview of the study area, its subdivision into WHS for the analysis and the water management problems identified by local stakeholders.

The Water Framework Directive

Water is normatively defined in Europe in the following terms: “Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such” (WFD pp. 1). This definition acknowledges the economic value of water, at the time stating other values that need to be protected (Hernández-Mora et al. 2014). The WFD shifts the core weight of water management from demand-satisfaction to "establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which prevents further deterioration and protects and enhances the status of aquatic ecosystems” and “promotes sustainable water use based on a long-term protection of available water resources” (Article 1).

The first deadline given to achieve the policy goal is 2015, following a tight schedule that started with the transposition to all national member states regulations in 2003. The WFD established water bodies as the scale for monitoring progress towards policy objectives with specific indicators and reference benchmarks of good status. These should be identified and classified in typologies according to a set of criteria, mainly hydrogeological. Once the status of water bodies is assessed, Environmental Objectives (EO) were set for each of them as horizons for recovery of the reference conditions for good status. However, flexibility to these objectives is introduced through exceptions and less stringent objectives (LSO) in heavily modified or artificial water bodies (Article 4). These are water bodies that are “so affected by human activity or its natural condition is such that it may be unfeasible or unreasonably expensive to achieve good status” (WFD pp. 10). This concept of heavily modified broaches the dubious issue of how to establish what is ‘so affected’ or what is the purportedly good status referring to in areas where water ecosystems have been co-evolving with human systems for centuries. Clearly influenced by ecological sciences, this narrative assumes that there is a pristine status of ecological integrity to which ecosystems can be returned through management by reducing human ‘perturbations’ (Bouleau and Pont 2015).

The principles of IWRM are patent in the WFD through the foreseen devices to pursue the ecological quality goal:

- The river basin is set as the management scale for all waters in Europe so that ‘surface water and groundwaters belonging to the same ecological, hydrological and hydrogeological system are coordinated’ (WFD pp. 4). The management unit is named river basin district (RBD) and should be delimited by 2003.

- Management cycles of six years are established starting in 2009 with the first River Basins Management Plans (RBMP). The planning process commenced in 2004 with the characterization and appraisal of water bodies’ status, identifying pressures and impacts, the establishment of Environmental Objectives, setting-up monitoring networks to measure progress and, finally, drawing a Programme of Measures (PoM) for all water bodies appraised in less than good status. The plans should pose water use scenarios for subsequent short-term and medium-term horizons, 2015 and 2027 respectively. In addition, periodic reporting is required to member states on the RBMPs, on the economic analysis of water uses and on the monitoring programs. The European Commission has to develop implementation assessments every six years from 2012, as well as interim assessments focused on specific topics[8].

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[8] So far there has been four assessments that can be accessed at http://ec.europa.eu/environment/water/water-framework/impl_reports.htm

- Mandatory public participation processes are to be arranged with local stakeholders, who are defined as any interested party ‘in the production, review and updating of the river basin management plans’ (Article 14). The process consists essentially on public information and consultation of official documents to which comments can be sent. More active forms of public participation are recommended. In addition, background information used for the plan has to be provided on request.

- Economic instruments are introduced as prior criteria for water management and decision-making. First, compulsory economic analysis of water services costs, including environmental and resource costs[9], is required. These costs should be recovered by water users (Article 9 -cost recovery principle). A socioeconomic analysis of water uses based on long-term forecast of demand and supply should be developed (Article 5). However, the directive does not pose specific methodologies to perform these analyses, neither to quantify environmental and resources costs. In addition an assessment of cost-effectiveness of measures should be undertaken in order to prioritize the most economically efficient courses of action in the PoM. Finally, an economic criterion of ‘disproportionate costs’ can be used to justify LSO(Article 4.4 WFD pp. 10).

Therefore, the WFD departs from a deep-ecology narrative that is institutionalized through environmental objectives and the river basin management scale, liaised to that of economic efficiency and participatory governance as core mechanisms to achieve common goals in all European RBD. However, the specificities of those mechanisms were initially fuzzy or feeble and provided flexibility for adaptation to every Member State, and every river basin, political culture and management tradition.

The Spanish water management tradition

Since the late ninetieth century, water policy in Spain consisted primarily in the publicly funded development of the country’s hydraulic capacity to serve growing irrigation and hydroelectric demands (Hernandez-Mora et al. 2015). Spain was one of the countries that first institutionalized the river basin as management scale in the 1920s, and river basin authorities (RBAs) are powerful political actors which staff is essentially made up of civil engineers corps. The epistemic community formed by irrigators, hydroelectric companies, the national government and the RBAs was initiated by an intellectual movement known as *Regeneracionismo* (del Moral and Sauri 1999, Swyngedouw 1999). With industrial modernization concentrated in mainly two regions, Catalonia and the Basque Country, the wide rural Spain was perceived as poor, undeveloped and a burden for progress of the country. Its modernization through the intensification of agricultural productivity became a national political priority, and water was an essential resource to make available. Dams multiplied during the dictatorship years (1939-1975) to the point of reaching the peak per capita number in the world.

The transition to a democratic regime in the seventies gave powers to the Autonomous Regions, whose governments became a new actor in water policy having management capacity in those river basins fully located within their boundaries. The flourishing economic model based on urban development and sun-driven tourism raised also a new range of powerful actors including building companies and developers, public infrastructure agencies and local political leaders. With the capacity of keep on incrementing dams reaching its peak, the dominant discourse focused on ‘the unequal distribution of water resources between the humid north and the arid southeast is a limiting factor for agricultural and economic development and

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[9] Environmental costs: cost of the required measures for ecosystems status deterioration prevention, mitigation and restoration; Resource costs: opportunity costs for water users when the resource is dwindled over its natural recovery capacity.

should be balanced through inter-basin transfers' (Hernandez-Mora and del Moral 2015)[10]. The successive governments promoted a series of national hydraulic plans with the aim of transferring water along thousands of kilometers from 'surplus' basins like the Tajo and Ebro to South-Eastern coastal regions of Valencia, Murcia and eastern Andalusia. Conservative political leaders of these regions defended for long time the 'water for all' claim, progressively anchoring in the public opinion their right to get water from other river basins. Indeed, this became a core electoral issue with frequently successful results (del Moral et al. 2007). Whereas the Tajo transfer started operating in 1981, the Ebro one, foreseen in the National Hydrologic Plan of 2001, encountered strong contestation in donor regions, environmental groups, social movements and academics. This new coalition developed its own counter-narrative known as the New Water Culture[11]. With the arrival of the WFD, these contesting groups mirrored their interests in the ecological quality goals of the new enforced governance regime (Hernandez-Mora et al 2015). A new national government was elected in 2004 with the socialist party, who supported that narrative by repealing the Ebro transfer. The WFD implementation process was initiated and the core strategy for augmenting water availability was shifted from river-regulation and inter-basin transfer to desalination (March et al. 2014). To this purpose, a new program A.G.U.A (*Actuaciones para la gestión y uso del agua*, Actions for water management and use) was launched funding the construction of desalination plants all over the Mediterranean coastline under a new win-win-win narrative of 'increasing water security against drought risks, coping with increasing pressures of urban development, climate change and population growth' (March et al. 2014, Swyngedow 2013). However, this new techno-social fix was not well received amongst major lobbies from the transfers receiving regions because of its high price, different financial arrangement reducing the traditional public subsidies to hydraulic works, and because they were ruled by the opposite party defending transfers as a right (Hernandez-Mora and del Moral 2015).

The WFD was brought into the Spanish legislation in 2003 as a modification of the previous national 1985 Water Law, through an addendum to another legal document (*Real Decreto Legislativo* 1/2001). The conservative government had been focused on the last National Hydrologic Plan of 2001, and did not pay much attention to carry out rigorous transposition of the new regulation (La Calle 2008). It was not until 2007 that the Regulation of Hydrological Planning (*Real Decreto* 907/2007) was endorsed and the Instruction for Hydrological Planning in 2008 (ORDEN ARM/2656/2008) launched the planning processes with three years of delay. As will be explained in Chapter 3, the regional government of Andalusia echoed the new water policy in a regional law for those basins within its management scope, as it is the case of the Andarax.

The Andarax River basin

The Andarax basin is an illustrative case of Mediterranean semi-arid area were uncontrolled expansion of irrigated agriculture has driven water scarcity, both in quantity and quality, and thus where the new European water policy poses great challenges of adaptation. The basin is located in the Spanish south-eastern province of Almeria, in the Andalusia Autonomous Region, renowned for being the major European vegetables exporter in Spain at the time one of the driest (year average 200–600 mm, 12–18 ºC). As a Mediterranean area, the precipitation pattern is irregular both seasonally and inter-annually and most rain evapotranspires. According to the nomenclature of the WFD, the Andarax belongs to the Water Exploitation System IV of the Andalusian Mediterranean River Basin District (Figure I1.1), for whose management is responsible the regional government of Andalusia.

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[10] Transfers have a long hydraulic tradition in Spain, but became the sanctioned rhetoric with the National Hydrological Plan of 1994 that foresaw connections among most Spanish basins.

[11] European Declaration for a New Water Culture http://www.unizar.es/fnca/euwater/index2.php?x=3&idioma=en

The Andarax River flows along 66.6 km from up to 2,512 meters height in Sierra Nevada National Park to the Mediterranean Sea in the city of Almeria. The basin occupies 2,187 km^2 and counts with two main permanent watercourses, Nacimiento and Andarax Rivers, and one seasonal, Rambla de Tabernas, flowing through narrow valleys between four mountain chains *sierras,* and converging at the mid area right at the end of Sierra Nevada (Figure I1.1a). A notable diversity of waterscapes is shaped by latitude and altitude, although predominant ones show badlands under erosion processes with xerophytic shrubs vegetation, leveraged around the river banks by agricultural terraces that give the impression of an oasis.

The total population in 2005 was of 53,500 people in 39 municipalities, most of them with less than 5,000 inhabitants, and Almeria city with 181,700 inhabitants. Despite being located outside the physical watershed, the twon represents the second major water demand for the Andarax at the time it generates of one of the main water sources: wastewater. As will be shown, rural-urban dynamics play an essential role in the water metabolism and the spatial segregation of population (Figure I1.1 c), economic activities and agricultural production modes. Agricultural administrative areas do not coincide with watersheds limits as observed in Figure I1.1 b. There are six agrarian units located fully or partially within the basin. Four of them (*Alto Andarax, Medio Andarax, Guadix* and *Nacimiento)* are placed in mountain areas with small rural villages and a cultural legacy from the Muslim period in terms of architecture, agriculture and water management (Caparros 2010). Diametrically opposed, *Bajo Andarax* is the area surrounding Almeria city, with an intensive greenhouse production of vegetables and larger towns with higher incomes per capita. *Tabernas* is a natural protected desert with a characteristic pictorial landscape and expanding irrigated olive groves. As a result, the Andarax basin contains a myriad of social-ecological peculiarities, shaping an interesting hybrid rurality “between the social and the natural, the human and the non-human, the rural and the non-rural and the local and the global” (Murdoch 2003, quoted in Woods 2007 pp. 495). Following these peculiarities, different SES can be defined depending on analytical purposes.

Defining social-ecological systems through feasibility check

As discussed in Chapter 1, SES or, specifically for water, WHS can be delimited using different criteria according to relevant problems and questions. One could use a pure hydrological criterion as the WFD does (Figure I1.1a), facing mismatches with other relevant divisions like the municipal (Figure I1.1c) or agricultural (Figure I1.1b).

In order to follow the implementation of environmental objectives of the WFD, the question turns into which are the constraints that the achievement of its objectives pose. EO are inversely related to the degree of impact in which water bodies were in 2005. Despite the overall goal was set for 2015, the directive foresees longer periods for water bodies in a situation of severe impact. This baseline assessment is indeed a feasibility check that normatively establishes which related societal metabolic patterns are sustainable (regarding the ecological status criteria) and which are not. Therefore, the spatial extent for which EO are set, the water body, becomes a relevant criterion. Being smaller than the watershed, water bodies can be easily linked to other geographies in order to delimit coupled water-human systems. In this case study, I subdivide the Andarax in four WHS according to the following division criteria:

1) Whole surface water bodies.
2) Whole municipalities extracting water from those water bodies.
3) Whole agrarian units extracting water from those water bodies as long as previous criteria are not violated.

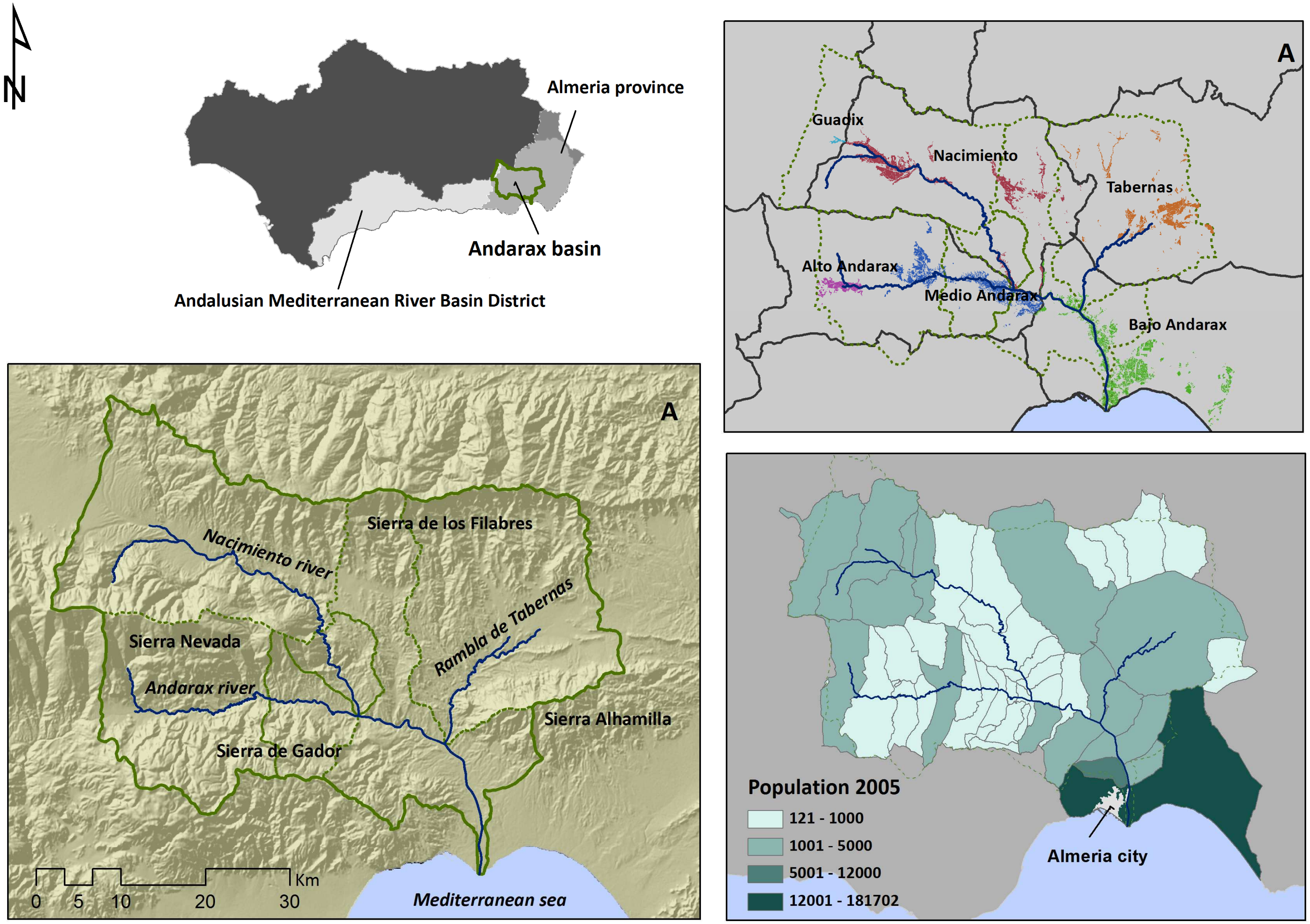

Figure I1.1 - Andarax river basin location and main spatial features: a - physical sub-basins and main watercourses; b - agriculture management areas (grey polygons) and agricultural units within the basin; c - municipalities population in 2005.

According to the RBMP 2009-15, the Andarax basin counts with eight surface water bodies and variable parts of nine groundwater bodies. Figure I1.2 a shows the ecological status assessment in 2005. Regarding surface water bodies, only the first segment of the Andarax river was considered in good status, whereas the rest were deemed in less than good status or heavily modified at the basin outlet. In regards to groundwater bodies, those located in Sierra Alhamilla and Sierra de los Filabres (Figure I1.1), with low exploitation rates, were appraised in good status. Nacimiento aquifer was deemed quantitatively impacted because water table levels were decreasing and its status was appraised as medium. The rest of aquifers were both quantitatively and qualitatively impacted and assessed in bad status.

Figure I1.2 b presents the EO set in 2005, and the four WHS resulting from the division. According to the RBMP 2009-15, only the surface water body known as Alto Andarax (Upper Andarax, until its convergence with Nacimiento River) would achieve the good status in 2015. EO in the rest of surface water bodies were set for 2027 with the exceptions of Lower Andarax and the Upper Nacimiento that received LSO (this latter despite not being assessed as very modified). Regarding the aquifers, as expected those in most severe impact situations, Sierra de Gador and Bajo Andarax, were assigned LSO. On the contrary, the aquifer in Nacimiento was expected to achieve the good status by 2015, whereas the one in Tabernas by 2021.

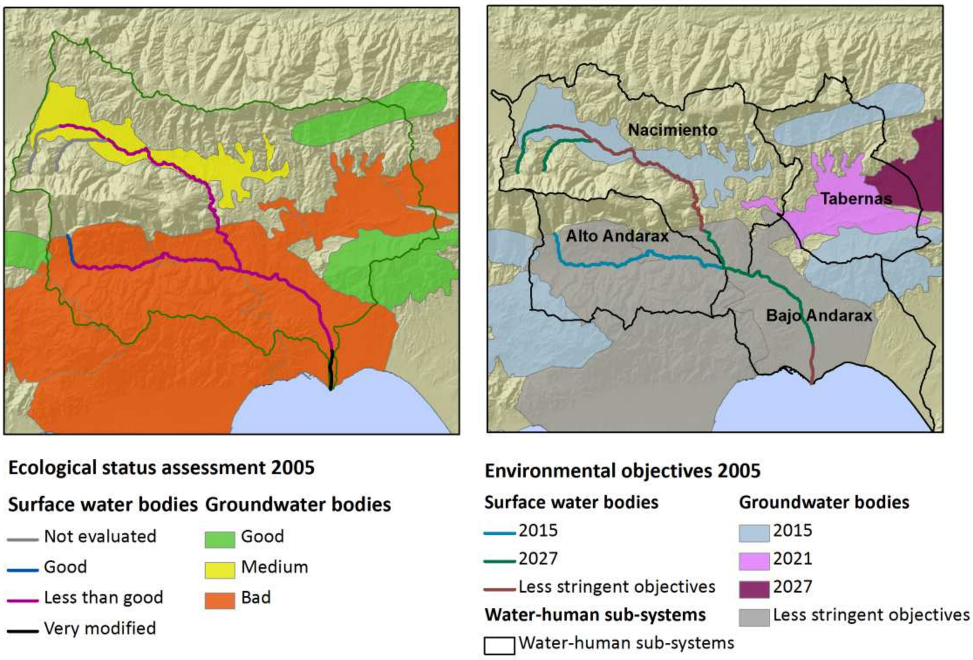

Figure I1.2 a - Environmental objectives in 2005 and b - Water-Human Subsystems

Water management problems in the Andarax

As discussed in the introduction and the methodological framework (section 1.3), the reason for choosing this case study was the existence of an on-going research project titled ‘Participatory search of water management solutions in the Andarax basin’, ALTAGUAX (Van Cauwenbergh et al. 2008, Van Cauwenbergh and Ballester 2015). Co-funded by the UNESCO

Institute for Water Education and the old Andalusian Water Agency[12], the project arranged a unique open participatory process with a wide range of local stakeholders during 2009-10, in parallel to the development of the RBMP. The aim of the project was to link the participatory process to the development of a decision support system that could contribute to the planning process and decision-making. During the workshops, a thorough diagnosis of water management problems and of potential courses of action was developed. By the end of the second year, the Andalusian Water Agency (now Direction for Hydrological Planning) repealed its support to the project and the final steps could not be carried out as planned. However, the inputs (materials and information used) and outputs (minutes) of the participatory workshops constitute very rich material to understand relevant water issues and perspectives in the basin.

Table I1.1 shows water management problems identified during one of the workshops and the average value given by participants to each of them in an evaluation exercise, according to four different criteria to be valued in a range from 1 to 25. As expected in a semi-arid area, top ranked problems in all criteria are those related to water quantity: aquifer overexploitation, insufficient runoff and attendance to increasing demands. Water quality problems are perceived as less troublesome, with the exception of wastewater pollution. Ecosystem degradation and loss of riparian systems are also perceived as the second more important environmental impact after aquifers overdraft. Erosion and vulnerability to drought are another package of relevant issues, whereas flood risk is considered an important socioeconomic impact. When looking to future trends, the perception is that water quantity problems, overdraft, drought and erosion will worsen. Finally, governance and access to information were also top ranked in the two criteria (here the ratio was from 1 to 20).

Table I1.1 – Evaluation of identified water management problems in the Andarax basin. Source: ALTAGUAX project

Problem	**Environmental impact**	**Socioeconomic impact**	**Spatial extension**	**Future trends**
Current and future demands satisfaction	19	**21**	18.5	**20**
Insufficient surface water flows	**21**	19.5	19.5	**20.5**
Aquifer overdraft & marine intrusion	**23**	**22**	19	**21**
Nitrates pollution	20	16	15	15.5
Pesticides pollution	19	12.5	13.5	11
Wastewater pollution	**20.5**	17.5	19	14.5
Industrial pollution	16.5	10	9	11
Ecosystem degradation	**21.5**	15.5	16	16
Impacts on habitats and species	18.5	12.5	14	15
River bank alternation and instability	18.5	14.5	16.5	14.5
Desertification and erosion	19.5	19.5	19	**20**

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[12] The Andalusian Water Agency existed as such until 2013. Thereinafter was turn into the Direction for Hydrological Planning with a substantially waned budget and decision-making capacity.

Vulnerability to floods	17.5	**20**	15.5	18
Vulnerability to drought	19	19	19	**20**

	Scale of the problem	**Difficulty to achieve policy goals**
Administrative and management problems	20	20
Insufficient access to information	19	19

Regarding stakeholders, Table I1.2 gathers those that participated in the ALTAGUAX process. The Andalusian Mediterranean RBD has an office in Almeria city that is responsible for the management of the four river basins located inside the province. This office is in charge of RBMP development, implementation of the PoM and monitoring of progress towards management goals. Urban supply is managed by local councils for most rural municipalities and supported by the regional delegation of the Andalusian government (Diputación de Almería). The Provincial delegation of Ministries of Agriculture and Fisheries was also invited to the process. Water supply in Almeria city is managed by the private utility Aqualia that, as most private utilities in Spain, belongs to a large civil engineering contractor, F.C.C. The city wastewater treatment plant is operated by another major water utility corporation named Acciona Agua. Finally, the national public water utility Acuamed is the one in charge of the operation of desalination plants in Almeria coastline.

Table I1.2 - Stakeholders types and their realm in water management. Source: ALTAGUAX project

Stakeholder type	**No. institutions**	**No. ALTAGUAX participants**	**Water management realm**
Public administrations related to water	3	10	River basin management
Local councils	40	6-10	Urban water supply
Water utilities (private and public)	3	2-3	Urban water supply
Irrigation communities	104	6-10	Agricultural demand
Rural development and agrarian offices	4	2	Protected areas conservation Hydraulic heritage protection Agricultural demand
Environmental groups	3	2-4	Ecosystem conservation
Academia	2	4-8	Protected area monitoring

There are 104 formal irrigation communities in the basin, 75% of which date from 1946 and have less than a hundred members. They lack of permanent staff and have a low influencing capacity over water decision-making at the basin level, although they do at their localities. There are a few large irrigation communities, especially those devoted to greenhouse production in the Bajo Andarax WHS. These are important institutions with more than a thousand members each, and a proper representative structure defending their interests. These are the irrigation communities that took part in the ALTAGUAX project.

The rest of stakeholders that took part in the project were: i) two rural development groups located in municipalities within the Sierra Nevada Park; ii) two agrarian offices supporting small farmers and irrigation communities; iii) three environmental organizations, including the New Water Culture Foundation, Ecologist in Action and a citizen organization defending the recuperation of the aquifers named Aquifers Alive. In addition, the academia was represented by the University of Almeria and the Global Change Observatory of Sierra Nevada that monitors evolution of ecosystems within the Sierra Nevada National Park area.

Chapter 2. River basins as socio-ecological systems: Linking levels of societal and ecosystem metabolism in the Upper Andarax

Recent efforts of integrated river basin modeling strive to predict the effects of decision making on water allocation and land uses over the hydrological system under a range of scenarios (Jakeman and Letcher 2003, Liu et al. 2008, Henriques et al. 2008). Although these models are powerful in hydrological response forecasting, uncertainty in societal choice predictions is still a major challenge (Letcher et al. 2007). This is partially due to the local specificity of the complex organization of social systems as driver for environmental change, making extrapolation between contexts difficult. Nevertheless, water accounting methods, like virtual water (Allan 1998), water footprint (Hoekstra and Chapagain 2006) or social metabolism (Fischer-Kowalski 1998, Swyngedouw 2006), have engaged in trying to understand the socioeconomic and political drivers of water use patterns, attempting to bridge scale mismatches with biophysical variables. As discussed, integrated analytical frameworks of SES can provide insights on the interactions between social, ecological and hydrological processes (Madrid et al. 2013).

The representation and analysis of river basins as complex SES is still incipient, although some important works have been developed recently. Rathwell and Peterson (2012) address cross-scale interactions between water management and the provision of ecosystem services. Pahl-Wost et al. (2012) have applied the Management and Transition framework in at least 29 river basins all over the world. Mix et al. (2014) combine qualitative and quantitative methods to approach a diachronic analysis of multidimensional drivers of water use change in an arid river basin in Colorado (USA). All these studies have two things in common: they depart from a networks approach to SES (Janssen et al. 2006) and they emphasize the role of policies and institutions shaping relations between social and ecological systems. However, none of them combine eco-hydrological modeling with socioeconomic quantitative analysis as integrated watershed modeling does, and none deal with the multi-scale organization of SES. Networks theory and hierarchy theory are not exclusive but rather complementary analytical lenses, each of them having strengths and purposes (Allen and Giampietro 2014). While network approaches to SES gain analytical dynamism by focusing on change (with conceptual devices such as drivers, thresholds and resilience), hierarchy theory is more robust on scaling issues and looking for principles of categorization of living systems organization (by using concepts such as descriptive domain, surfaces or holons).

This analytical chapter has a methodological purpose of operationalization the WMSES framework (Figure 1.5) in order to link the analysis of societal and ecosystem metabolism of water in the Upper Andarax basin. I aim to show that this type of comprehensive representation provides more thorough understanding of water systems dynamics than the pure hydrological or societal one. To this purpose, the eco-hydrological model BalanceMED (Willaarts et al. 2012) is calibrated in the Alto Andarax WHS (Figure 2.2), from now on Upper Andarax, and integrated in the MuSIASEM water grammar. I attempt to answer the following questions: how does the socio-eco-hydrological functioning of the Upper Andarax watershed work? What are the main drivers of socioeconomic change and their impacts over aquatic ecosystems? What are the water management challenges in the context of the current European water regulatory framework?

2.1. A long social-ecological history driven by international markets

The Upper Andarax is a genuine catchment because of its uneven topography and its striking hydraulic heritage. The narrow valley runs between two great elevations, the Sierra Nevada foothills, on the North, and Sierra de Gador on the South. Land occupation in the Upper Andarax is extremely constrained by topography, with agriculture occupying 14% of the territory. Vegetation series correspond to *Quercus* spp. in the Meso-mediterranean zone (until 1280 m) and *Juniperus* spp. in the Supra-mediterranean zone (up to 2000 m), but representatives of these species are now very limited. *Pine* spp. plantations are the most extended forest form usually mixed with shrubs. The major vegetation cover includes different types of xerophytic shrubs, well adapted to the prevailing arid conditions. Predominant species are *Stipa tenacisima* (esparto), *Ulex parviflorus* and *Festuca scariosa*. A system of traditional irrigation infrastructure (infiltration channels called *acequias*, flood collection *turbias* and subsurface water collection *galerias*) and their local management communities have long ensured water availability in this dry environment (Pulido-Bosch and Ben-Sbih 1995). The social-ecological interest of the basin has driven a large amount of rich historical studies in the area (the Martínez and Usero 2010 book is a good compilation), yet there is less scientific literature on current socio-eco-hydrological functioning of the basin (Sanchez-Martos et al. 2013).

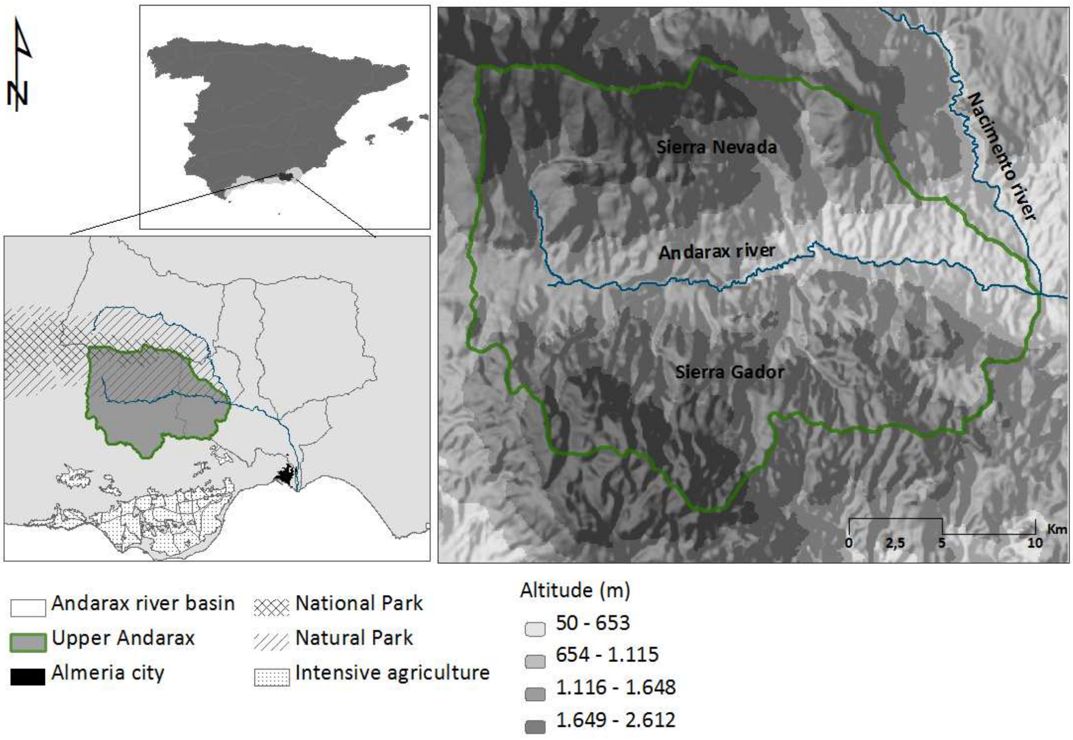

Figure 2.1 - Upper Andarax and its location within Andarax river basin

Human-environmental relations in the Upper Andarax are described from the Neolithic. I focus here on the period when the international economic and political arena became key drivers for regional change. Contrary to other regions in Spain, Almeria had, from the onset of 19th century, an export based economy thanks to its important harbor (Sánchez-Picón et al. 2011) (Table 2.1). This first globalization brought a flourishing lead mining activity lasting over a century until its international depreciation. The depression was succeeded by a second mining boom, the iron time, as well as the cultivation of grapes, oranges and esparto grass, which were in high demand in England through much of the 19th century. These activities drove major land use changes, including a massive process of deforestation which forced the development of an impressive system of agricultural terraces on the river banks to reduce the risk to floods (Latorre et al. 2001). Miners excavated cisterns, which collected subsurface water flow for agriculture, leading to the creation of important water user communities to manage the new resources. Much of the mountainous areas were also terraced and reforested with *Pine spp.* during the reforestation campaigns of the Franco's dictatorship (Martínez et al. 2008). The second globalization begun at the end of 19th century, and elicited the decline of this economy and the first emigration boom between 1980-2000 (Sánchez-Picón et al. 2011). Part of this boom followed an internal drift from upper mountain areas to the coast region where the grape cultivation infrastructure was repurposed to introduce intensive vegetable production in plastic greenhouses for distribution in the European market (Mateo 2013).

Table 2.1 - Drivers of social-ecological change

International driver	Regional driver	Period	Social-ecological changes
First globalization	Mining	End of 18th – end of 19th	Deforestation, floods, cisterns excavation
Economic crisis	Grape production	End of 19th – end of 20th	Terrace system
	Reforestations	1939-1975	Pine plantations extension
Second globalization	Emergence of greenhouse production in coastal area	1980-2000	Rural exodus, agricultural land abandonment
United Nations Program Man and the Biosphere	Sierra Nevada protection	1986-1999	Land uses regulation
Water Framework Directive	Environmental objectives achievement	2010-2027	Good ecological status of water bodies
Common Agricultural Policy	Competitiveness within international markets	2008-2014	Agricultural intensification

The northern Sierra Nevada is one of the most important hotspots for plant diversity and endemism in the Western Mediterranean region, and includes an impressive geomorphological system with more than 15 peaks over 3000 meters at 50 Km from the sea. It was declared a Biosphere Reserve in 1986 by UNESCO and Natural Park by the Andalusian government in 1989, a legal status aimed at integrating sustainable human activities within conservation goals. The most ecologically valued area (the higher peaks covered by snow in winter) was declared a National Park in 1999, a more restrictive form that phased out traditional human activities like agriculture, hunting and gathering within its boundaries.

The basin currently consists of an aged population of 8873 inhabitants distributed in 14 municipalities (INE 2011). The pictorial agricultural landscape is an identity element being gradually abandoned as agricultural productivity decreases. The main occupations in the upper municipalities closer to the National Park are related to ecotourism, turning to agriculture in the central part until last municipalities at the basin mouth which are mainly working in the services sector. European water and agricultural policies are new drivers of social-ecological change, since they impose new goals and strategies aimed at transforming water metabolic patterns. The interplay between these two policies is analyzed in Chapter 3. In this chapter I mainly focus on the integrated characterization of the Upper Andarax as a SES, including water governance as mediator of human-environmental relations.

2.2. Methods

The Upper Andarax as complex holarchic social-ecological system

Figure 2.2 shows the multi-axes representation for the Upper Andarax. The focal level (e/i/s) is the WHS defined by the intersection between the physical river basin and its municipalities and agrarian administration boundaries (Figure I1.2), linked through the River Basin Management Plan (RBMP). Upper and lower levels in the axes establish the external and internal constraints to the self-organization of the socio-ecosystem. The multi-axes holarchy is structured into the general analytical framework in Figure 2.3, adapted from Figure 1.5. Analytical categories are arranged in four quadrants: ecosystem/societal metabolism and water exchange/organization. Four interfaces are depicted with different types of interactions between i) the organization of social systems and water use/demand (A), ii) the organization of ecosystems and water supply (C), iii) water demand and water availability (B) and iv) the organization of social and that of ecosystems (D).

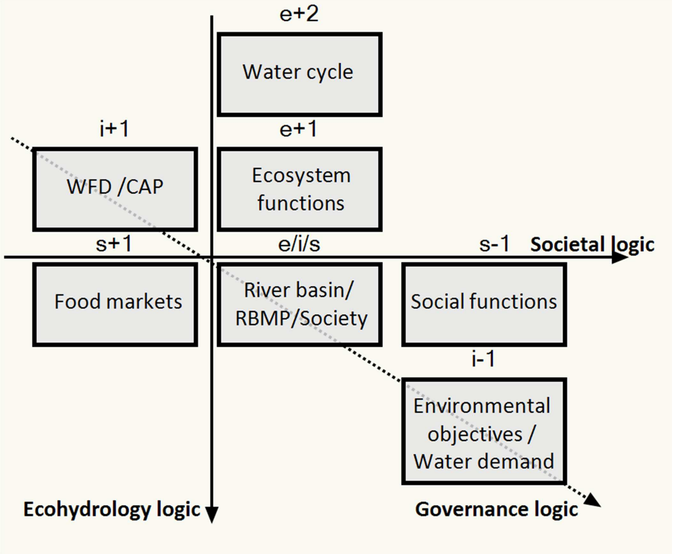

Figure 2.2- Multi-axes holarchy for the Upper Andarax basin

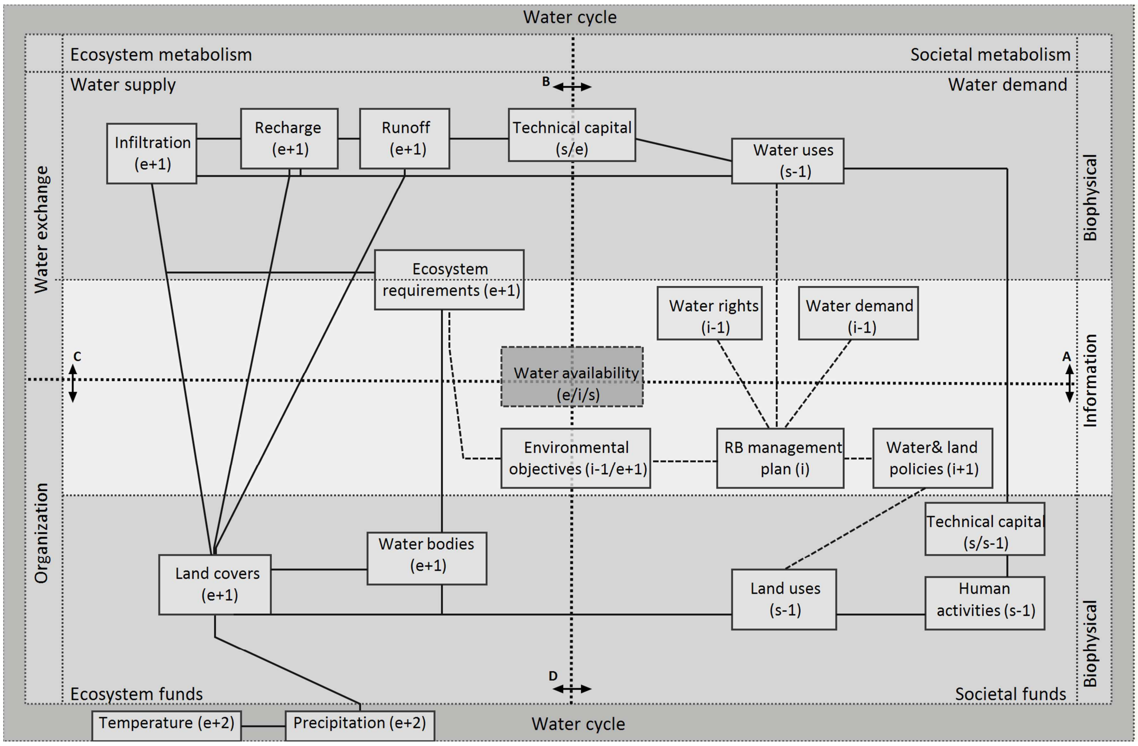

Figure 2.3 - SESWM analytical framework adapted to the Upper Andarax basin

Grammar

The methodological purpose of this chapter is the operationalization of SESWM in order to link the analysis of societal metabolism to variables of ecosystem metabolism that are relevant for river basin management. My observation lenses are located on the social scale of observation: I do not study the functioning of ecosystems themselves but the interactions between ecosystems and society as a consequence of societal organization. Therefore, as an ecosystem water metabolism analysis, I focus on the eco-hydrological processes that control water resource renewability (supply side), the impacts caused to ecosystems (sink side) and the boundary concepts of water availability and ecosystem water requirements[13]. To this purpose, water metabolism is formalized through the MuSIASEM grammar in Table 2.2, tying the holarchic organization considered (Figure 2.2) to the semantic representation of the system metabolism (Figure 2.3).

The grammar is quantified through extensive variables (total flows and funds) and relational indicators (flow/flow, flow/fund) are summarized in Table 2.3. As shown in Figure 2.3, four types of interactions between ecosystems and society are characterized. Relation A describes the intensity of water use required to maintain a human activity or land use type. Relation B describes the degree of exploitation of water funds (supply side) for direct human uses while the feedback D, environmental loading, refers to the impact of the societal metabolism over aquatic ecosystem health (sink side). Type C relations are two-sided: on one hand, the generation of water funds (runoff, recharge, soil infiltration) per type of land cover; on the other, the ecosystem water requirements mediated by normative societal decisions on availability and land uses.

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[13] Boundary because the shape interactions at the societal-ecosystem interface

Table 2.2 - Water grammar for the Upper Andarax basin

Levels	**Water exchange**			**Organization**		
	Role	**Semantic categories**	**Types**	**Role**	**Semantic categories**	**Types**
Water cycle e+2	Fund	Climate	Precipitation	Fund	Climate	Potential evapotranspiration
Ecosystem functions e+1		Water funds turnover	Runoff Recharge Infiltration		Land covers	Quercus and riparian forests Plantations Shrubs Pastures Irrigated agriculture Rain-fed agriculture Abandoned agriculture
Water funds Focal level e		Available water for societal appropriation	Surface Groundwater Soil moisture		Water bodies	Rivers Aquifers
Society Focal level s	Flow	Gross water use	Withdrawn Soil	Fund	Human activity	Physiological overhead Social, Leisure & Education Unpaid work Paid Work
Societal functions s-1		Net water use	Urban supply Food production Forestry Esparto gathering Cattle		Managed land uses	Plantations Shrubs Pastures Irrigated agric. Rain-fed agric.
i-1		Demand	Withdrawals		Technical capital	Transport infrastructures Irrigation technology
				Flow	Money	Agricultural costs Gross added value Water costs Municipal gross rent

Table 2.3 - Relational indicators

Relation	Indicator	Description
A	Water metabolic rate	Gross water use per hour of human activity
B	Water extraction index	Surface water: ratio of water withdrawals out of total runoff, e-flows discounted
		Groundwater: ratio of water abstraction out of total recharge, discharges to springs discounted
C	Environmental impacts	Surface and groundwater quality
		Water table level changes
		Erosion rates
D	Ecosystems water requirements	Soil: transpiration
		River: e-flows
		Groundwater: discharge to springs

Modeling

To build up this grammar into formal categories several models/tools have been integrated:

- Climate: series of monthly median precipitation and mean temperature measurements for the period 1970/71-2000/01 from 24 meteorological stations have been interpolated through Inverse Distance Weighting (IDW) in ArcGIS 10.2 and used for potential evapotranspiration calculation with a Thornthwaite based Microsoft Excell macro.
- Eco-hydrology: the BalanceMED model (Willaarts et al. 2012) is a semi-deterministic model able to quantify the mean hydrological functioning (i.e. partition of annual precipitation into runoff, aquifer recharge and soil moisture) of Mediterranean basins using long time series of mean monthly rainfall and potential evapotranspiration. Since BalanceMED is a spatially explicit model, the Upper Andarax was divided into so-called "hydrological units" (HU), which are unique combinations of land use and land cover polygons (LULC) and soil types polygons. Such divisions allow identifying potential differences in the eco-hydrological functioning across the basin. The model uses the APLIS equation (Andreo et al. 2004) to assess the soil percolation capacity (i.e. potential aquifer recharge).
- Societal metabolism accounting including water and monetary flows and land, human activity and technical capital funds. We use the pie chart representation for rural systems analysis adapted from the Serrano-Tovar and Giampietro 2014 template. It includes their interactions with three types of context (urban system, external markets and water funds). Land cover uses and green water flows associated were estimated with a fuzzy approach of shares use coefficients per type of cover (see Appendix 2).
- Environmental impacts: annual rates for erosion and water table level changes have been averaged for available series between 1992 and 2006. Water quality measurements in existing control points in the watershed were averaged for available

series between 2002 and 2013.

The process consisted of spatial processing of physical variables in ArcGIS 10.2 to feed the eco-hydrological model on one side, and of secondary data processing to feed the societal metabolism accounting on the other (Figure 2.4). Both of them have been conducted in R and results were gathered in ArcGIS geodatabases. For a detailed methodological description on data sources, model calibration, variables calculation and links to databases and codes please refer to the methodological Appendix 2. Note that the levels specified in the grammar follow an organizational scale of observation, i.e. holons in a socio-ecological system. Formal categories of the grammar and the spatial and temporal scales used for modeling are given in Table A2.1 and Figure A2.1 of the Appendix.

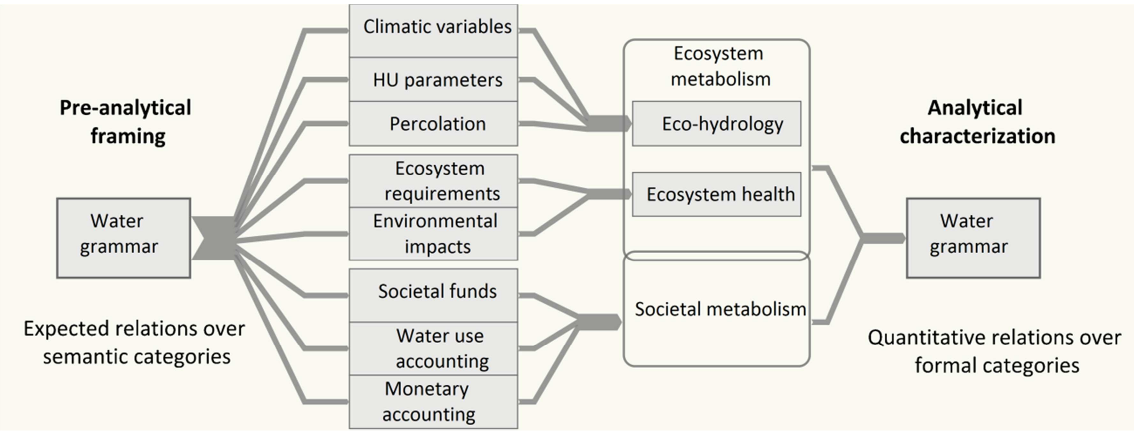

Figure 2.4 - Process overview

How do I calculate water availability?

As Del Moral (2005) and Zhou (2009) illustrated, water availability is almost impossible to calculate on a general basis due to its strong dependency on normative frameworks, technical capital and accepted trade-offs of water withdrawal. The Spanish water management legislation only defines water availability for groundwater as “the average year-to-year value of total recharge of the water body minus the average year-to-year flow required to achieve environmental objectives, to prevent any further significant deterioration of the ecological status and significant damage of dependent terrestrial ecosystems” (MARM 2008). This complex definition is not complemented by a harmonized framework for its assessment, especially in regards to the connection of ground to surface water bodies, leaving the definition of “significant” damage open to interpretation. As a result, aquifers are usually treated as black boxes in the RBMPs and the lack of spatially explicit aquifer modeling hinders their governance robustness (De Stefano et al. 2014). The year availability for societal appropriation of water is calculated as:

$$WA_{Surface} = DSF - EF$$

$$WA_{Ground} = RE + IRF + IIR + IF - OF - EF$$

Where *DSF* are water diversions from the river, *EF* are the e-flows, *RE* is the annual recharge from rain, *IRF* the infiltration from runoff, *IIR* the infiltration from irrigation returns, *IF* the lateral inflow, *OF* the lateral outflows to other aquifers. I assumed the regime of surface e-flows estimated in the RBMP as well as the average annual estimated discharge to the 58 natural springs as a proxy for groundwater ecosystem dependency.

Modeling limitations

The most important drawback of this study is the unavailability of a temporal series of water use data hampering a diachronic analysis. In addition, the wide and diverse secondary data requirements for the social metabolism analysis forces the integration of data measured in different periods. For this reason, we can only get a snapshot of the average water metabolism in the region between 2000 and 2008. This is the same timeframe than the baseline measurements produced for the River Basin Management Plan released in 2010. Regarding the eco-hydrological model, the surface-groundwater interactions and the influence of the snow on the hydrological regime are not considered. In addition, one of the main limitations is the difficulty to model the pronounced human alteration of the basin hydrology. Only human terracing was considered in regard to its effect to slope reduction but their explicit relation to erosion rates is not covered within our model. I decided to calibrate on a monthly average resolution because it is sufficient for the descriptive purpose of this paper given the constraints on social data.

2.3. Results

Water funds *(e+2/e+1)*

The Upper Andarax climate is representative of Mediterranean areas: high evapotranspiration and marked seasonal and inter-annual irregularity of precipitation. Nonetheless, the high elevations of both sides of the basin and its orientation shape a harsh gradient in the spatial distribution of precipitation and potential evapotranspiration (Figure 2.5 a and b). The North-West, mountainous Sierra Nevada presents a sub-humid 630 mm of annual precipitation and temperature of 11 ºC. The lower, South-Eastern area is classified as semiarid with a range 200-300 mm of annual precipitation, mean temperatures of 16 ºC and potential evapotranspiration of up to 890 mm. The presence of arid zones, characterized by the alternation of extreme events (drought and torrential rainfall), is usually a more determining factor than the small fluctuations in the mean values of the climatological variables. This irregularity is revealed by annual Pearson's coefficients of variation around 42%, increasing to over 200% for the driest months.

Water bodies are classified in typologies in the RBMP. There are two surface water bodies: the Alto Andarax, which runs from the spring until the first urban area, and the Medio Andarax, which continues then flowing down until the outlet. The two main groundwater bodies extend far beyond the watershed to coastal areas where major exploitation takes place. Gador Sierra is a huge karst aquifer composed of permeable and fractured limestone and dolomites. As observed in Figure 2.5 c, the recharge model shows a recharge capacity over 80% for this area while siliceous Sierra Nevada has low permeability and the detritus aquifer of Low Andarax medium (70-80%). Total mean annual precipitation for the modeled period was 138.2 Hm^3; of which 76.6 turn into soil moisture, 36.4 percolate to aquifer recharge and 15.7 flow as runoff. Figure 2.5 d-f shows the spatial distribution of these water funds. The influence of the precipitation pattern is clear in that 80% of runoff generation is concentrated in the North-East corner while most of the recharge is also distributed all along the eastern strip. Middle and lower parts of the basin show lower runoff and recharge generation but still hold an important fraction of the soil moisture.

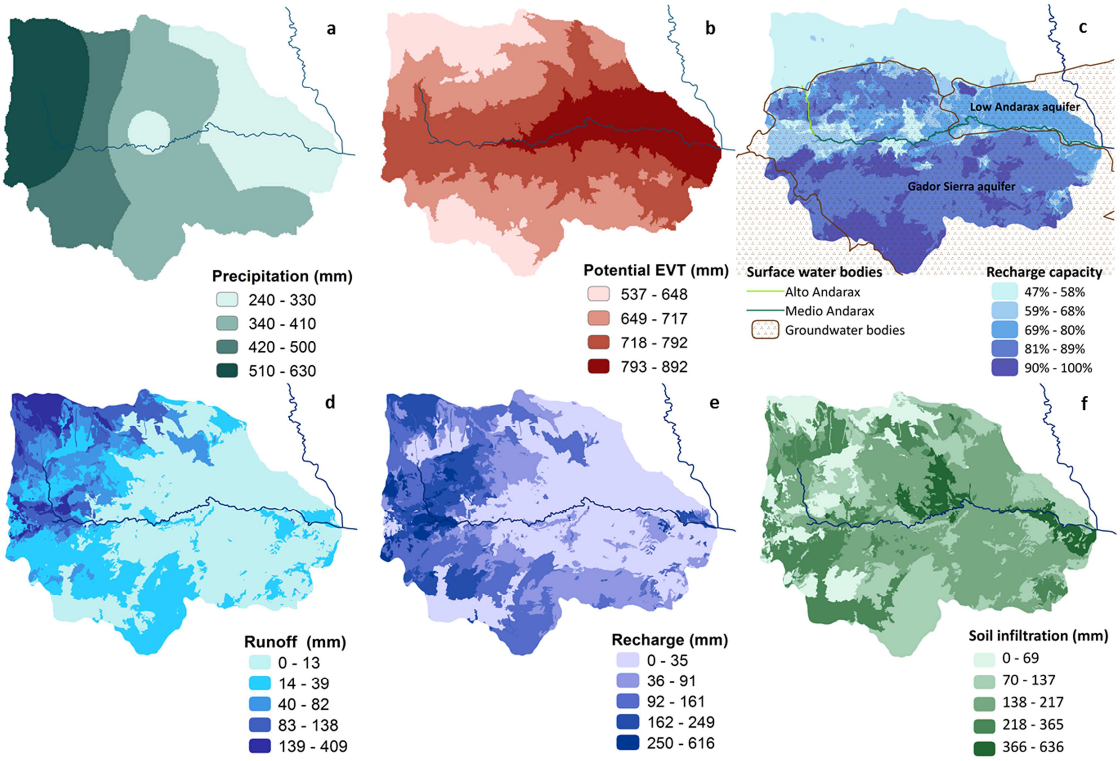

Figure 2.5 - Spatial distribution of a- median annual precipitation; b- potential evapotranspiration; c- recharge capacity; d- soil infiltration; e- runoff; f- recharge

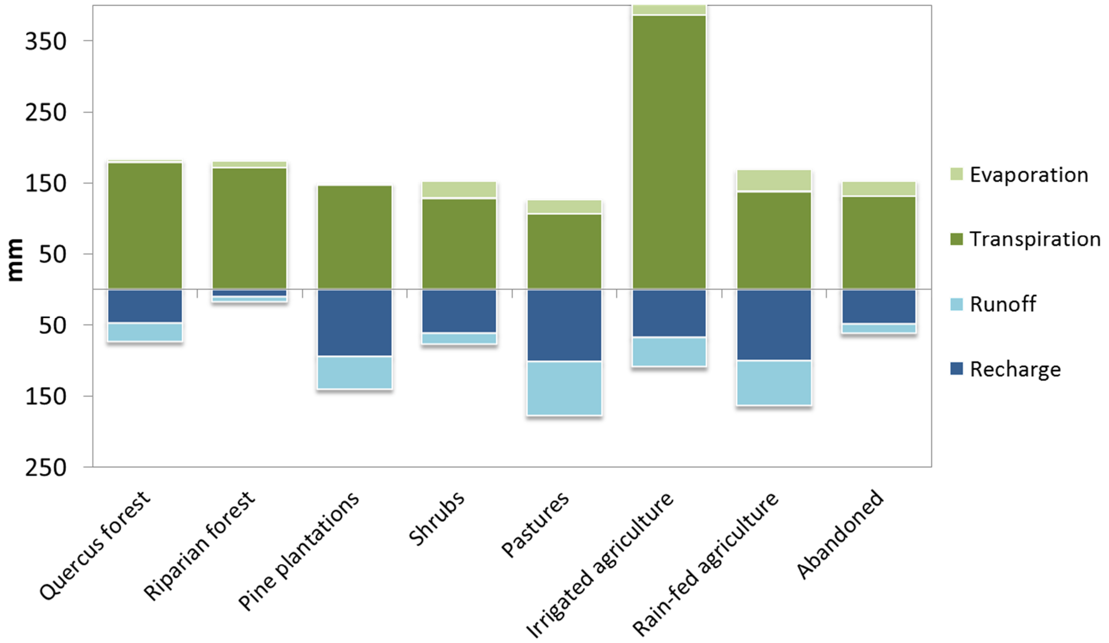

Figure 2.6 - Land ecosystems requirements and surface and groundwater recharge density per LULC type (mm)

The average eco-hydrological indicators (Relations C) per land cover type are presented in Figure 2.6. Transpiration, as the share of soil water invested in biomass productivity, is shown along with the annual rate of water evaporation (non-productive fraction of soil water). While representing a small fraction of the territory, *Quercus* spp. forests and its combination with other types of vegetation (shrubs or pastures) and riparian forests transpire the largest fraction of soil moisture, followed by *Pine* spp. plantations. As expected, more densely vegetated areas are more efficient in terms of water used to produce a unit of biomass as they have less water losses from soil water evaporation. The ratio of transpiration out of total evapotranspiration decreases in lower covers such as shrubs and pastures. The effect of terracing in agriculture can be detected in the rather high productivity of rain-fed agriculture as compared to similar cover vegetation like shrubs and pastures. Abandoned agricultural areas are substituted by shrubs showing a similar productivity. Indeed, the Analysis of Variances showed significant differences in transpiration rates between all typologies ($p<0.05$) except between plantations and rain-fed agriculture (both terraced), and between abandoned agricultural areas shrubs and pastures. Irrigation significantly intensifies plant productivity in comparison with all other land uses. Recharge and runoff rates in this watershed are not so much determined by the land cover as they are by the geology, slope and spatial distribution of precipitation. For this reason, there are no clear statistical clusters based on LULC typologies. However, we found a significantly lower recharge rate on *Quercus* spp. forest compared to *Pine* spp. plantations in both sierras, but no statistical difference with shrubs or pastures. Abandoned agricultural areas do not show statistical differences on their recharge rate with any other land cover type whereas both irrigation and rain-fed agriculture have significantly higher average recharge rates than *Quercus* spp. forest and shrubs.

Societal metabolism (*s/s-1*)

Figure 2.7 shows the representation of societal metabolism of the whole Upper Andarax. The Human Activity budget shows a low share of hours devoted to paid work activities (7%) which have to sustain the monetary requirements for the rest of hours (93%). A relevant point is that unpaid work (7 million hours) in households is higher than paid work hours, with 88% of these hours sustained by women (gender disaggregation of human activity can be found in this chapter geodatabase). Main working activities are the services and government sector (50%), building (18%) and mining and industrial activities (9%). All of these occupy only 2% of the total land used (urban areas), whereas most of human land uses are agriculture and other extensive land cover exploitations (grazing, forestry and esparto gathering) accounting for 23% of formal working hours.

About 77% of the watershed's agricultural production is traded in external markets, whereas the internal one sustains 33% of revenues obtained from agricultural products. The total municipal gross rent in 2006 was of 73 M€, indicating an important contribution of agriculture to the local economy. Water costs represent 13% of agriculture expenditures and are very low for surface water (between 1-3 cents €/m^3), and more fluctuating for groundwater (between 6-18 cents €/m^3). The consequence of the emigration flow from the basin villages to downstream urban areas is an increasing input of working/leisure hours on weekends and the inflow of cash generated there.

The region contains a diverse pattern of rain-fed and irrigated crops, with a predominance of almond trees typically found in mountain regions in Spain because of their high adaptability to extreme conditions (i.e. poor soils, low soil moisture and cold winters). Table 2.5 presents the economic and technical indicators of the different crops. As observed, irrigation substantially increases monetary productivity. The highest economic labor productivity (Gross €/hour) is shown by almond production, because it is low labor intensive, followed by horticulture, because of high market prices. Water transport systems are primarily *acequias* and surface flooding represents the main irrigation technique. Only citrus production at the basin outlet has introduced drip irrigation.

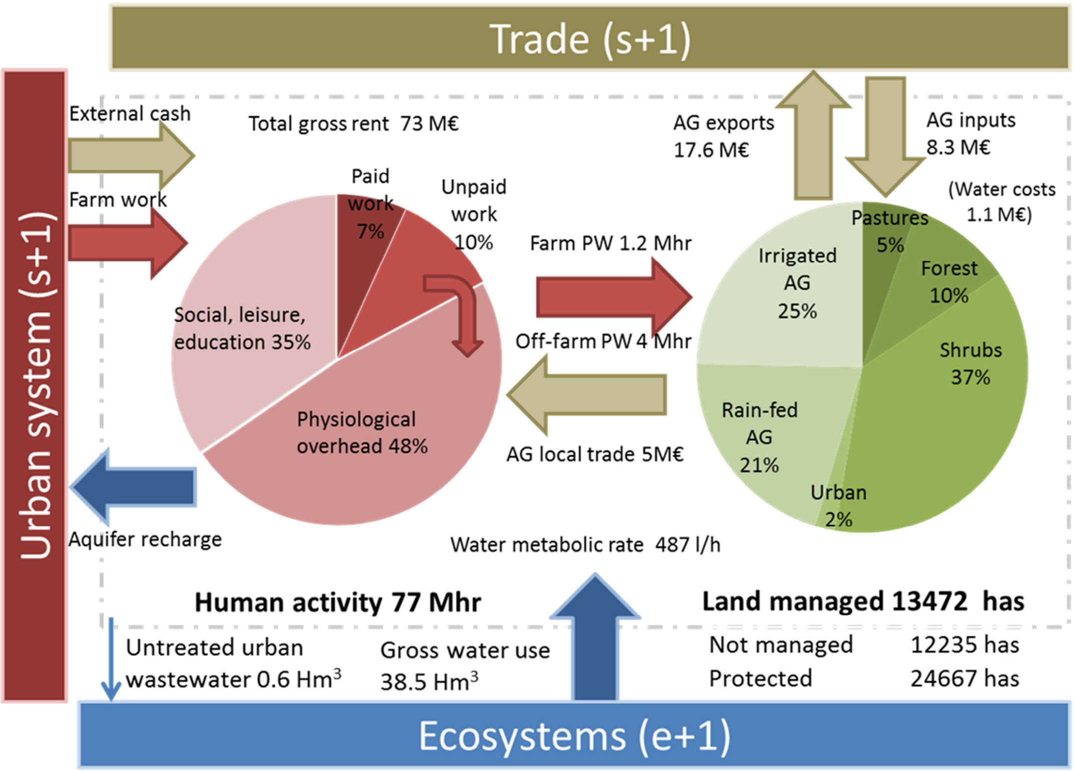

Figure 2.7 - Annual societal funds and interactions with main contexts. AG: Agriculture; PW: Paid Work; M – Millions; Mhr: Million hours

Table 2.4 - Irrigated and rain-fed crops

		LU (has)	Gross €/ha	Gross €/hr	Use of acequias	Drip irrigation
Irrigated	**Almonds**	1100	6708	20.0	56%	32%
	Olive	847	4275	9.9	84%	15%
	Horticulture	661	7333	14.2	98%	1%
	Citrus	634	4773	9.1	62%	50%
Rain-fed	**Almonds**	1092	1699			
	Olive	333	1549			
	Extensive	326	176			
	Vineyards	312	2504			

The ecosystems-society interface (*e/i/s*)

This section explores the main interactions on the ecosystems-society interface: water exchange, impacts on aquatic ecosystems and water management.

Water exchange (e→s)

Table 2.3 - Annual water uses in the Upper Andarax (Hm3)

		Withdrawn	Soil
s	**Gross water use**	14.2	21.6
	Loses	3.7	3.4
s-1 **Net uses**	**Urban supply**	0.7	-
	Food production	8.8	8.2
	Forestry	-	1.9
	Esparto gathering	-	2.1
	Cattle	0.5	5.8

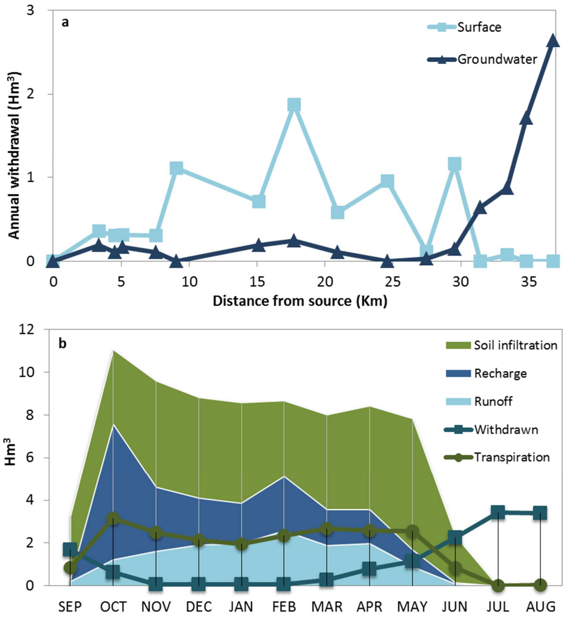

Figure 2.8 a- Spatial distribution of water withdrawals; b- Seasonal distribution of water funds and flows

Table 2.5 shows the water flows sustaining provisioning services in the watershed. Soil moisture use is 50% higher than water withdrawals and sustains a greater variety of extensive land uses and associated services. Since there are no major industries or big urban areas in the region, most of the water is used for food production. Cattle grazing also account for important soil water yields. Regarding the location of water withdrawals (Figure 2.8 a), most of the basin relies on surface water, with a special increment in the middle area for irrigation. Groundwater pumping concentrates in the last 7 kilometers over the Low Andarax aquifer, mostly devoted to citrus production. This change is caused by the drying out of the river at this point, whose main inflow comes from urban wastewater discharges. When considering the seasonal variability (Figure 2.8 b), autumn and spring months are the rainiest acquiring most of the water inflow. In October soil and aquifers refill after the summer and vegetation reaches its maximum transpiration. As observed, transpiration is almost coupled to infiltration while most withdrawals take place during summer to compensate soil moisture drought.

Environmental impacts (s→e)

The river ecological status assessment in the RBMP considers the Alto Andarax in good status and the remaining section (Medio Andarax) in bad status. The main drivers underneath this poor status are the dry out of the river during the summer months because of diversion for agriculture, untreated wastewater discharge and sediment deposition from erosion. Groundwater bodies are assessed as quantitatively and qualitatively poor status.

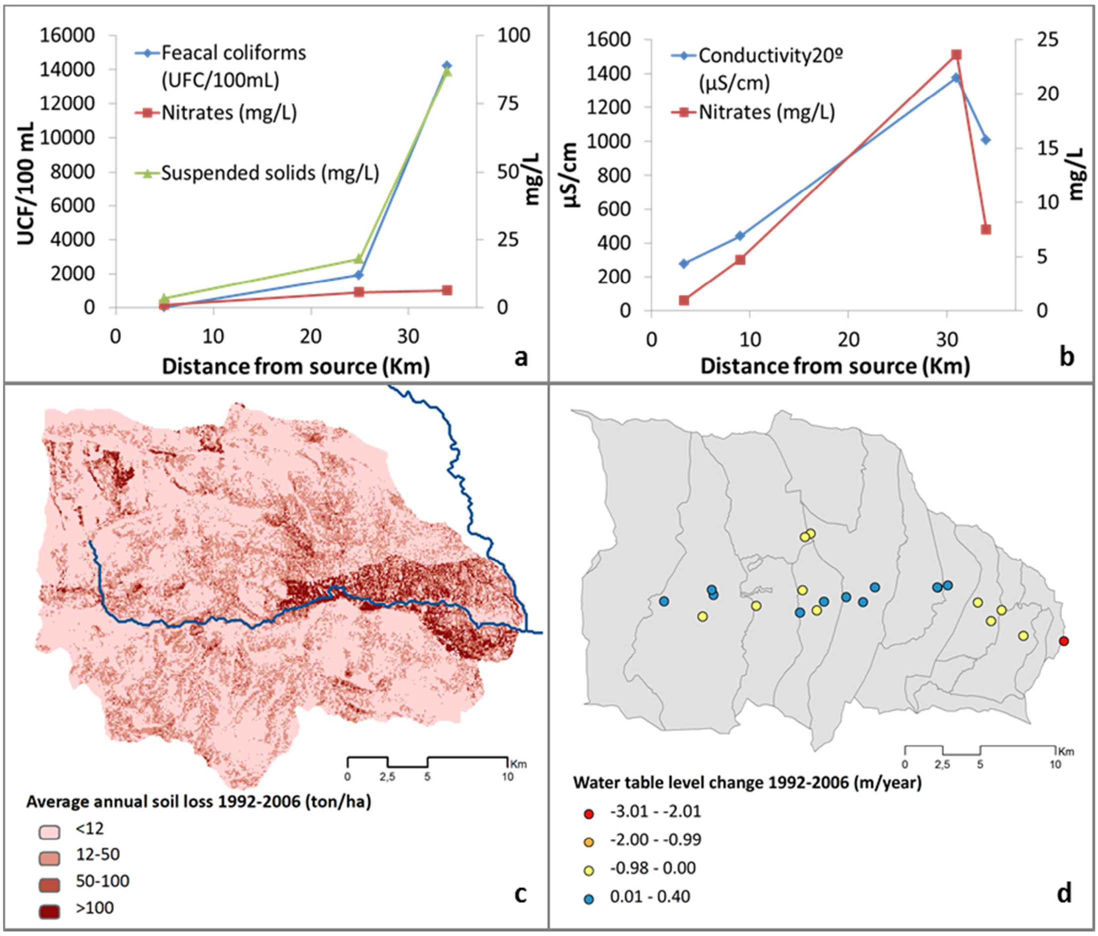

Figure 2.9 a- Average annual water table change; b- average annual soil loss rates; c- average groundwater water quality; d- average surface quality

Figure 2.9 gathers relevant impacts over water bodies, showing a clear spatial gradient up to downstream. In Alto Andarax (within the Natural Park), human activities are very constrained, and surface and groundwater quality meets drinkable standards (Figure 2.9 a). In the middle section (from km 10-25) main irrigation areas are located and nitrate concentration in water increase, yet it falls within the category of good state according to WFD reference of 6.5-9.5 mg/L. Along the last 10 km of the Andarax river, fecal coliform concentrations are very high (up to 14,000 CFU/100 mL proper of untreated wastewater) and suspended solids reach 87 mg/L (EU Directive 2006/44/EC guidance level for surface waters of ≤25 mg/L), making water unusable for urban and agricultural purposes. According to the Andalusian scale for regional erosion, the average annual rate of soil loss between 1992 and 2006 is deemed low (12 tn/ha yr) in 65% of the basin, moderate in 27% (12-50 tn/ha yr) and high in 9% (>50 tn/ha yr). Highest erosion rates are found from the middle section of the basin towards the outlet, clearly overlapping marls and conglomerates areas were most agricultural and abandoned agricultural areas are located (Figure 2.9 c). These results aling with other studies in the region in areas with abandoned terraces (Romero and Belmonte 2008, 2009). However, they are extremely severe as compared to the threshold of 1 ton/ha recommended in other parts of Europe (Verheijen et al. 2009, Glavan et al. 2013b).

Regarding groundwater (Figure 2.9 b), the Low Andarax aquifer clearly shows a higher conductivity and nitrate concentrations compared to the upper North Gador Sierra. This salinity has been related to the marl composition of the aquifer bed (Sanchez-Martos et al. 2005) and does not surpass the reference threshold for this type of water body in the WFD (3610 µS/cm). The nitrate peak indicates an influence of agricultural diffusive pollution yet lower than the 50 mg/L threshold for groundwater bad state. Finally, water table level variations between 1992 and 2006 spatially overlap with groundwater withdrawals, decreasing in pumping areas (primarily concentrated on the Low Andarax aquifer) and increasing where the river is the major water source (Figure 2.9 d).

Water management (e/i/s)

In line with the ecological status assessment, both groundwater bodies have been declared as subjected to LSO within the RBMP, due to the complex overdraft situation created by downstream intensive greenhouse farmers. This means that they need a longer recovery horizon (beyond 2015), conditioned to the generation of additional resources through desalination in the coast. There are no aquifer restoration measures foreseen for the Upper Andarax area but new dwells are forbidden along the whole water body until regularization of existing water rights is accomplished. On the other hand, the river horizon for good status achievement was set for 2015. This poses a new external constraint to the societal metabolism: impacts have to be remediated and the e-flows regime implemented on the river.

The current annual water extraction index for the average water funds in the modeled period shows that surface water bodies are more exploited than groundwater (Table 2.6). When considering a drought subperiod (1976-1988) a 17% reduction of renewable resources is obtained, as well as a considerable increase of the annual WEI if the same water use is to be maintained. In addition, water demand is 37% higher than current water use since additional resources are claimed for irrigation. This demand can be met with available resources by substituting surface withdrawal for additional pumping, but this multiplies water costs by a factor of six.

Table 2.6 - Water demand vs availability (Hm3)

	Withdrawals	**Ecosystem Requirements**	**Water extraction index (%)**		**Water availability average year**	**Water demand**
			Average year	Dry year		
River	5.8	2	0.46	0.67	3.8	17.6 (in total)
Aquifers	7.2	10	0.34	0.50	13.2	

The proposed e-flows regime barely reaches 10% of runoff from October to March, but in summer months would require almost no diversion. Middle basin users who rely on surface water are those mainly affected by the e-flows implementation. The situation is stagnant because of the banning over new dwells and the lack of negotiation process with local irrigation communities on the proposed e-flows. This area counts with highest rates of agricultural employment and its rent per capita is low (4,500-8,000 € p.c.) as compared to upper and downstream municipalities (8,000-10,000 € p.c.) Therefore, turning to groundwater or to rain-fed crops has an economic impact that needs to be further evaluated. The foreseen strategy in the RBMP to solve this conundrum is to not implement the e-flows regime until new available water resources are generated through irrigation efficiency improvement by replacing the galleries and *acequias* by drip systems.

2.4. Discussion

Several authors have described the alteration of the Upper Andarax hydrology through centuries of human transformations of the territory (Latorre et al 2001, Sánchez-Picón et al. 2011). This research supports these works by quantifying the increment of water availability for human productive uses, especially of soil water. Despite the importance of local wisdom on managing surface, flood and subsurface flows, it is in soil water management where the traditional water culture of this Mediterranean region implements its more effective adaptive practices (terracing, adapted crops). Current land abandonment is perceived as a major driver of landscape change threatening this traditional system. Abandoned agricultural areas are transforming into xerophytic shrub covers, and walls of terraces are slowly eroding into the river. The combined effect of climate change/drought periods, collapse of traditional land uses and vegetation evolution over water funds appears to be a key question for long term water supply maintenance.

A marked spatial gradient on water supply and demand was found, but also on impacts to water bodies. The Alto Andarax water body contains healthy ecosystems protected by the Park. The finding of high recharge rates occurring in the low permeability soils of the upper catchment supports the reported high interaction of subsurface-surface flow in this area by Sanchez-Martos et al. (2005). As also shown by Contreras et al. (2008), the North Gador Sierra area is a key provider of water recharge to the Southern part of the aquifer and plays a key role supporting intensive agriculture there. This Northern part of Sierra de Gador is affected by the assessment of ‘bad ecological status’ of the whole water body that our findings contravene (water tables are not lowering and water quality does not rearch bad state thresholds). The almost exclusive dependence on surface water by most upstream users limits its availability to downstream ones, driving groundwater stocks depletion on quantity and quality at the basin outlet.

The societal metabolic pattern shows an intermediate situation between a low and a high external input agricultural system (Giampietro and Lomas 2014) common in high-mountain areas with multifunctional landscapes. Agricultural trade openness to external markets is important but does not sustain the whole economy, whereas the services and public sectors are bigger in terms of employment. This study findings uncover the crucial role of women work unpaid in households, indicating a more reproductive (functions fulfillment) than productive (market oriented) metabolic pattern. Population ageing poses a major challenge for continued viability of this pattern in the future. The adaptation strategy seems twofold: first, an increasing interaction with the urban downstream areas in terms of external revenues and agricultural land maintenance for leisure or supplementary rent; second, a sector of the population claims extending irrigation to increase agricultural productivity in line with the intensive agricultural model dominating in the surrounding geographical context. This is constrained by environmental objectives established at the water governance level that require a reduction of water withdrawals.

The expectations generated over the possibility of obtaining additional resources through efficiency improvements might be counteracted by the effects of the progressive abandonment of the *acequias.* There is a feedback signal between technological and social transformations. The functioning of local irrigation communities has been inherently linked to the use and maintenance of the galleries and *acequias* system (Segura 2010). Their substitution by pipes and drip irrigation will permit automation thus reducing the time required for agricultural land maintenance, and at the same time, phasing out local institutional rules. In addition, there are ecological trade-offs. The declaration of the National Park forced farmers to abandon *acequias* within park boundaries. A key consequence of this abandonment has been a decline in riparian vegetation living on their banks. This forced the Park administration to maintain the *acequias* at a considerable public cost. The question of whether it will be possible to increase productive water uses at the same time as complying with environmental objectives of the Water Framework Directive will depend on i) the willingness of local irrigation communities to adapt their institutional rules; and ii) whether the additional available water is allocated to meet e-flows or will generate a rebound effect i.e. a further intensification of the saved water use. There is an increasing literature (Dumont et al. 2013, Sampedro and Del Moral 2014) showing that efficiency, so far, has not been effective in controlling water demand in the absence of proper monitoring and withdrawal control protocols.

Conclusions

This chapter focuses on the representation of river basins as SES through the operationalization of the SESWM framework for the Upper Andarax basin. I emphasize the importance of including governance as a key driver shaping human-environmental interactions. The production and evolution of hydro-social landscapes are filled by a variegated set of social agents with changing and more or less acute confrontations. The diverse and changing features of water funds and flows, together with its contentious uses, demands and imaginaries around it, are always mediated through political institutions and policy networks and regimes, including those through which access or ownership over nature and the tools of its distribution are organized.

In the particular case of the Upper Andarax, the current water metabolism is the result of centuries of social-ecological evolution. This basin is an illustrative case of European high mountain rural areas striving to face rural exodus with an economy in transition from the agricultural to the service sector. I have shown how its societal organization is integrated within the ecosystem water metabolism and how it has influenced the eco-hydrological functioning of the basin. The observed impacts to aquatic ecosystems have some direct causes like an excess of withdrawals in dry summer periods and wastewater discharge, but also other long-term socio-economic processes like agriculture abandonment or lack of control over extractions. From the discussed results, a few key water management challenges can be pinpointed in the basin: i) the inclusion of soil moisture formally in water planning as the water fund providing the greatest variety of services to the social system; ii) the separation of the misleading linkage of the North and South Gador Sierra aquifers in one sole water body with one ecological status assessment; iii) the appropriate monitoring to ensure that efficiency improvement is a conducive strategy to meet e-flows and additional societal demands; iv) finally, a socio-ecological approach to water governance would require policy measures that tackle the sustainability of societal funds beyond the continuous augmentation of water flows, addressing the long-term drivers of metabolic change.

On a methodological level, this chapter bridges the analysis of societal metabolism and ecosystem metabolism in the MuSIASEM accounting scheme on a spatially explicit basis. The analysis of ecosystem metabolism of water in river basins is proposed through the eco-hydrological processes that control water resource renewability (supply side sustainability), the impacts caused to ecosystem health (sink side sustainability) and the boundary concepts of water availability and ecosystem water requirements. The proposed method requires the integration of several models and multiple types of data with the associated accumulated uncertainty. The eco-hydrological analysis was limited to averaged climatic series and a snapshot of societal metabolism that is sufficient for descriptive purposes and linkage to water planning. Further steps of scenario building would require a more thorough analysis of historical trends as well as a higher temporal resolution for hydrological calibration. In addition, the focus was on provision water-related ecosystem services but the inclusion of cultural and regulating ecosystem services is suggestive for future works. Further research in the area can focus more specifically on i) relevant linkages between land abandonment, erosion and their impact on aquatic ecosystems, ii) efficiency improvement and its impacts on aquifer dependent systems and iii) conflicts between local and regional scales of water governance.

Chapter 3. Water and agricultural policies in Europe, an unresolved governance gap

Land use and water use are inherently related. The presence of water is one of the main biophysical constraints for land use management, especially regarding water availability for agriculture. In arid and semi-arid regions, the history of agricultural change is connected to the evolution of water grabbing and the improvement of the social strategies of adaptation to drought (Rulli et al. 2013). Water ecosystems have largely co-evolved with social systems by means of the most ingenious hydraulic infrastructures and landscape modelling to attend the intensification of agriculture. Among the most important changes in the water use pattern brought by this process is an increasing dependency on blue water for irrigation in addition to green water that, as shown in Chapter 2, maintains a richer variety of ecosystem services. While green water is still mainly silent in formal water policies, blue water has been traditionally perceived as a renewable and unlimited resource whose appropriation is constrained only by technological and infrastructural factors (Madrid 2006, Medeazza 2008).

European rurality is an exemplary outcome of the permanent debate and tension among the multi-level forces of rural change. At global scale, the World Trade Organization and the Doha Round push towards the elimination of subsidies coupled to agricultural production distorting free international trade (Potter and Lobley 2004). At national levels, big farmers' organizations maintain a neo-mercantilist discourse of state protectionism (Potter and Tilzey 2007). In between, the European Union acts as institutional mediator, dealing also with the awareness on food safety and the environmental damaging effects of agriculture.

The Common Agricultural Policy (CAGP[14]) is the legislative framework that regulates agricultural production in Europe. From the original goals established in the Treaty of Rome in 1957 - increasing productivity to secure food supply, ensure farmers' standards of living and stabilize markets- it has gone through several reforms. The recent ones in 2003, the 2008 "Health check", and the latest in 2014, maintain a patent twofold stake: promotion of an agro-industrial market based model through the Direct Payments[15] while, at the same time, green and rural development subsidies are incorporated into the CAGP scope. Relevant consequences are gathered by McMichael (2011): On one hand, Direct Payments allow prices to be lowered below production costs in order to seek for competitiveness. On the other hand, greening and rural development funds enable the institutionalization of multi-functionality (Losch 2004) as an environmental and social form of governance that remains within market calculations, maintaining the reductionism to the monetary dimension.

Similar to the WFD, the marriage between neoliberal economics and environmentalist narratives in the CAGP unveils inclusiveness as a strategy to cope with multiple contested stakes. However, whereas the CAGP maintains the heavier weight on the market function of agriculture, with the cross-compliance and agri-environmental payments as mechanisms for 'externalities correction', the WFD shifts it towards ecological quality, with economic

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[14] The standard acronym is CAP but here I use CAGP to differentiate it from the CAP – Central Arizona Project in the Tucson Basin case study (Part III).

[15] Direct Payments are lump sums to farmers decoupled from production based on the amount of CAP direct subsidies received by each farmer in the reference period 2000–2002.

instruments as facilitators for its achievement. The outcome of these nuances is an insufficient integration of the objectives of these policies, their management devices and their criteria for decision-making (Bartolini et al. 2007).

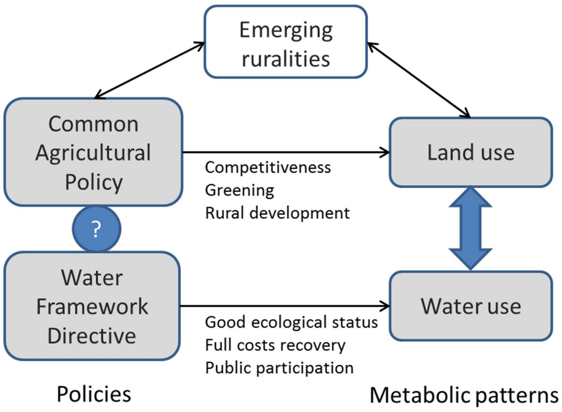

Figure 3.1 - Relation between policies, narratives and metabolic patterns

CAGP has obviously shaped landscapes in Europe in its more than fifty years of existence. Its subsidies determine the difference in profitability between irrigated and rain-fed crops and thus the water-use pattern (Bartolini et al. 2007). After the 2003 reform, the decoupling of payments from production seems to have fostered the shift towards less water intensive crops in some areas (Hernandez-Mora and De Stefano 2012 pp. 38). However, these changes are extremely variable depending on the crop pattern during the reference period and the price of water (Kampas et al. 2012). The debate on the integration of water and agricultural policies has been on-going for the last fifteen years. Good water management practices were not specifically considered within the greening cross-compliance, neither as agri-environmental measures within the second pillar (Table 3.1). The Health Check in 2008 mentioned water management as an important issue to bring into the CAGP scope together with climate change. Besides, the 2012 European Commission report “A Blueprint to Safeguard Europe's Water Resources”[16] recognized the integration of policies as mayor challenge for an effective implementation of the WFD, proposing specific measures to be included in CAGP reform of 2014. As a result of those recommendations, the legal proposals for the new CAGP after 2013[17] explicitly echoed this integration and incorporated some of those measures. However, the long and intense negotiation process finally dropped out any reference to the WFD in the cross-compliance of Pillar I, leaving some open doors within the agri-environmental payments of the Rural Development programs in Pillar II which were later negotiated between the European Commission and each of the Member States within the new Partnership Agreements 2014-2020[18].

The semi-federal architecture of the European Union anticipates a complicated down-scaling of these policies to national, regional and local levels and the divergence between objectives is likely to magnify. This chapter aims at addressing the interplay between water and agricultural policies in the Andarax river basin before the last CAGP reform. The following questions are

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[16] Communication from the Commission (COM(2012)673)
[17] http://ec.europa.eu/agriculture/cap-post-2013/legal-proposals/index_en.htm
[18] http://www.dgfc.sgpg.meh.es/sitios/dgfc/en-GB/ipr/fcp1420/p/pa/Paginas/inicio.aspx

addressed: How does the mismatch of water and agricultural policies shape metabolic patterns in the Andarax? How is this mismatch resolved in water planning in order to cope with WFD objectives? Which are the tradeoffs associated to the chosen management strategies? In order to answer these questions, I first present the regional institutional framework in Andalusia along with a revision of the main regional regulatory documents. Building on that, water metabolism is analyzed for 2005, baseline of the WFD, with particular focus on agricultural metabolic patterns. Finally, a comparative assessment of planning scenarios is presented in order to discuss trade-offs associated to decision-making.

3.1 Regional institutional framework

The Andalusian region, southern Spanish Autonomous Community, has a long tradition of agricultural production that, in the last decades, has progressively shifted from rain-fed to irrigated crops. Sampedro and Del Moral (2014) review the last thirty years of regional water policies that they summarize with the term ‘a territorial un-government regime’. This refers to the uncontrolled expansion of irrigated agricultural land and urban development with neither comprehensive planning nor precaution about ensuing environmental impacts. The results are observed in the boosting water demand, soaring erosion processes, diffusive nitrates pollution and increased vulnerability to floods. Water management in Andalusia, aligned with the traditional national hydraulic paradigm (Sauri and del Moral 2001, Bukowski 2007), has been mainly focused on incrementing surface water regulation to attend a ‘structural deficit’ that is perpetuated by snowballing demands. The expansion of irrigation has also been possible through a spectacular raise in groundwater pumping, especially after 2002 (CAP 2011 pp. 9). New wells are frequently in illegal or semi-legal situation due to the slow pace in which the water administration handless concessions. As a result, common situations of aquifers overdraft face a great uncertainty due to the very limited information and knowledge about their real balance.

With this background, a new water law was endorsed in 2010 echoing the new principles of the WFD. The Andalusian Water Law defines water as a common good and goes beyond the national transposition in some points like the explicit recognition of environmental flows as requisite for good status recovery, as well as of the need for policy integration. A great emphasis is posed on the reform of water administration according to the WFD requirements and on the creation of new institutions for permanent participation of stakeholders (especially water users) on a representative basis. Economic instruments are acknowledged and two new taxes are introduced for the recovery of water services costs: one for funding new wastewater treatment plants (*canon de mejora*) and another one for funding the water administration (*canon de servicios generales*). However, no methodology for the accounting of these costs is specified. In addition, while the law explicitly mentions the importance of integration with other sectoral policies like agriculture, it does not propose any institutional reform to advance in this sense.

Table 3.1 - Levels of water and agricultural policies

	Water	Agriculture	Rural Development
European Policy	Water Framework Directive (WFD)	Common Agricultural Policy (CAP) Pillar I	Common Agricultural Policy (CAP) Pillar II
Competences in Spain	Autonomous Communities for intra-community RB, central government for inter-community RB	Autonomous Communities	Autonomous Communities, based on National Rural Development Plan
Regional referents	Andalusian Water Law 9/2010[19] Andalusian Mediterranean River Basins Management Plan 2009-2015[20]	Andalusian Irrigation Agenda 2011-2015 (AIA)[21]	Andalusian Program for Rural Development 2007-2013 (APRD)[22]
Relevant narratives	Water as a common good Environmental flows Permanent participation through representation Policy integration New taxes for costs recovery	Efficiency augmentation to reduce demand New water sources Technical support and training to farmers	Modernization of agricultural exploitations (Axes 1) Compensatory allowance and agri-environmental payments (Axes 2) Diversification of economic activities (Axes 3,4)

The Andalusian Irrigation Agenda 2011-2015 (AIA) addresses current challenges of the sector in the region, including the implementation of the WFD, echoing the 2008 CAGP Health Check. It foresees an increment of irrigated land in about 70,000 hectares until reaching what is catalogued as irrigable land. For the first time, a ceiling to the expansion of irrigable land is set acknowledging the difficulties to keep on incrementing water availability. The core strategy of the AIA is to control the expansion of water demand through the *modernization* of 396.456 hectares of irrigated land in Andalusia (86.000 hectares in the Mediterranean RBD). This modernization attempts to bridge water and agricultural challenges in order to achieve sustainability in the use of water, raise employment and increase land productivity (CAP 2009 pp. 29-43). This win-win-win scenario would be reached through i) the improvement of supply

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[19] Parlamento de Andalucía. 2010. Ley de Aguas de Andalucía. http://www.parlamentodeandalucia.es/webdinamica/portal-web parlamento/pdf.do?tipodoc=coleccion&id=49573&cley=9

[20] Agencia Andaluza del Agua. 2011. Plan Hidrológico de la Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas. http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=3bba6ff4a9743310VgnVCM2000000624e50aRCRD&vgnextchannel=75b3e6f6301f4310VgnVCM2000000624e50aRCRD

[21] Consejería de Agricultura y Pesca. 2011. Agenda del Regadío Andaluz. Horizonte 2015. http://www.juntadeandalucia.es/agriculturaypesca/portal/areas-tematicas/infraestructuras-agrarias/regadios-e-infraestructuras-agrarias/agenda-del-regadio.html

[22] Consejería de Economía y Hacienda. 2007. Programa de Desarrollo Rural de Andalucía 2007-2013. http://www.juntadeandalucia.es/agriculturaypesca/portal/la-consejeria/planes-y-politicas/programa-de-desarrollo-rural-de-andalucia-2007-2013.html

chains and irrigation efficiency and automation devices, ii) new surface water regulation and, especially, new water sources (reclamation and desalination), and iii) technical support and training to farmers. In addition, the crop pattern would change 'from low economically productive and high water-demanding to highly productive and/or low water-demanding crops' (CAP 2009 pp. 30-31)[23]. But the main assumption underlying this plan is that the improvements in efficiency through drip irrigation technology will generate water savings of about 352.5 Mm^3 in Andalusia (68.1 Mm^3 in the Mediterranean RBD). This assumption is based on the aggregation of expected savings in all irrigation communities without explicit consideration about who, for which purpose and how is going to manage that water.

Funding for the installation of the new technologies comes in 65-85% from the Andalusian Program for Rural Development (APRD, total public budget of 3.764.161.518 €). Its clear priority is the Axes 1 (54% of the budget), devoted to the improvement of competitiveness in agricultural exploitations. Within Axes 1, modernization of infrastructures accounts for 44% the budget (a total of 903.252.084 €, pp. 78). Axes 2 and 3, respectively devoted to agri-environmental measures and diversification of economic activities, receive the 35% and 11% of the budget. These two axes are essential components for funding WFD implementation measures, like compensations for changing to less water intensive crops or pastures, hydro-forestry and wetlands restoration, or proper wastewater reclamation (Moral 2006, Moyano and Garrido 2009).

3.2 Methods

Grammar

Table 2 shows the water grammar for this chapter. Levels *e+2/e+3* include a basic description of the system hydrology (water funds) as it is provided in the RBMP. Surface water availability is calculated in the same way than in Chapter 2. Groundwater availability is the one considered in the plan for all aquifers except for Sierra de Gador that was recalculated in the previous chapter for the area inside the Andarax basin. Levels *s-x* include the services related to surface and groundwater that are covered in the RBMP. Water flows types are set per water source and maintained through societal levels. Data sources are the RBMP 2009-2015 (Annex II, IV and V[24]), and the Inventory of Irrigation in Andalusia 2008[25] that provides agriculture water use data at irrigation community level. The societal funds included in the analysis are land use (has) and human activity (hours). Intensity ratios for the different societal metabolism levels are calculated by combining water flows and societal funds. Results are presented in a dendogram using a Sanskey diagram.

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[23] Consejería de Agricultura y Pesca. 2009. Report on the impact of the Water Framework Directive and the Common Agricultural Policy on irrigated agriculture in Andalusia.

[24] http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=6d3173f2c746a310VgnVCM2000000624e50aRCRD&vgnextchannel=0bb66af68bb96310VgnVCM1000001325e50aRCRD

[25] Inventario de regadíos 2008: http://www.juntadeandalucia.es/agriculturaypesca/sigregadios/servlet/regadios.

Table 3.2 - Water grammar for the Andarax basin

Role	Level	Semantic categories	Formal categories
FUND	e+3	Precipitation	Average precipitation (Mm^3/year) considered in the RBMP for the series 1980/81 – 2005/06
	e+2	Evapotranspiration	Average real evapotranspiration modeled in the RBMP for the series 1980/81 – 2005/06
		Recharge	Average recharge modeled in the RBMP for the series 1980/81 – 2005/06, recalculated for those parts of aquifers actually exploited within the basin according to Chapter 2 results
		Runoff	Average natural run-off in the estuary modeled in the RBMP for the series 1980/81 – 2005/06
		Ecosystem water requirements	Minimum e-flows (Mm^3/year) to achieve potential habitat
	e+1	Available water	Appropriated surface minus non implemented environmental flows + Available groundwater according to RBMP aquifers' balance + Desalinated + Reclaimed
STOCK		Overdraft	Groundwater stocks depletion
FLOW	s	Gross water use	Total appropriated water (Mm^3/year)= sum of water use by households and paid work
	s-1	Gross water use	Urban households (Almeria) and rural households Paid work
		Efficiency	Net water use/Gross water use
	s-2	Net water use	Agriculture Industry and mining Services and tourism
		Deficit in agriculture	Additional water demand for agricultural production

The characterization of agricultural metabolic patterns in this chapter focus on irrigated crops. In addition to water and land use patterns, other indicators are included (Table 3.3): Water Monetary productivity, Water Price, Jobs Creation and Energy Intensity associated to water supply. Energy use is particularly relevant because it is one of the main constraints to intensification of water use (Hardy and Garrido 2010). Finally, the qualitative indicator of ecological status of the water bodies from where the water is withdrawn is also included.

The indicators are calculated for the six agrarian units considered in the RBMP (Figure I1.1b) and then aggregated in four according to the WHS boundaries established in Figure I1.2b. Each agrarian unit is composed by a variable number of irrigation communities, and some extend beyond the river basin. Only those irrigation communities inside the WHS boundaries were used for the calculation of indicators through weighed means based on acreage. Energy Intensity ratios have been estimated per water source through the following procedure: for those irrigation communities devoted to self-subsistence farming nearby small rural municipalities, the same ratio per source than the urban supply was assigned. There is a previous study in all municipalities of Almeria province developed by Martínez (2011) that provides ratios per type of water source in Kwh/m^3. For the rest of irrigation communities, the ratios have been estimated with the following equations:

$$EI = P * t/V$$

$$P = n * Q * h * d * g$$

Where EI is the energy intensity ratio (kwh/m3); t the pumping time (s); V the total water pumped (m3); P is the pump power capacity (Wat); n is the pump efficiency, assumed 0.9; Q is the pumping flow (l/s); h is the pumping depth (m); d water density (kg/l) and g gravity (kg*m/s2). Average pumping flow is provided per irrigation community in the Inventory of Irrigation in Andalusia. Wells depth was averaged per irrigation community using spatial analysis of the latest wells layer (2009) from the public environmental management company TRAGSA. In absence of data from wastewater treatment plants, the average for water reuse in Spain calculated in Hardy and Garrido (2010). In order to account for the energetic costs of transportation, a variable ratio of 0.1-0.5 kwh/m^3 was added to each water source depending on the transport distance. Energy intensity for the whole WHS is calculated through the weighted mean of all irrigation communities based on the water use pattern.

Radar diagrams are employed for integrated representation of metabolic patterns, divided in four quadrants referring to four criteria. The down quadrants show the water and land use patterns in terms of the percentage of water used per source, and of land used by the three main crops in each agricultural area. The grey line represents the 50%. The upper quadrants present a qualitative comparison of the indicators in terms of biophysical and economic performance. Values of the indicators have been normalized to the range of values for the four WHS, being the grey line their average.

Table 3.3 - Indicators for agriculture water metabolism

Criteria	Formal categories	Semantic categories	Unit and calculation
Biophysical performance	Water Use Intensity (WUI)	Gross or net water use per hour of paid work activity	m^3/h GAW_i/HA_i
	Water Use Density (WUD)	Gross or net appropriated water per hectare of land used	m^3/ha GAW_i/CL_i
	Energy Intensity (EI)	Energy used per m^3 of gross water used	KWh/m^3 TET_i/GAW_i
Economic performance	Water Monetary Productivity (WMP)	Gross added value generated per m^3 of gross water used	€/m^3 GAV_i /GAW_i
	Water Price (WP)	Price of the water supply	cts.€/m^3 WP_i/GAW_i
	Jobs Creation (JC)	Hours of human activity required per hectare of land used	hr/ha HA_i/CL_i
Water use pattern	Water Used (WU)	Percentage of gross water used per type of source	% $GAWSource_j/GAW_i$
Ecological status	Ecological Status (ES)	Status of water bodies from where water is withdrawn	Qualitative variable Good/ Medium/ Bad
Land use pattern	Land Used (LU)	Percentage of land used for main crops	% $CLCrop_j/TCL_i$

Definition of scenarios

Forstarter (2004) defines scenarios as "complex narratives and possible routes leading to a vision of the future, mixing both prospective and normative elements". The RBMP proposes scenarios of water use in 2015 and 2027, providing the foreseen extension of irrigated land and irrigation efficiency, as well as the resulting water balance from different sources. I assess this scenarios by analyzing the trade-offs in terms of resulting water and energy use. For illustrative purposes, I compare them with alternative scenarios using a different narrative; this is making different decisions about water sources and allocation. In addition to land use (has), efficiency (%) and gross water use (Mm^3/year), ecosystem water requirements (Mm^3/year), net water use per hectare (m^3/ha*year) and total energy use (GWh) are considered. The two types of scenarios are defined in Table 3.4 using a simplified adapted version of the interpretative for water-related scenarios of March et al. (2012).

Table 3.4 - Definition of scenarios

Dimension	**RBMP scenarios**	**Alternative scenarios**
Objective	Strategic planning within WFD	Planning evaluation
Process design	Structured, developed for the RBMP	None-structured, based on authors' perspective
Temporal extent	Short term (2015 and 2027)	
Temporal nature	Snapshot	
Spatial extent	Agrarian units	
Water uses	Agriculture; ecosystems	
Land use consideration	Increment in irrigated land (has) and irrigation efficiency (%) foreseen in the RBMP	
Other variables integration	Environmental flows (Mm3) foreseen in the RBMP scenarios Total energy use (GWh) resulting from the new water-use patterns	Same variables with different decisions made: - Environmental flows are implemented in 2015 - Efficiency improvement used to decrease appropriation of water - Extension of irrigated land based on same crop pattern (constant net water use per hectare) - Water-use pattern established according to the most energy-efficient available sources
Degree of normativeness	High, the RBMP is a norm to be implemented	Medium, feasible future is drawn
Nature of the data	Quantitative	
Use of quantitative models	Not described in the RBMP. Linear extrapolation of indicators based on the assumption of same energy intensity of the water sources	Linear extrapolation of indicators based on the assumptions of same crop pattern and of same energy intensity of the water sources

Method of data collection	Not described in the RBMP	Individual desk research
Social learning	No	Results for Bajo Andarax were presented to stakeholders in a workshop of the ALTAGUAX project

3.3 Results and discussion

Water metabolism in the Andarax river basin in 2005

Figure 3.3 shows the multi-level representation of water funds, stocks and flows in 2005, considered as the baseline in the RBMP 2009-2015. Hydro-climatic variables at *e+3/e+2* show the importance of evapotranspiration by terrestrial ecosystems, amplified by irrigation as shown in Chapter 2. Headwaters of Nacimiento and Alto Andarax are nearly permanent flows thanks to snowmelt, mostly diverted but also infiltrated before their point of connection. In south and eastern areas of Bajo Andarax and Tabernas watercourses are dry most of the year, except during rain events, and the predominant flow is subsurface. Some available water is generated through springs and traditional infrastructures for the collection of floods and subsurface flows *(turbias* and *galerías*).

Overall human appropriation of water in the basin was below availability in 2005, although this relation greatly varies from west to east and depending on the source of water. As explained in Chapter 2, surface water withdrawals exceed availability when e-flows are considered in the equation. Regarding groundwater, whereas most of the basin recharge is generated in Alto Andarax, greater withdrawals take place in Tabernas and Bajo Andarax. The aquifer in Tabernas was formally declared overexploited in the RBMP - 2.9 Mm^3 withdrawals, 2.3 Mm^3 available, thus it is 0.6 Mm^3 of stock-flow or overdraft. On the other hand, total withdrawals in the Bajo Andarax aquifer were deemed below availability in 2005 (12.9 Mm^3 withdrawals, 13.9 Mm^3 available) but marine intrusion caused qualitative deterioration with a feedback impact over agricultural productivity. Nevertheless, the information available about this process is insufficient to separate stock and funds using a qualitative criterion. Desalination was introduced to attend the expected exponential growth of urban water demand from Almeria city. For this reason, the plant was designed for double production capacity that is currently operating (about 5 Mm^3/year), in line with most desalination plants in Spain. The rest of the water supply in the city (up to 16 Mm^3) come from groundwater pumping in the neighbor basin, enabling the generation of the third most important water source in the basin: 8.7 Mm^3/year of reclaimed water for surrounding agriculture.

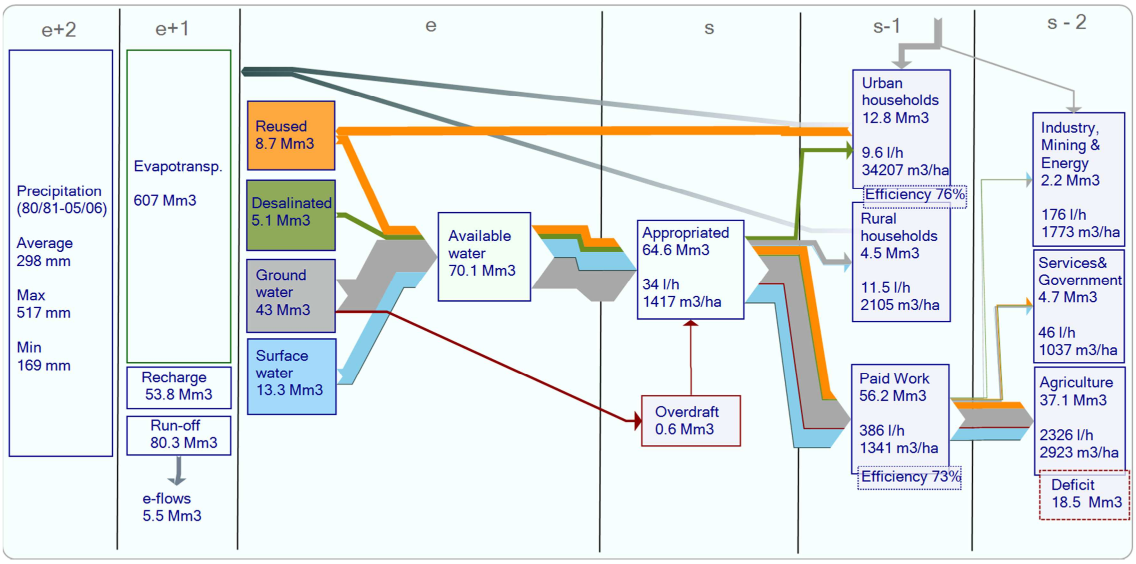

Figure 3.2 - Water metabolism in the Andarax basin (2005)

Water supply to households represented 23% of the overall gross consumption, mainly driven by Almeria city. Rural households were slightly more intense than urban ones in terms of water used per hour of human activity, whereas the effect of the types of urbanization system (dense vs extensive) was observed in the important difference in terms of water use per hectare. Only 8% of the total human activity was devoted to paid work, and therefore the ratio of water use per hour was substantially higher than those of households. Regarding the different economic activities, the industry, mining and energy sectors had a small cut in the total water used, with relatively intensive water use per hour of activity (176 l/hour= 366 m^3/year per job, low job generation per unit of water used) concentrated in small areas. The services and government sectors showed a remarkably low water use per hour (4.6 l/hour= 9.5 m^3/year per job, high jobs generation per unit of water used), while they showed an intense water use density per hectare (mainly due to golf courses irrigation). Finally, agriculture was by far the most water intense sector both in absolute and relative terms (2,326 l/hour=4,838 m^3/year per job, very low jobs generation per unit of water used). The RBMP considered a deficit for agriculture that encompasses two categories: i) the deficit due to crops receiving less irrigation than they demand for optimum productivity; and ii) the deficit due to the foreseen increase in irrigated land. Thereby, additional demands of water were already foreseen in 2005 as expectations to be met.

Agricultural metabolic patterns

The multi-scale multi-resource representation in Figure 3.2 provides a holistic view of the Andarax basin as a whole WHS. Given the importance of the agricultural activity as driver for water use, Figure 3.3 zooms into a lower indicator level, splitting agriculture in the different sub-systems and presenting metabolic patterns in radar diagrams.

Both Alto Andarax and Nacimiento show a balanced use of natural water sources and medium gross water use per hectare, typical for traditional farming systems with flood irrigation of low water-intensive crops (olive groves and almonds, and small vegetable gardens mostly devoted to self-consumption). Their energy requirements are rather low, associated to groundwater pumping from average depths between 50-80 m, and they pay the lowest prices for water[26]. Their monetary productivity is also low, but it still maintains medium requirements of human activity. These are characteristic patterns of rural areas with low productive agriculture, which is either maintained by an aged population in a nearly self-sufficiency situation, or it is a complementary activity to other economic sources (De Arazabal et al. 2008).

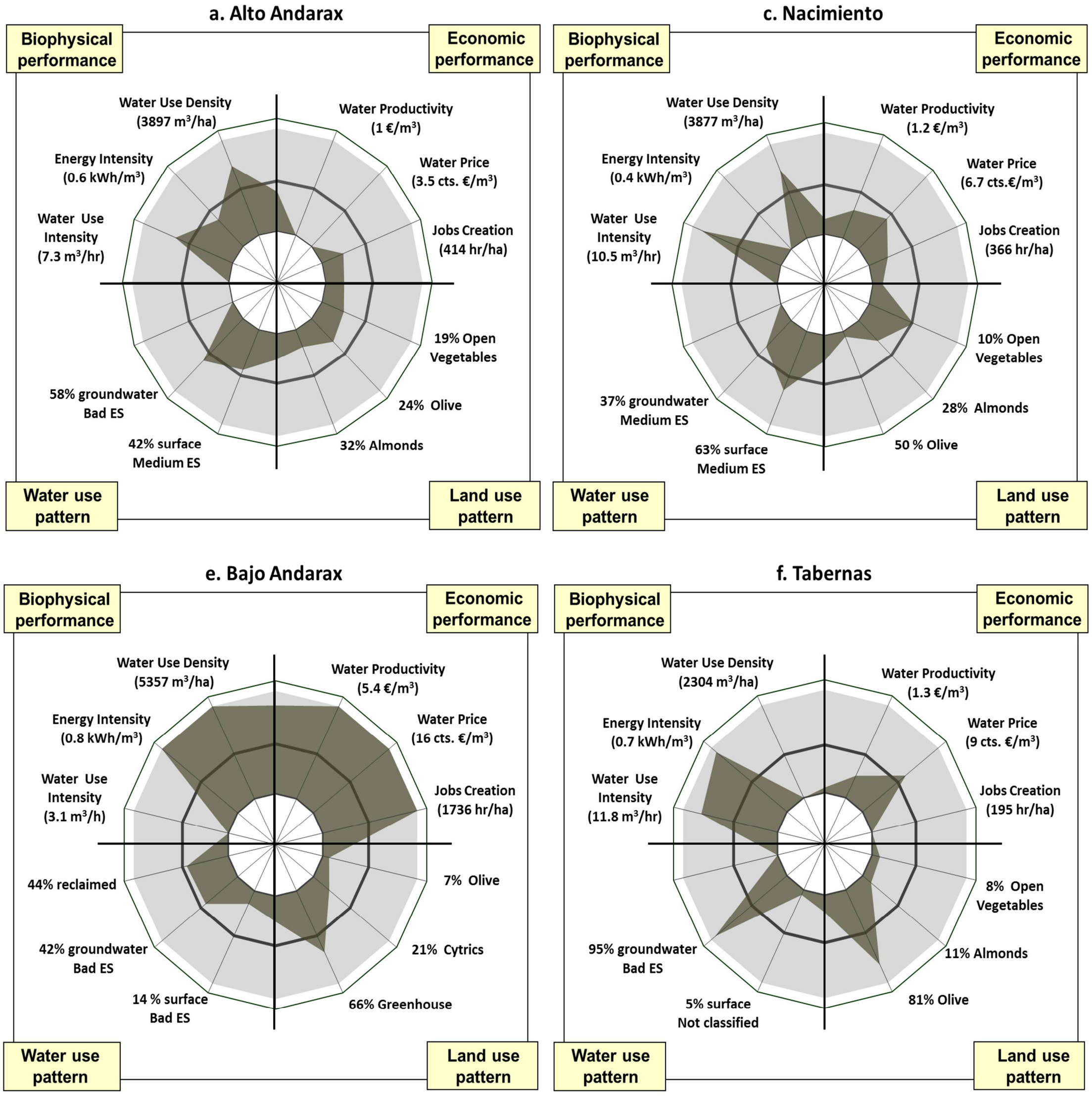

Figure 3.3 - Agricultural metabolic patterns

A very different pattern is found in Bajo Andarax, which drastic predominance of greenhouses was feasible thanks to the introduction of wastewater reclamation as an additional resource. Yet, groundwater use is also important and flood water collection and natural springs maintain 14% of overall demand, mostly employed in citric production at the head of the area. Despite the highly efficient irrigation in greenhouses, this is the most intensive system in terms of water use per hectare, since savings from technical efficiency are balanced by several cropping

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[26] Water-users communities using surface and groundwater do not pay for it to the water administration. The price reflects the operation costs they estimate for its extraction, transport and management. Reclaimed water is brought from the wastewater reclamation plant at no costs but those of transport and later tertiary treatment.

periods (2-3 for tomato). In addition, it is the most intense also in jobs generation associated to harvesting and five times more profitable than the other three. As expected, energy requirements are also the greatest in the basin due to the costs of reclamation and transport, but also of drills that reach 400 meters at some points. The Bajo Andarax is an exemplary type of techno-agroecosystem, as highly sophisticated technology is continuously incorporated to increase productivity and retrieve environmental damage to the aquifer. The greenhouse sector is the most subsidized of the region by the European common organization of fruits and vegetables markets (60% of the total agricultural payments received in Almeria[27]), but does not receive Direct Payments from the CAGP.

Finally, Tabernas is the eastern most arid area, the only desert in Andalusia. Monoculture of olive groves relies almost exclusively on groundwater, part of which is over-drafted. A small share of surface water is collected through ancient *qanats* in a seasonal watercourse. Energy intensity associated to pumping is quite high, and so it is the price of water. As a result, water productivity is low despite counting with agricultural subsidies from CAGP[28]. This type of olives production under irrigation has been labeled as intensive, with gross water use between 2000-3000 m^3/ha and low temporary human activity requirements restricted to one harvesting season (Martínez 2015).

Given the described metabolic patterns, a few challenges can be posed regarding the WFD implementation in each WHS. Alto Andarax challenges were described in detailed in chapter 2. Nacimiento faces a very similar situation: the implementation of e-flows reducing surface water withdrawals in an area with low productive agriculture, aged population and rural exodus. In addition, Nacimiento has a conflict between upper and lower parts of the basin since a dam was built to collect snowmelt at the head, enabling the expansion of crops there at the time reducing surface availability downwards. Moreover, water tables were decreasing, requiring an improved collective management of the aquifer in this area. Tabernas shall reduce overdraft without any surface water available. The problem of groundwater quality in Bajo Andarax aquifer is really complex in the absence of reliable monitoring and proper modeling of the aquifer. All agricultural systems claimed additional demands in 2005 (deficits).

The viability of the reorganization of these systems in order to achieve good ecological status at the time maintaining economic performance is a multi-level institutional problem: maintaining farmers' income, either raising product prices or subventions, is a matter of global/European levels decisions. Some identified local adaptation schemes from large water-users communities include the reduction of production costs (energy), the increment in irrigation efficiency or the generation of additional resources at a cost that farmers are able to pay for (Lopez-Gunn et al. 2013a). The Andalusia Mediterranean RBD is the key institution mediating in the organization of these strategies at the river basin scale. Next section explores which of them are foreseen in the RBMP and assess the foreseen scenarios of water use in agriculture.

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[27] Payments distribution per sector and region is published by the Spanish Ministry of Agriculture here http://www.fega.es/PwfGcp/es/el_fega/index.jsp.

[28] Inventory and characterization of irrigation in Andalusia 2002. Consejería Agricultura y Pesca.

Water management strategies and scenarios

Since Nacimiento and Alto Andarax show similar metabolic patterns, for the sake of simplicity I focus the assessment in three of the four subsystems: Nacimiento, Bajo Andarax and Tabernas. The core strategies in the RBMP in these systems to pursue EO at the time meeting additional water demands are:

- Increment irrigation efficiency, core strategy in Nacimiento along with a slight augmentation of regulation in the upstream dam (RBMP 09-15, Appendix 3 to the Memory, pp. 272).
- Introduce desalination as water source for agriculture. To this purpose, a desalination plant located in Carboneras town, 50 km away from Almeria, would be enlarged to double its production capacity. The water would be pumped into a closer reservoir and from there connected to Bajo Andarax and to Tabernas through another connection (RBMP 09-15, Appendix 3 to the Memory, pp. 246 and 335-336).
- Augment the reclamation capacity of Almeria wastewater treatment plant, enlarging the plant and collecting wastewater from other urban areas in Bajo Andarax that at that moment were discharging untreated water to the river (RBMP 09-15, Appendix 3 to the Memory, pp. 335-336).

Table 3.5 shows the scenarios posed in the RBMP for 2015 and 2027 in the three agricultural areas. As explained in section 3.2.2, the RBMP scenarios are opposed to alternative ones (Alt.) that use the same variables but with different allocation choices (Table 3.4). Increasing variables in the two scenarios are marked in bold.

Table 3.5 - Water management scenarios for 2015 and 2027

Agrarian Unit	Indicator	2005 RBMP	2015 RBMP	2015 Alt.	2027 RBMP	2027 Alt.
Nacimiento	**Irrigated Land (has)**	3673	3673	3673	3673	3673
	Efficiency (%)	56	**78**	**78**	**84**	**84**
	Ecos. Req. (Mm^3/year)	0	0	**2.5**	0	**3.6**
	Net WUD (m^3/ha)	2172	**3155**	2172	**3172**	2172
	Gross WU (Mm^3/year)	14.6	**15**	9.7	14	9.3
	% Surface	61	62	65	66	57
	% Ground	37	38	35	34	43
	Total Energy Use (GWh)	5.6	**5.9**	3.7	5.2	3.9
Tabernas	**Irrigated Land (has)**	2057	2057	2057	**2471**	**2471**
	Efficiency (%)	88	**90**	**90**	90	90
	Ecos. Req.	0	**0.32**	**0.6**	**0.3**	-
	Net WUD (m^3/ha)	2028	**2905**	2028	**2775**	2028
	Gross WU (Mm^3/year)	4.7	**6.6**	4.6	**8**	**5.5**
	% Surface	5	4	5	3	5
	% Ground	95	61	84	38	70
	% Desalinated	0	36	2	59	19
	% Reclaimed	0	0	8	0	7
	Total Energy Use (GWh)	5.8	**17.7**	5.7	**27.3**	**10.6**

Bajo Andarax	**Irrigated Land (has)**	3398	**4351**	**4351**	**4478**	**4478**
	Efficiency (%)	83	**90**	**90**	90	90
	Ecos. Req. (Mm^3/year)	0	0	0	0	0
	Net WUD (m^3/ha)	4492	**6111**	4492	**6503**	4492
	Gross WU (Mm^3/year)	18	**26.6**	**21.7**	**32.4**	**22.3**
	% Surface	14	10	11	8	10
	% Ground	43	23	34	21	33
	% Desalinated	0	18	0	23	0
	% Reclaimed	44	50	55	48	57
	Total Energy Use (GWh)	19.2	**47.8**	**22.9**	**65.7**	**23.6**

Irrigated land is expected to expand in Bajo Andarax by 2015 and also by 2027, whereas in Tabernas is only expected by 2027. In both of these areas efficiency is already high but it is projected to be upgraded to 90%. In Nacimiento, no increment in irrigated land is foreseen but the installation of drip irrigation is predicted to substantially increment overall efficiency in 22%. As explained in the regional institutional framework, these investments are 65-85% covered by the APRD (an average of 3.265 €/ha). All RBMP scenarios project an increment in the net water use per hectare despite increments in efficiency. This indicates that the crop pattern will become more water-intense. Therefore water *savings* are directly devoted to cover claimed *deficits* and not to reduce appropriated water in any of the cases. This accounting anticipates a potential case of what is known as Jevon's Paradox, in which efficiency improvements do not only generate rebound effect (increment in overall demand) but also qualitative change of the system identity through new crops and technologies (Giampietro and Mayumi 2008, Giampietro and Sorman 2009 pp. 18-19).

In addition, e-flows in Nacimiento are left unattended in the RBMP scenarios. As shown in the alternative scenario for this area, these volumes (2.5 Mm^3 in 2015 and 3.6 Mm^3 in 2027) could actually be covered through the saving resulting from efficiency improvements. In the case of Tabernas (EO set for 2021), the RBMP solves aquifer overexploitation along the two deadlines. However, the 2% increment in efficiency could do it already in 2015 if the same water allocation per hectare is maintained.

The analysis of energy flows associated to the planned scenarios is missing in the RBMP. The AIA includes an assessment of the energetic costs related to the installation of drip irrigation, but there is no further appraisal of the economic costs of operation and maintenance according to the expected evolution in energy prices. This is a relevant concern because the highest energy consumption in agriculture in arid regions is related to water extraction or production (Corominas 2010). Bringing desalinated water from Carboneras plant to Bajo Andarax and Tabernas entails a tradeoff of 5.25 kWh/m^3. As observed in Table 3.5, this choice would multiply by 3.5 and 4.6 the energy requirements in these respective areas by 2027. In the alternative scenarios, available wastewater for further reclamation is considered in priority to desalination. As observed, resulting energy use would at least stabilize.

According to Rico-Amorós (2010) affordable water costs for agriculture in south-eastern Spain do not surpass 0.2-0.3 €/m^3 with current already intense farming systems. However, desalinated water prices around 0.5 €/m^3. If the costs recovery principle of the WFD is implemented, the costs of installation, operation and maintenance of the new desalination plant should be covered by farmers and not by public taxes. In addition, the liberalization of the energy sector added another source of uncertainty over high-energy demanding water production, with prices soaring in 75% in the last years (Lopez-Gunn 2013b, March et al. 2014). However, the RBMP does not include any economic analysis of this new water source, despite its construction costs budgeted in 69.7 M€, and 78% of agricultural water costs are deemed already recovered (RBMP 09-15 Annex IX pp. 50). March et al. 2014 discuss how desalination, as the new technological strategy to maintain the hydraulic paradigm in Spain, was launched basing on the assumptions of lower costs than inter-basin transfers, and of continued urban and touristic expansion associated to the pre-2008 development model. According to the authors, these premises have been unraveled in the last years but still desalination is publicly defended as a secure alternative to mitigate the impacts of recurrent droughts. During 2014, a new drought episode in the region prompted the debate around subsidizing energy costs for desalination in agriculture in the media, with farmers' organization lobbying the central government of Spain to reduce their electricity toll[29].

Conclusions

European water and agricultural policies are the outcome of multiple co-existing strains that are reflected in inclusive discourses liaising environmental and economic interests. However, the dominant narrative in agricultural policies is the market function of agriculture, whereas the WFD sets ecological quality as main political priority. Both policies have enormous influence over the evolution of waterscapes shaping metabolic patterns. This study aimed at addressing the interplay between these policies in the process of down-scaling on to the Andarax basin. The regional government of Andalusia echoed the challenge of policies integration in more ambitious terms than the European Commission and the Spanish government. This integration is deployed through an agenda for agricultural modernization in the sake of a win-win between EO and productivity boost without major institutional reform. The RBD is in charge of coordinating management strategies in order to pursue the achievement of good status of deteriorated water bodies. The bulk of rural development funds from the CAGP are devoted to the fulfillment of this agenda.

Water metabolism in the Andarax is mainly driven by agricultural production, although the influence of the urban system of Almeria is increasingly relevant in both water demand and supply. The different metabolic patterns in agriculture have been characterized, from upper rural areas with low productive agriculture adapted to their ecosystem water metabolism, to intensive techno-boosted greenhouse vegetables production and stock groundwater-fueled olive monoculture. These two latter were in a situation of social scarcity as water demand exceeded availability from natural funds in 2005, either in quantity or in quality. The achievement of EO posed serious challenges of adaptation to all of these systems. The prior strategies of the RBMP to face these challenges are: i) substitution of flood for drip irrigation in rural areas, fostered by the AIA and APRD; ii) desalination as a new alternative source for

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[29] http://almeria360.com/agricultura/11022015_feral-alerta_124751.html ; http://elperiodicodelaenergia.com/el-gobierno-da-un-respiro-al-regadio-al-eximirle-del-85-del-impuesto-a-la-electricidad/; http://www.editorialagricola.com/v_portal/informacion/informacionver.asp?cod=798&te=46&idage=1813&vap=0

intensive agricultural systems, fostered by the national A.G.U.A program; and iii) increment wastewater reclamation, fostered by the Andalusian Mediterranean RBD through the new tax set in the Andalusian water law to fund full wastewater treatment in the region. These strategies suppose an evolution from previously dominant river regulations and transfers, but yet reflect the strong cultural belief in technology and large infrastructures to keep on incrementing availability at the time avoiding core governance challenges such as ex-ante comprehensive land planning, controlling the expansion of water-intense agricultural patterns, or effective monitoring of aquifers and reduction of overdraft.

The analysis of water use scenarios unveils a potential case of Jevon's paradox associated to agricultural modernization, with a rebound effect in water demand and/or transformation of production systems, and relevant tradeoffs in energy demand. The so-called 'deficit' or breach for agriculture is prioritized to environmental flows, a compulsory measure of the Andalusian water law, and to aquifers overexploitation retrieval. Therefore, the integration of the agrarian strategy in water planning blurs the purportedly ecological conservation ambitions of the WFD and allocates public funds to an intensification of water use. Another aspect to be considered is the total missing of the implications of the nexus between water, energy and food: the proposed solution seeks to solve the problem of water availability by shifting it to the problem of energy availability. The lack of appraisal of the economic burden of desalination as an alternative for agriculture, in a context of raising energy prices and decreasing food products ones, anticipates a not despicable risk of unsuccessful implementation. In addition, these scenarios were formulated under the expectations of continuous urban development-driven economic growth before the real-state bubble blown in 2008, assumptions that now need to be revised.

Chapter 4. Assessing the first cycle of the Water Framework Directive

The enforcement of the WFD in Spain was initiated in 2003. The first RBMPs had to be released in 2009, implemented during the next 6 years and assessed in 2015 against progress towards achieving EO. Building on the outcomes of that evaluation, the second plan 2015-21 would be elaborated.

In the Andalusian Mediterranean RBD, the draft documents of the RBMP 2009-15 were released for public consultation in 2010. During the next year, the formal participatory process was arranged at the scale of the whole Almeria province (containing four and a half basins). In addition to the comments to the draft plan, one workshop with farmers, another with representatives of all types of users, and a third one focused on e-flows negotiation, were arranged by the RBD (Ballester and Espluga 2012). Adding to this endeavors, the ALTAGUAX project enabled stakeholders from the Andarax basin to develop their own participatory diagnosis of water problems, and to propose courses of action (Van Cauwenbergh et al. 2008, Van Cauwenbergh and Ballester 2015). The final RBMP 2009-15 was endorsed in 2012 with hardly three years for executing the program of measures until the draft of the new RBMP 2015-21 was opened to consultation at the beginning of 2015. Van Cauwenbergh and Ballester (2015) evaluate the relation between the institutional and the project processes, pinpointing the factors that hampered a more effective implementation of the ALTAGUAX outcomes. The most important one was the lack of real political commitment and of mandate of the water administration over budget allocations. They identified the following research challenges for the Andarax: 1) To improve the discussion on policy outcomes (reflected in the PoM of the RBMP); 2) to create mechanisms aimed at monitoring and evaluating the extent of the implementation of stakeholders’ preferences, and the effectiveness of the implementation of those decisions.

The objective of this chapter is to assess the implementation of the first cycle of the WFD in the Andarax basin. This is undertaken on a twofold basis: First, through the evolution of narratives during the planning process, and second, through the evolution of societal metabolism of water. To this purpose, I build on the concept of semiotic process of water management described in section 1.2.3, attending to the following questions: Which are the main narratives about water management in the Andarax basin? Which are the main conflicts and coalitions amongst these narratives? Which are the dominant narratives in the RBMP 2009-15? How did societal metabolism evolve during the first cycle of the WFD? Did the actions implemented respond to the perceived problems by stakeholders? Did they contribute to achieve policy goals? How did the RBMP perform in terms of discursive closure, social accommodation and problem closure?

4.1 Methods

This chapter focusses on discourse analysis as main analytical tool to identify non-equivalent narratives. This is combined with a diachronic analysis of societal funds and water use during the management period in order to appraise its outcomes.

Discourse analysis

The definition of narratives or story-lines typifying perspectives over water management was undertaken through discourse analysis. Four documents produced during ALTAGUAX workshops, another four from the RBMP 2009-15 and the draft memory for the RBMP 2015-20 were reviewed (Table 4.1). In order to code the text, a flexible top-down procedure was followed, departing from three defined common contrasting perspectives about water management, at the time paying attention to other knowledge claims that did not fit into the pre-defined categories. These three prior narratives were supply-side, demand-side and deep ecology. Throughout the analysis, another two narratives emerged as relevant: rural livelihood and knowledge and governance. Codes were extracted and classified in a matrix according to two criteria: i) type of narratives and ii) problems vs course of action. Codes consisted on whole knowledge claims, sentences with specific identifiable meaning. The two first ALTAGUAX documents enabled narratives identification on a general basis, while the documents from workshop 4 enabled a geographical distribution of these narratives.

Table 4.1 - Documents reviewed for discourse analysis

Document	**Date**	**Contents**	**Analytical objective**
Altaguax Workshop 1 minutes	2009	Water management problem diagnosis	Categorize and characterize narratives
Altaguax Workshop 2 minutes	2009	Proposal of management measures to solve problems	
Altaguax Workshop 4 preliminary document	2010	Problem diagnose and program of measures for each water body in the RBMP draft	Identify contrasting narratives Spatialize dominant narratives
Altaguax Workshop 4 minutes	2010	Allegations to the RBMP draft per water body	
RBMP 2009-2015 draft program of measures	2010	List of measures classified per type and other attributes	Pinpoint dominant narratives
RBMP 2009-2015 final program of measures[30]	2012	Same than draft but with required budget in total and until 2015	
Appendix XI.3. Report on allegations to the draft RBMP 2009-2015	2012	Answer to allegations from ALTAGUAX workshop 4. New PoM	
RBMP 2015-21 draft program of measures[31]	2015	List of measures classified per type and budget until 2021	

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[30] Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas. Documentos plan hidrológico de la demarcación hidrográfica de las cuencas mediterráneas andaluzas, periodo 2009-2015 http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=6d3173f2c746a310VgnVCM2000000624e50aRCRD&vgnextchannel=0bb66af68bb96310VgnVCM1000001325e50aRCRD

[31] Planificación Hidrológica 2016-2021 http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=4b90cfa0d2f0f310VgnVCM1000001325e50aRCRD&vgnextchannel=fd0f122f4df3f310VgnVCM2000000624e50aRCRD

Because the objective of the workshops was to create consensus information about water management issues, workshops facilitators merged the different perceptions into inclusive statements. Stakeholders denounced ambiguity in the measures proposed in the RBMP. Ambiguous concepts are often used as a discursive strategy in order to gather consensus over grand objectives, like recover aquifer health, even though different actors may disagree on the motivation for reaching a certain goal or on the means to be used. Therefore, apparent coalitions among actors have to be carefully analyzed in order to identify possible ambiguities and distinguish them from actual consensus. In this context, the coding of the text in terms of definition of the problem and course of action proves very useful in shedding light over recurrent concepts and issues.

In order to pinpoint dominant narratives, the draft documents of the RBMP 2009-15, the answers from the Andalusian Water Agency to the comments presented by ALTAGUAX stakeholders, and the PoM in both the draft and final RBMP 2009-15, as well as the draft RBMP 2015-21 draft, were reviewed. The analysis of the answers to the allegations of stakeholders, and the measures proposed in the final RBMP, sheds light about the extent to which comments from stakeholders influenced final decision-making and which narratives pervaded those decisions.

Interviews, field observations and focus group

Nine semi-structured interviews to key stakeholders were undertaken during April-May 2014 (Table 4.2). The purpose of the interviews was to update water problems defined in 2009. Interviewees were asked to give their opinion on whether each of the problems identified in 2009 had been solved, were being solved, remained the same or were worsening.

Table 4.2 - Stakeholders interviewed

Stakeholder type	Area	Gender
Mayor from a rural municipality	Nacimiento	Woman
Representative from traditional irrigation community	Alto Andarax	Man
Organic farmer	Alto Andarax	Woman
Environmentalist, independent consultant on cultural heritage	Bajo and Alto Andarax	Man
Representative from agriculture administration	Alto Andarax, Nacimiento and Tabernas	Woman
Representative from intensive greenhouse farming irrigation community	Bajo Andarax	Man
Representative from Almeria province administration responsible for urban water supply	ALL	Men
Representative from the Andalusian Mediterranean Hydrological District in Almeria province	ALL	Men

In addition, a focus group was organized in May 2014 with the aim of developing an exercise of multi-criteria evaluation of water management alternatives and of discussing the implementation of the RBMP. Main results from this workshop are gathered in Appendix 3.

Grammar

The water metabolism was updated with the information from the new RBMP 2016-21 draft, using the same grammar than the previous Chapter 3, and visualizing it in a similar dendrogram for comparative purposes. In addition, a multi-level accounting of human activity was calculated for 2001 and 2011 (dates of the Spanish National Census, latest in 2011 http://www.ine.es/censos2011_datos/cen11_datos_inicio.htm), as well as of land uses for 2005 and 2011 (from the Spanish Land Occupation Information System http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=ca74d2aa40504210VgnVCM1000001325e50aRCRD&vgnextchannel=7b3ba7215670f210VgnVCM1000001325e50aRCRD&vgnextfmt=rediam).

4.2 Results

Water management narratives

Five different narratives on water management have been identified through knowledge claims, gathered in Table 4.3, regarding the perception of problems and the proposed course of action. In what follows, a general characterization of the narratives is presented including its broad perception over water scarcity (as a concept that invokes 'the essence' of water problems in semi-arid areas), underlying assumptions, the scale of observation and type of story-tellers in the Andarax.

Supply-side management: this narrative deems water scarcity as a technical problem and its underlying assumption is that increasing demands can, and shall, be attended through new technologies and infrastructures. It focusses on the level of the whole society (*s*) by considering the total water demand (not specific uses) to be met by introducing more resources in the system as a whole, disregarding internal metabolism (society is treated as a black box). Story-tellers of this narrative are the traditional epistemic community of the hydraulic paradigm that includes engineers from water utilities and desalination plants, large agricultural lobbies and mayors with expectations of incrementing urban development.

Demand-side management: this second narrative acknowledges water scarcity as a problem of excessive water demand (we use more than what is available), and proposed solutions orbit around measures to control its expansion, mainly through economic instruments and increasing efficiency. The narrative is based on a low scale of analysis, associated with individual water users (*s-x*). The focus is on the consumers of water and proposed courses of action build on the assumption that water savings at individual level leads to a reduction of the overall water demand. Story-tellers of this narrative are typically advocates of IWRM that shift from supply to demand-oriented perspectives, that in the case of the Andarax groups together different coalitions depending on specific problems and measures as will be discuss in next section.

Table 4.3 - Water management narratives in the Andarax river basin

Claims	**Supply-side**	**Demand-side**	**Deep ecology**	**Rural livelihood**	**Knowledge & Governance**
Problems	Insufficient resources to satisfy increasing demands; aquifers overdraft and untreated wastewater discharges				
	- Decrease on available run-off due to excessive upstream withdrawals - Insufficient quantity and quality of water - Insufficient production of water through reclamation and desalination - Desalination plants are under-exploited - Insufficient regulation of surface water bodies	- Lack of awareness to save water - Obsolescence of supply infrastructures - Irrigation needs to be modernized with more efficient systems - Real water costs are not paid - Nobody wants to raise water tariffs because it entails a political cost	- Inter-basin transfers increment vulnerability to drought - Natural springs and dependent ecosystem are drying out due to water table decrease - Biodiversity loss (birds) - Reforestation projects do not take into account contextual ecological constraints - Pollution problem due to pesticides and fertilizers use in intensive agriculture - Untreated wastewater discharges is causing severe habitat deterioration - Desalination plants increment aquifer salinization and brine impacts marine ecosystems	- Desertification and erosion due to abandonment of agriculture and terraces - Water scarcity is new in upper basin, water used to be abundant thanks to traditional infrastructures like mines and *acequias* - Vulnerability to drought - Agriculture is not economically viable anymore, facing continuous productivity decrease - Ageing population, youth people are moving to urban areas - Fountains are drying - Untreated wastewater discharges are a source of conflicts - Insufficient support to traditional agriculture - Not clearing the riverbed increases vulnerability to floods	- Lack of monitoring and control over illegal extractions - Insufficient knowledge about aquifers functioning - Insufficient data and information used in decision-making - Lack of transparency, lack of access to the required data for public participation - Lack of coordination between different administrations (water, land use, agriculture), information is not shared neither reused - Inefficient performance of institutions - Insufficient justification of goals and deadlines. Cost-effectiveness of measures decided without scientific evidence. Ambiguity - Lack of drought emergency plans - Political use of water - We don't need more infrastructures but better governance

Claims	Supply-side	Demand-side	Deep ecology	Rural livelihood	Knowledge & Governance
Courses of action	- New desalination and wastewater reclamation plants. Increment capacity of current plants - Build new dams and increment current ones - Inter-basin transfers from groundwater dwells - Refill aquifers with wastewater to increase availability - Rainwater harvesting - Diversify water sources and adjust water quality to end use	- Irrigation efficiency improvement - Full water services costs recovery, raising water tariffs, including environmental costs of aquifers overdraft - Improving efficiency of the urban supply by renewing infrastructure and better maintenance - Awareness-raising campaigns	- Adapt water demand to natural water availability. Limit growth, especially of agriculture - Implementation of environmental flows on regulated rivers and extractions for irrigation - Cross-compliance for agricultural subsidies Promote conversion to organic farming - Protect high-value ecosystems - Hydro-morphological restoration. Improve river connectivity - Soft not hard infrastructures are needed - Reforestation of abandoned agricultural lands - Improve wastewater treatment plant - Do not increase desalination until impacts over aquifers are known and controlled	- Economic support to rain-fed crops like olives, almonds and vineyards and organic farming - Maintain traditional irrigation infrastructures and farming practices as a form to prevent erosion - Develop new types of economic activities within the Natural Park - Natural recharge through traditional irrigation practices for aquifers recovery - River bed cleaning according to protocol of good practices	- Monitor withdrawals and ecosystem quality. Improve data for management - Improve knowledge and management of aquifers - Control over illegal extractions, and wastewater discharges - Better administrative efficiency on water rights procedures - Application of law on Transparency and Access to Environmental Information - New governance structures at both supra-municipal level (for urban supply and wastewater treatment) and river basin level (for different uses coordination), combining public and private entities - Integrated water and land planning - Grand Social Agreement to not politicize water

Deep ecology: this narrative follows an ecosystem integrity perspective. It considers that water scarcity is human-induced and that the conservation of ecosystems should be a constraint over human activities. It focusses on the contexts (*e+x*), on ecosystem metabolism and the water cycle, and management measures are twofold: on one hand, they emphasize the need for adapting/reducing the size of human activities to the limits imposed by ecosystem conservation and renewability of resources; on the other hand, they claim for ecosystem restoration to a purportedly pristine ecological status. This is based on the premises that the thresholds of ecosystem integrity can actually be predicted by models within an accepted interval of confidence and that human systems can adapt to 'live with less'. Story-tellers are environmental groups and other advocates of the WFD environmental objectives fulfillment, amongst them some of the managers and technicians from the Andalusian water administration.

Rural livelihood: this is the narrative of rural communities, their mayors, traditional farmers and irrigation communities, and rural development groups. It has a social-ecological metabolism perspective; the level of analysis is the whole community but with a focus on its practices linked to the perception of water as part of their identity (*s/e*). They do not perceive water scarcity as a problem since they consider themselves adapted to their context. Courses of action claim for integrative policies that support the maintenance of the community in their territory, battling against rural exodus and conserving heritage and traditional practices.

Knowledge and governance: this narrative deems water scarcity as a governance problem. Existing institutions are incapable of dealing with water problems because they are considered culturally obsolete according to the challenges of the WFD. It focuses on the information side of the hydro-social system and courses of action are related to the improvement of information and knowledge, and the need for institutional reforms seeking better adaptive management structures. Story-tellers include most stakeholders that are not decision-makers from the RBD, but special emphasis is posed by the advocates for the New Water Culture narrative.

The narratives have been typified in the belief that they may be applicable to similar contexts along the Mediterranean. The first three narratives (supply-side, demand-side and deep ecology) are common contested perceptions about water issues in semi-arid areas with intensive agriculture in competence with urban growth for limited and degraded water resources (Del Moral et al. 2007). The rural livelihood narrative is important in river basins containing both rural and urban systems and/or where traditional agriculture is being replaced by intensive practices, like the Upper Andarax. The knowledge and governance narrative is particularly relevant in Spain where multiple citizen networks follow the implementation of the WFD and participate in planning processes. These groups develop an active quality control over the information used for decision-making (Hernandez-Mora et al. 2015). Next section discusses the specificities of how these narratives appear in the Andarax case, how do they hybridize or oppose and which are the narratives permeating the final decisions, thus becoming dominant.

Narrating 2009

There is an overall agreement amongst Andarax stakeholders in that water resources are insufficient to attend current and future water demands, and in that aquifers are overexploited either in quantity or in quality. However, perceptions around the causes of the problem (detailed diagnosis) and the effective course of action in order to face these challenges greatly diverge. It is generally assumed that water demand would increase with economic growth, and therefore this is an *a-priori* belief from which many claims are stated. Another consensual problem was the pollution along the river caused by untreated wastewater discharges due to the lack of maintenance of collectors and treatment plants. It appears in claims associated to all types of narratives: as a social drama, as a cause for habitat degradation, as the need for more reclaimed water, as the capacity to refill aquifers and as an institutional failure.

The governance and knowledge claims dominate the problem structuring indicating that the information used for the draft RBMP was not considered valid by stakeholders. Proposals go in the direction of refining information and access to it on one side, and of renovating institutional functioning on the other. The course of action that received the most support in a voting exercise was “improving knowledge and management of aquifers overexploitation”. This is a consensus that links improved scientific knowledge to better decision-making and management. On the other hand, enhancing the agility of the water administration in processing water rights, a better coordination with other public administrations, and an effective monitoring of withdrawals are important repetitive claims. An interesting statement is the claim for “avoiding *politization* of water management”, referring to the intentional use of water problems rhetoric by political leaders for gaining clout. It came from water managers and received a lot of votes in the ranking exercise. This uncovers a perception that water problems can be technically handled through better knowledge but should not be used with political or electoral purposes.

The rural livelihood narrative states itself in opposition to the supply-side narrative of large agricultural lobbies from intensive systems in downstream areas (“we have nothing to do with them”). It is the second largest list of problem claims of the five narratives, including structural problems like population ageing, agricultural abandonment and erosion, discussed in Chapter 2. Certain tension is observed with the installation of new water-intensive farms in their communities in what regards the future of rain-fed crops and of traditional irrigation systems. In addition, traditional farmers have a conflict with the deep ecology claim for legally binding ecosystem requirements of water because they perceive themselves as part of the ecosystem to be maintained. The efficiency argument from the demand-side narrative is very persuasive in solving this conflict, because it is defended as a win-win for both the river and farmers. A second conflict comes in hand of the perception of mayors about an increased vulnerability to floods due to the lack of clearance of the river-bed, what the RBD representatives accused to the ecological quality mandates of the WFD. Courses of action within the rural livelihood narrative include protection and support of traditional farming systems and rain-fed crops, and diversification of economic activities taking advantage of the Sierra Nevada Park.

Deep ecology problems gather together pressures and impacts detected by decision makers in the draft RBMP, plus some others denounced by stakeholders like unsuccessful reforestations or the impact of brine from desalination plants. The course of action with more proposals is found within this narrative, what is expected insofar as they pursue the ecological quality policy goals. These measures are twofold: on one side there are actions aimed at ecosystem restoration as a strategy to achieve the good status, defended by the technical staff from the

RBD; on the other hand, there are measures claiming for an eco-integration of human activities within natural resources renewability boundaries, defended by environmental groups.

Supply-side problems refer to the insufficiency of resources to attend demands, and the need for new technologies (wastewater reclamation, desalination) and infrastructures (dams and regulation) to increment water availability. These claims were not so abundant but their advocates are in very influential positions. An innovative claim from this narrative is a better management of water quality allocation so that each end use receives water with appropriate quality but not better than required. Soft proposals for incrementing water supply are rainwater harvesting and aquifer recharge with wastewater.

Finally, demand-side problems gather together advocates for efficiency improvement, which are closer to the supply-side, and those for awareness raising and pricing as instruments for controlling demand, which are closer to the deep ecology perception. This coalition reveals that the ambiguity of demand-side arguments, core in IWRM, enables different interpretations, working as a consensual-boundary strategy. The problem is that the aggregation of changes produced at individual level may lead to different emerging outcomes depending on how those changes are managed. The Jevons paradox tells us that savings at the individual level result in spare capacity at the higher level, which in turn increases overall consumption in the long run. In the case of irrigation technical efficiency, the rebound effect has been explained by the lack of a parallel reduction of water rights, as well as by the lack of effective monitoring and planning of withdrawals and uses (Sampedro and del Moral 2014, Berbel et al. 2015). If volumes granted by water rights are not diminished and actual consumptions are not controlled, users reuse the ‘saved’ water in something else for their own profit. A strong opposition to this coalition comes from the knowledge and governance narrative. As stated by an actor “there are no legal guarantees of what to do with water savings, they are just used in the water administration creative accounting to close balances”. In other words, there is no strategy at upper levels to manage what happens at lower levels so that the outcome is the one expected. In the case of the Andarax, the underlying reason is that the RBD deems efficiency as a strategy to meet agricultural demands (a supply-side measure) and not to reduce demand. However, the discourse around efficiency in planning documents is ambiguous enough to induce its interpretation as a demand-control or even as a deep ecology measure.

It is noteworthy to mention that there is a current observed trend in multiple cities in Spain towards a decrease in urban water demand, both in absolute and relative terms, as a result of the reduction of households’ consumption (Sampedro and del Moral 2014, March et al. 2014). However, this is explained by the effectiveness of awareness-raising campaigns, usually during drought events. Finally, thorough studies around pricing mechanisms in agriculture reveal great uncertainty around the elasticity of water demand, and around its actual effectiveness as a conservation measure, depending on a variety other factors (Venot et al. 2007, Molle 2008b). As declared by stakeholders, raising water tariffs is extremely unpopular in Spain and usually triggers social protests both in agriculture and urban end users.

Dominant narratives 2012

Table 4.4 presents the dominant narratives observed in the final RBMP 09-15, in what regards the main courses of action foreseen for the main water bodies in each WHS, and the opposed alternative narratives from stakeholders. This does not mean that all stakeholders have a homogenous position; indeed some of them supported the proposals of the RBD, or even went further proposing measures within the same narrative. My aim is to show that there were at least some contrasting narratives in the different areas. From all the measures proposed by stakeholders in the comments, those positively responded and included in the RBMP were: the increment of irrigation and urban supply efficiency, the improvement of wastewater treatment and augmentation of the reclamation capacity, and the creation of supra-municipal institutions for management of wastewater treatment plants. The improved knowledge proposals were partially incorporated in 38 programs devoted to enrich data and information for the whole RBD, and to create new management communities for aquifers. The deep ecology measures included in the plan were, as expected, those dealing with ecosystem restoration. On the other hand, the proposals from the rural livelihood narrative were rejected considered "out of the scope of water planning" (RBMP 2009-15, Appendix XI.3, pp. 193). Attending these petitions would require a better coordination amongst several public administrations, and the integration of land and water planning, proposals that were also deemed beyond the responsibility of the RBMP (pp. 245).

Table 4.4 - Contrasting narratives in different WHS

WHS	Dominant narratives	Alternative narratives
Bajo Andarax	Supply-side	Knowledge & governance and deep ecology
Alto Andarax	Demand-side and deep ecology	Rural livelihood
Nacimiento	Supply-side and demand-side	Rural livelihood
Tabernas	Supply-side and knowledge & governance	Knowledge & governance and deep ecology

Table 4.5 - Number of measures and budget for each RBMP horizon. Source: RBMP 09-15 Annex X

	RBMP 2009-2015		RBMP 2016-2021	
	nº measures for 2015/total	Budget 2015 (€)	nº measures for 2021/total	Budget 2021 (€)
Supply augmentation	4/5	85.700.000	2/3	13.575.000
Efficiency improvement	5/5	50.695.000*	0/2	14.332.394*
Pollution control	4/8	14.899.000	2/9	5.668.000
Ecosystem restoration	3/4	3.227.000	1/4	2.658.500
Knowledge & governance	34/38	6.026.945*	11/34	4.065.075*

* Proportional share of the RBD budget for the Andarax

The budget for the PoM is shown in Table 4.5, split in typologies according to the RBMP. It can be observed that the measures related to knowledge and governance and ecosystem restoration counted with the lowest shares in the RBMP 2009-15. Pollution control was in the third position, with funds mainly allocated to the improvement of wastewater treatment. There was not any measure of actual water demand management, since water prices were not raised, and efficiency was considered a supply-side measure in the RBMP. On the other hand, 84% of the funds were allocated to nine supply-side measures including desalination, more surface water regulation, reclamation and efficiency of urban supply and of irrigation (this latter receiving up to 38 M€ from the rural development funds from the CAGP as explained in Chapter 3).

Narrating 2014

In spring 2014, interviewed stakeholders considered the problem diagnosis of 2009 still valid with some minor changes. Table 5.6 shows in columns the number of interviewees that agreed with the one of the current situation of the problems identified in 2009. In general, their opinion on the RBMP operation was very poor because almost none of the foreseen measures had been executed and those implemented either faced barriers or were simply ineffective. A prominent example is that institutions for collective management of wastewater treatment plants had been created but municipalities did not provide sufficient funding for their maintenance, thus they were not operative. There is a conflict between local and regional administrations regarding the new tax imposed by the Andalusian Water Law to urban users to fund wastewater treatment. This money is defended by the regional government for funding the construction of new infrastructures, whereas mayors in the Andarax claim it for maintaining current operation costs. The lack of transparency of the Andalusian administration about the destiny of these funds intensifies the dispute.

Regarding the shortage of surface flows, two stakeholders claimed that once the process of change to drip irrigation had finished, environmental flows could be attended. On the other hand, two other stakeholders considered that this on-going process of technical shift was already triggering the abandonment of some *acequias* and *galerias* with a negative tradeoff on aquifer recharge and dependent vegetation. In the Upper Andarax, some agricultural modernization projects had been because small farmers with low productive systems could not cover the 10-20% share of costs that were unsubsidized. Furthermore, they perceived the situation with agricultural land abandonment and erosion of agricultural terraces in the area and in Nacimiento as worsening. However, none of the reforestation or ecosystem restoration projects had been executed in order to retrieve this process. Regarding the dry up of springs, four interviewees considered that this was not a permanent situation but dependent on climate inter-annual variability.

Table 4.6 - Water problems 2014

Problem	**Worse**	**Same**	**Solving**	**Solved**
Current and future demands satisfaction		9		
Insufficient surface water flows	1	6	2	
Aquifer overdraft & marine intrusion		9		
Nitrates & pesticides pollution		5		2
Wastewater pollution. Lack of maintenance of wastewater treatment plants	2 (Bajo)	1(Alto)	3	1 (Nac)
Ecosystem degradation		5		1
River bank alternation and instability	1	6		
Springs dry up		4		4
Erosion. Agricultural land abandonment. Lack of maintenance of agricultural terraces	2	7		

Vulnerability to floods	1	8		
Vulnerability to droughts		9		
Lack of coordination amongst administrations	1	6		
Integration of land and water planning	1 (Reg)	5	2 (Local)	
Lack of control over withdrawals		9		
Insufficient access to information		7		

Comprehensive land plans had been developed in the previous years at municipal level and were about to be endorsed, what is a step forward in the integration land and water planning. However, at the level of the Andalusian administration that is responsible for regional planning, no progress was perceived in regards to agricultural areas expansion and to control or at least regularization of unauthorized wells. According to the RBD representative, an important attempt to join agricultural and environmental public administrations had failed due to an excessive bureaucratic burden. The issue of data and transparency was one of the most problematic for the interviewees. Collected data is not released afterwards, and the available information does not reach water users. Small farming organizations and minor groups are not invited to decision-making tables, neither are the mayors from small municipalities. The RBD representative argued that there is a problem of sufficient data to make it available to the public. Authorized wells were installing accounting devices but the RBD had no capacity to monitor them, and those in unauthorized pumping situation were directly out of the water balance. There was a general mistrust to the regional water administration, which was perceived as opaque and working for big economic interests "…after the crisis the logic of anything for profit is good has been installed".

The economic recession was precisely the main explanation given by the RBD representative acknowledging these deficiencies in the plan implementation. The water administration in Andalusia has gone through continuous reforms during the decade, in a context of intense socio-political changes and tensions between the central and the regional governments. The main battle between them regarded the competences over management of Guadalquivir River basin, finally won by the central administration. As a result, the budget allocated to the maintenance of the water administration in Andalusia was substantially waned, as well as its competences and power to make decisions. Only those measures getting external funding (irrigation efficiency and augmentation of reclamation capacity in Almeria wastewater treatment plant) were being executed in spring 2014. The transfer of desalinated water was stalled because of the farmers' rejection to pay for its costs.

Becoming 2015

The draft of the new RBMP 2016-20 is almost an update of the previous one and the PoM remains nearly the same (Table 4.5). However, it counts with a significantly less ambitious budget, barely 25% of the previous one. Regarding progress towards policy goals, there was no formal evaluation of the achievements of the previous PoM. However, the assessment of the status of water bodies was updated. In this sense, some small but relevant changes are observed: the aquifer in the area of Nacimiento is now considered good status, whereas the one in Sierra de Filabres is deemed in bad status and its EO is deferred to 2021. It is noteworthy that these changes are due to an improvement of the available information through several monitoring campaigns but not related to the previous plan implementation.

The rest of aquifers did not change their assessment. In regards to surface water bodies, the horizon for good status achievement in the Upper Andarax is deferred to 2021, whereas all the rest are set for 2027, including those that previously had been previously assigned LSO.

Table 4.7 - Evolution of societal funds

		Land use 2005 (has)	**Land use 2011 (has)**		**Human activity 2001 (Mhr)**	**Human activity 2011 (Mhr)**
s	SOCIETY	45001	46554	SOCIETY	1883	2205
s-1	Households	2259	2546	Households	1731	2028
s-2	Residential	2055	2247	Physiological overhead	901	1068
				Unpaid work	161	365
	Education	28	29	Education	47	103
	Leisure & other	176	270	Leisure & other	622	492
s-1	Paid work	42742	44008	Paid work	151	177
s-2	Industry, mining & energy	1238	1648	Industry, mining & energy	12	15
	Water regulation & infrastructures	207	224	Building	22	8
	Public services	4314	4465	Public services	35	44
	Private services	167	255	Private services	66	95
	Agriculture	37001	37615	Agriculture	16	14
s-3	Almonds	7956	8088			
	Citric	1672	1647			
	Open vegetables	8697	8291			
	Olive grooves	5126	5086			
	Greenhouses	2888	3194			
	Vineyards	760	737			
	Other	486	475			
	Rain-fed & natural vegetation	8668	8552			
	Abandoned	489	707			
	Newly plowed	16	452			
	Cattle	242	387			

Table 4.7 presents a multi-level accounting of land uses and human activity. Although land covers are not included in the table, a notable change is that all types of vegetation covers slightly diminished their area from 2005 to 2011 (less than -2% on average), with the only exception of *Quercus* sp. forest that grew in 7%. Overall direct land occupation increased in 3.5% between the two dates, a total of 1,569 has. This expansion was mainly driven by urban development (+9% of expansion in residential areas, +53% in leisure areas, +56% by public and private services), new solar and wind energy farms (+33%), and by agriculture and cattle farms (+1.7%). The net expansion of this sector in 624 has results from different trends. First, there are some crops in recession, especially open garden vegetables (-407 has), and rain-fed multi-crops areas that usually contain a mix of almond, vineyards, olive groves and natural vegetation (-115 has). Second, this recession is partially balanced by the expansion of almonds (+132 has)

and greenhouses (+306 has). Third, agricultural areas considered abandoned increased in 208 has as well as the same time newly plowed areas that were not planted yet (+435 has). Finally, the surface occupied by cattle farms experienced a notable increase of 60% (+145 has).

Population grew in 17% during the reported decade. The most remarkable observation is that statistics do not show a decrease in the overall hours devoted to paid work, as would be expected considering the economic recession and the sharp decline of the building sector (-61% of paid work hours). This decay has been balanced by an outstanding boost of employment generated by the services sector, especially in Almeria city and the largest towns. In addition, the public services and the industry, mining and energy production sectors did also increased their working hours. Interestingly, overall agricultural working hours decreased in 15% despite the expansion of work-intensive greenhouse farms. Another significant change is the increment in hours devoted to education, as well as to unpaid working activities such as household work or volunteering, whereas the reported time in leisure hours notably decreased.

Regarding the water metabolism, Figure 4.1 presents an update of Figure 3.2 in Chapter 3 to the new accounting for 2015 in the RBMP 2016-20, as well as the intensive ratios of water use in relation to societal funds in 2011. Precipitation series were extended to 2011/12 and show a slight increase in statistical values. However, the recharge and run-off models were not updated and the new plan assumes the same hydrological regime. E-flows have not been implemented at all. The only remarkable change on the *e* side of the figure is the recognition of an official overdraft of 3.4 Mm^3/year for Bajo Andarax aquifer, with the ensuing reduction in groundwater availability. On the other hand, overdraft in Tabernas aquifer had been reduced from 0.6 to 0.42 Mm^3/year despite no reduction in withdrawals was reported.

Overall societal appropriation of water (*s*) slightly decreased in 0.3 Mm^3/year regarding 2005. Almeria city gross water use (*s-1*) also decreased in 0.5 Mm^3/year despite population and urban growth, thus becoming less intense per hour and hectare. The demand of other residential areas in the basin (rural households at *s-1*) grew in 0.6 Mm^3/year, becoming more intense per hectare of land use but yet maintaining more hours of human activity per liter of water. Gross water use of paid work activities decreased mainly due to the removal of golf irrigation as a demand within the Andarax basin in the services sector. On the other hand, the new solar and cogeneration energy production plants raised industrial demand in 0.4 Mm^3/year. Both of these sectors are now generating more jobs per liter of water, especially the services sector which water accounting does not mirror the boost in jobs generation, neither the expansion of related land used. Technical efficiency of urban supply was not reported to increase. On the other hand, overall irrigation efficiency incremented in 4% as a result of modernization programs in Nacimiento and Bajo Andarax areas. According to the accounting, these efforts generated 2.2 Mm^3 of spare water resources that were assigned to attend additional demands, increasing net water use but maintaining withdrawals constant. Notwithstanding, the reported deficit was only reduced in 1.2 Mm^3 because new demands appeared during the period. Despite the expansion of greenhouse farms shown in Table 4.7, no change in irrigated land was recognized in the RBMP 2016-20. Considering the average greenhouse water consumption, this would sum up to 1.7 Mm^3 that are out of balance and out of planning.

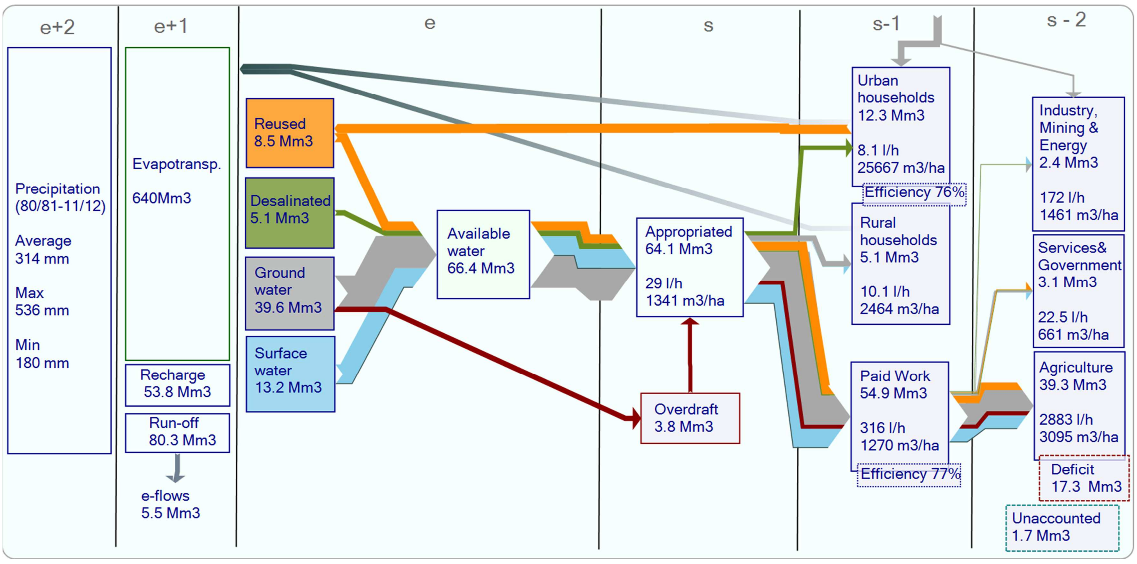

Figure 4.1 - Water metabolism in the Andarax basin (2015)

4.3 Discussion: a semiotic cycle of the WFD in the Andarax

The ALTAGUAX project was an initial loop of *narrating experience (dθ)* (Figure 1.8 in Chapter 1), complementing the formal participatory process of the RBMP with a thorough identification of problems and proposals for actions in the Andarax river basin. The analysis of narratives during this process reveals the existence of several different perspectives about water management in the area, that sometimes conflict with each other while others ally. Stakeholders in the basin agreed in the core problems – unsustainability of water demand, aquifers overdraft and wastewater pollution – whereas they greatly diverge in the detailed causation of those problems as well as in the strategies to duly address them. In addition to the problems identified in the RBMP, stakeholders pinpointed structural issues corresponding to a social-ecological perception of rural communities' livelihood, critical claims towards institutional and political performance of the water administration, and eco-integrative perspectives on the economic development model.

Dominant narratives pervading the RBMP 09-15 combined a problem structuring from a deep ecology narrative mirroring the environmental objectives of the WFD, with a course of action that prioritizes new demands through supply-oriented measures, and ecosystem restoration as means to pursue those goals. The IWRM narrative based on water demand control has not significantly permeated dominant discourses and management actions but through efficiency as an intentional boundary discursive strategy, enabling strong coalitions among otherwise contested narratives. In addition, there is a clear defense of the role of technicians as water experts, and of a technical de-politicized management. This vision is deeply rooted in the hydraulic paradigm but perpetuated through IWRM story-lines (del Moral et al. 2014). On the other hand, those proposals questioning the efficacy and effectiveness of the water administration, or its capacity to cope with structural problems of sustainability are disregarded as too burdensome or beyond the scope of water management.

The first horizon of the WFD (*reproducing the story-teller* dT=15 years) was reached with inchoate progress towards policy goals. A delayed endorsement and a halved *constructing* period (dt=3 years) liaised to the high budgeting requirements of the chosen management strategies in a context of financial austerity, stymied the implementation of the PoM. Not only the system did not noticeably change in order to pursue policy goals (*becoming*), but it is deferring EO for later planning horizons. The core strategy of irrigation modernization did not appear very effective in reducing the so-called 'deficit' despite accruing most of the available budget, neither in yielding a better status of water bodies. Remarkable changes in the water metabolism were more due to an improvement of the information about water bodies than to social-ecological transformations prompted by the actions of the RBMP. Societal organization has not dramatically changed in the last decade because economic stagnation hinders large interventions, and the weight of building sector shifted towards private urban services. Important trends of agricultural land abandonment in upstream areas and unplanned greenhouse expansion remain unattended. However, the consequences of these trends are not reflected in the new plan draft. Moreover, there is no formal evaluation by the RBD on the implemented actions. This is the 'territorial un-government' described by Sampedro and del Moral (2014): the lack of comprehensive planning at the regional level on an ex-ante basis allowing uncontrolled growth of human activities, which later impacts are faced through techno-social fixes that create temporal buffers but do not actually solve problems.

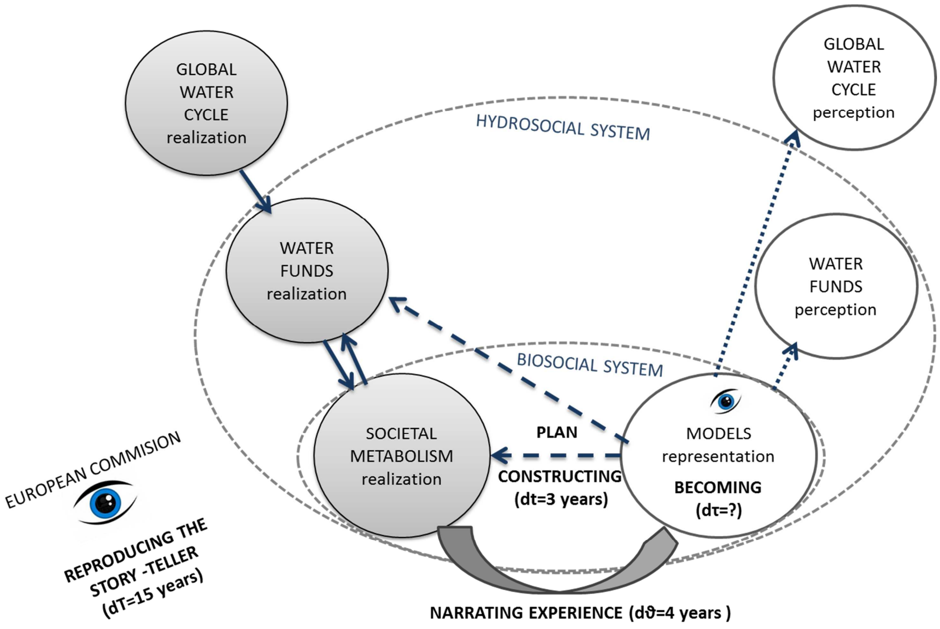

Figure 4.2 - Semiotic process during the first cycle of the WFD in the Andarax basin

The second *narrating* experience (dθ=4 years) showed very little progress towards problem closure and a generalized mistrust to the water administration. Local stakeholders did not feel reflected in the current deployment of EO within the WFD, neither on the RBMP as a tool to cope with perceived water problems. On one hand, the ecological status goal in a river basin like the Andarax with centuries of social-ecological evolution is perceived unrealistic; on the other hand, the RBMP did not attend critical demands neither is driving significant social-ecological changes. In addition, there is a patent problem of insufficient information and transparency, and ineffective communication that has been set aside during the management cycle.

Conclusions

This chapter adds on the concept of semiotic process of water management in order to assess the first cycle of implementation of the WFD in the Andarax river basin. Despite the existence of contested narratives, the dominant discourse is still anchored within the hydraulic paradigm with some nuances from IWRM. Social accommodation of antagonistic perceptions is undertaken through purportedly win-win technological interventions, which so far have proved highly cost-ineffective or stagnated due to the costs-recovery principle of the directive. Other alternative claims are gainsaid but uncover a complex multi-level and multi-dimensional network of water problems that the RBMP does not echo. Perceptions about the lack of both discursive closure -inadequate problem definition through top-down environmental objectives- and problem closure –institutional incapacity to deal with complex problem-solving- unveil a serious problem of mistrust to the water administration that reinforces stagnation.

The management system during the first cycle of WFD was not reflexive, since it only mirrored those narratives that are in accordance with dominant ones, neither responsive, since the new RBMP does not build on the feedback from stakeholders. In addition, its adaptation capacity was meager, since the system barely changed to solve perceived water problems. Rather, the system was highly vulnerable to perturbations such as the financial crisis, regional political changes or the rejection of local stakeholders to implement cooperative actions.

PART III

The Tucson basin

Introduction to case study: the Groundwater Management Act in the Tucson basin

In the setting of the SWAN Project (Sustainable Water ActioN): Building Research Links between EU and US (FP7-INCOLAB-2011), an interdisciplinary group of young researchers from Europe and America set a collaborative research agenda in order to promote a transatlantic dialogue on water governance. This goal was pursued through cooperation on comparative analysis of water management issues in different case study locations in the European Union and the United States of America. During meetings in spring 2013, the group agreed to focus on the Tucson region, Arizona, as the geographical area to realize a common case study in which to integrate our different models and approaches (Figure I2.1).

This part of the dissertation is my contribution to this collaborative research and it aims at reviewing the state of the art of current debates around the sustainability objectives in Arizona water policy focusing on the Tucson basin area. This is undertaken through a dialogue between water researchers and managers from Arizona and Spain, areas with a common background of hydraulic paradigm tradition in water management (Reisner 1993, Sauri and del Moral 2001)[32]. In the sake of a transdisciplinary research experience, this work has followed an iterative process in order to identify key management issues, research questions and sustainability indicators. It commenced with a first literature review and interviews to regional water managers in February-April 2013 that enabled drafting a set of scientific questions that were presented, reframed and prioritized in a participatory workshop in October 2013. The minutes of this workshop are presented in Appendix 4 including: 1) Identification of key management challenges; 2) research concerns and knowledge gaps; 3) stakeholder mapping. Some key research issues identified that I attempt to tackle in this research to different degrees are:

- The effect of changes in the socioeconomic structure over water demand
- The effectiveness of Tucson basin water Management Plans (MP) towards achieving safe yield by 2025
- The impact of the groundwater credit system on the present and future dynamics of the water budget in the Tucson Basin
- The impact of groundwater dynamics on biodiversity conservation

Further collaboration with stakeholders is explained in the methodological section of the following Chapter 5. This introduction presents the institutional framework for water management in Arizona, a discussion of the concept of safe yield, an overview of the study area, and a review of stakeholders' perspectives around regional water management.

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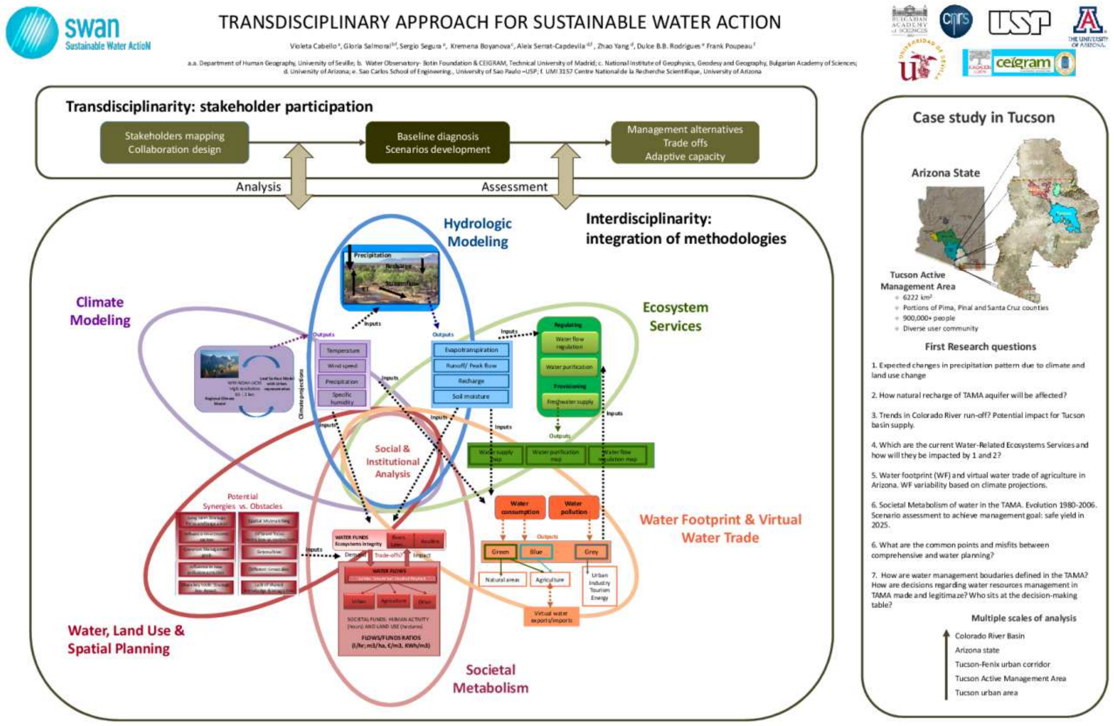
[32] Part of this case study will be published as a chapter in a book that will be the main research output of the students group. The chapter was coauthored by Nuria Hernandez-Mora (University of Sevilla), Aleix Serrat-Capdevila (University of Arizona), Leandro del Moral (University of Sevilla) and Ed Curley (Pima County).



TRANSDISCIPLINARY APPROACH FOR SUSTAINABLE WATER ACTION

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Case study in Tucson

Tucson Active Management Area
- 6222 km²
- Portions of Pima, Pinal and Santa Cruz counties
- 900,000+ people
- Diverse user community

First Research questions

1. Expected changes in precipitation pattern due to climate and land use change

2. How natural recharge of TAMA aquifer will be affected?

3. Trends in Colorado River run-off? Potential impact for Tucson basin supply.

4. Which are the current Water-Related Ecosystems Services and how will they be impacted by 1 and 2?

5. Water footprint (WF) and virtual water trade of agriculture in Arizona. WF variability based on climate projections.

6. Societal Metabolism of water in the TAMA. Evolution 1980-2006. Scenario assessment to achieve management goal: safe yield in 2025.

6. What are the common points and misfits between comprehensive and water planning?

7. How are water management boudaries defined in the TAMA? How are decisions regarding water resources management in TAMA made and legitimaze? Who sits at the decision-making table?

Multiple scales of analysis

Colorado River Basin
Arizona state
Tucson-Fenix urban corridor
Tucson Active Management Area
Tucson urban area

Figure I2.1 - Poster presented to the VIII Iberian Conference on Water Planning (Lisbon, December 2013): theoretical approach to an interdisciplinary framework in SWAN to be applied in the Tucson basin.

Institutional framework for water management in Arizona

The evolution of water law and management in Arizona has been characterized by an ongoing effort to augment water supplies to support unconstrained economic and population growth (Waterstone 1992, Akhter et al. 2010). The institutional context for water management cosists of a complex system of regulations, norms, agencies and public and private operators that have evolved over time in response to changing socioeconomic, political and technological realities.

Groundwater use in Arizona was largely unregulated until the approval in 1980 of the Groundwater Management Act (GMA) while surface water law is governed by the prior appropriation doctrine. Before 1980, groundwater abstractions were only limited by the reasonable use doctrine (Jacobs 2009). Starting in the 1940s, strong socioeconomic and population growth resulted in significant aquifer overdraft and land subsidence. By the 1970s it was clear that something had to be done to regulate groundwater pumping. In 1976 the Arizona legislature created a groundwater commission to write a groundwater law, but political resistance from agricultural users (who held a majority of groundwater rights) prevented any proposal from advancing. Negotiations finally succeeded when the Federal Government conditioned the approval of funding for the construction of the Central Arizona Project (CAPR) to the passing of groundwater management rules in Arizona (Akhter et al. 2010). The GMA was approved.

The GMA designated four Active Management Areas (AMAs) in parts of the state where groundwater pumping was particularly intense around major urban and agricultural areas (see Figure I1.2). A groundwater management goal was established in each AMA to be achieved by

2025 through the implementation of 5 consecutive management plans. The management goal for the Phoenix, Tucson and Prescott AMAs is to achieve safe yield. The goal for the Pinal AMA is to maintain the agricultural-based economy for as long as possible. In 1995 a portion of the Tucson AMA was separated out and became the Santa Cruz AMA. Its management goal is to maintain safe yield and prevent local water tables from experiencing long term declines.

Within the AMAs, existing groundwater uses prior to 1980 received a 'grandfathered right' and a moratorium on new irrigated agricultural land was imposed (Megdal et al. 2014). Management plans for each AMA established mandatory conservation goals for groundwater users that apply to most non-exempt wells (wells that pump in excess of 35 gallons/minute or 70.000 m^3/year) in the agricultural, industrial and municipal sectors (Jacobs 2009). The GMA established clear guidelines for the first three MPs but was vague on the requirements for the 4th and 5th, given the uncertainties associated with such a long-time planning horizon. Finally, the GMA created the Arizona Department of Water Resources (ADWR), centralizing all quantity-related water management responsibilities.

The three first MPs (1985-1990, 1990-2000, 2000-2010) followed specific guidelines established in the GMA. As of August 2015 (when this paper was completed) the IV MP had not yet been and the III MP's rules continue to apply (SYTF 2015). MPs are primarily regulatory documents establishing conservation programs for the different sectors (municipal, agricultural and industrial). They are not true management plans in the sense of roadmaps towards achieving objectives (Megdal et al. 2008 pp. 35). Management per se is done by providers in a decentralized governance regime, without regional (basin scale) common planning over resources allocation.

The CAPR is the primary source of renewable water supplies in central Arizona. Every year it delivers 1.6 MAF (1900 Mm^3) of Colorado River water to portions of the Phoenix, Pinal and Tucson AMAs (Prescott and Santa Cruz AMAs do not have access to CAPR water), representing 57% of Arizona´s 2.8 MAF entitlement of Colorado River water. The Central Arizona Water Conservation District (CAWCD) was created to manage and operate the CAPR and generate the resources to repay the federal government for the investment. To help ensure long-term water supply given that Arizona's CAPR water entitlement exceeded instate demand, a groundwater recharge and storage system was devised to utilize Arizona's surplus water and firm its supply from Colorado River water.

Given the expectation that the municipal water sector would continue to grow, the Assured Water Supply (AWS) program was created to link water and land use planning (Jacobs 2009). The draft rules set by the ADWR in 1988, that restricted allowable groundwater declines, encountered strong opposition from the development community, agricultural sector and cities without CAPR access (CAGRD 2014 pp. 17). The outcome was the AWS program, a new rules package (approved in 1995) that requires all new urban developments to provide proof of physical, legal, and continuous access to a 100-year supply of water.

The Central Arizona Groundwater Replenishment District (CAGRD) was created in 1993 to facilitate municipal water users meeting the AWS rules. It encompasses the Phoenix, Tucson and Pinal AMAs. Membership in CAGRD allows landowners and water providers without access to CAPR water or other renewable supply to use mined groundwater to prove AWS. Members pay the CAGRD to replenish any water pumped in excess of AWS rules. The CAGRD thus serves a double function of firming larger amounts of CAPR water while at the same time facilitating development and growth in the AMA regions by ensuring 100 years of water supply to those municipal users outside CAPR service areas. The CAGRD has priority over the recharge capacity of CAWCD sites (CAGRD 2014 pp. 11).

A final but important piece of the institutional puzzle for water management at the state level is the Arizona Water Banking Authority (AWBA), created in 1996 with the double purpose of allowing intrastate and interstate water banking and of facilitating the firming of Arizona's full Colorado water entitlement. Funding for the operation of the AWBA comes from property a tax on all real-state owners in the 3 CAPR counties (Maricopa, Pinal and Pima), and a fee on groundwater pumping and state appropriations (Megdal et al. 2014). Until 2012 AWBA had spent 197 M$ and stored 3947 Mm^3 in long-term storage credits, the majority in Phoenix and Pinal AMAs (AWBA 2012). AWBA does not hold rights and it does not operate a water market. It also does not own or operate storage facilities and is not responsible for recovering the water it stores—the CAPR recovers the water in times of shortage (Jacobs 2009). The target of the AWBA is to store up to 3.6 MAF (4493 Mm^3) to ensure long-term municipal uses in times of shortage (AWBA 2012).

The ADWR regulation functions are mainly related to conservation programs, data collection, water accounting and information generation and technical support to regional water management processes within the AMAs (ADWR 2015a). The GMA established Groundwater Users Advisory Councils (GUAC) in each of the AMAs to act as intermediaries between the multiple parties involved in the water management networks and the ADWR and AWBA. The Tucson AMA is an acknowledged example of active regional cooperation. Besides the GUAC, several initiatives have been undertaken in the last 15 years analyzing and promoting regional water policies. The Institutional and Policy Advisory Group (IPAG) was specifically formed to develop the recharge plan for the TAMA in 1995[33]. Recently, a new working group called the Safe Yield Task Force (SYTF) was created to coordinate efforts towards the achievement of the AMA's management goal.

Safe Yield and Sustainable Yield

Safe yield is technically defined as a groundwater pumping level in which human pumping is equal or less than natural recharge. This concept as a management goal arose during last century from over-abstraction and aquifer mining in many regions in the United States. While safe yield is a laudable goal in severely over-exploited aquifers with pumping regimes that by far exceed natural recharge, it may not be the optimal sustainability goal to aim for in the long term, especially in regions with riparian areas and other groundwater-dependent systems. The explanation is very simple if we look at a simple mass balance of an aquifer:

$$\textit{Change in Aquifer Storage} = \textit{Recharge} - \textit{Pumping} + \textit{GW Inflow} - \textit{GW Outflow} - \textit{Riparian ET}$$

If, as in the case of safe yield, *Recharge = Pumping*, then the mass balance is as follows:

$$\textit{Change in Aquifer Storage} = + \textit{GW Inflow} - \textit{GW Outflow} - \textit{Riparian ET}$$

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[33] http://www.azwater.gov/azdwr/WaterManagement/AMAs/TucsonAMA/TAMA_GUAC.htm

GW is groundwater and ET evapotranspiration. As it can be seen, the two negative terms in the equation are responsible for the decrease in aquifer storage. When all of the recharge is pumped, the groundwater outflow and the riparian evapotranspiration may not replenished by the groundwater inflow. Thus, with a progressive lowering of the water table, systems depending on shallow groundwater will likely be impacted by this negative mass balance. In Arizona, safe yield is calculated for whole AMAs as black boxes where flows come in and out of groundwater stocks. This enables blurring spatial distributional aspects, like the economic impacts of increasing cones of depression, dry out of riparian vegetation and natural springs, or the deterioration of groundwater quality affecting other uses. This 'groundwater budget myth' has for long been unraveled by hydrologists, but still persists in the management realm (Bredehoeft 1997, Sophocleous 1997, Devlin and Sophocleous 2005).

In response to these critics, the concept moved to that of sustainable yield referring to a pumping rate that accounts for such impacts in a long-term perspective to groundwater resources management (Maimone 2004, Zhou 2009). A sustainable yield would be achieved by assessing what level of pumping and what spatial distribution will have the least undesirable effects over groundwater dependent systems (Zhou 2009). This requires a negotiation of compromised sustainable pumping rates that can be maintained in different loci of the same aquifer while entailing the lowest trade-offs over others. In words of Molle (2011) 'because of the fluid nature of water, my use, right, vision or values are not independent from those of other people equally connected to the same hydrologic regime'. Therefore, participatory mechanisms become as instrumental for the success of that negotiation as sound scientific evaluation of trade-offs, which will be always subjected to power asymmetries and variations of political clout.

The Tucson basin

The Tucson basin is the name given to two wide alluvial valleys, bounded by mountain ranges, in which the city of Tucson (Pima County) is located. The climate is semiarid, with erratic precipitation patterns concentrated in two periods during winter and summer and has an annual average rainfall of 12 inches (310 mm) (NWS-NOAA, 2015). The basin overlies the interconnected aquifers of the Avra Valley and the Santa Cruz River (Figure I2.2a), and this delimitation was used by for water planning by the ADWR to establish the Tucson basin as a management unit in the GMA. The Santa Cruz River used to flow in Southeastern-Northwestern direction, as did the groundwater flow of the underlying aquifer, until aquifer overdraft in the region caused water table depletion and drying up of the river in the second half of the twentieth century. Most of the runoff and aquifer recharge originates from higher precipitation rates along the mountain front during both winter rainfall and monsoon summer storms. Ephemeral channel recharge from storms in the basin can also be significant. After Phoenix, the TAMA is the second most populated region in Arizona, with a total population of one million people distributed in four main urban areas (City of Tucson, and towns of Marana, Oro Valley and Sahuarita), other urban sprawl areas (Census Designated Places) and part of the Tohono O'odham Nation.

The TAMA is the second most populated area of Arizona after Phoenix, with a total population of one million people distributed in four main jurisdictions, thirty census designated places and part of the Tohono O'odham Nation. Human occupation in the basin dates back to paleoindians of the *Archaic Period* (~7000 BC to 300 AD), who already planted corn on the banks of the Santa Cruz River. The Hohokam culture flourished from 200 AD in-after, developing irrigation farming with a whole range of new crops varieties that propelled population growth and a more settled lifestyle. Spanish settlers arrived in 1695, introducing cattle and extending irrigation through *acequias,* what increased the pressure over the river. The Anglos commenced to settle after the United States bought the area to Mexico through the Gadsden Purchase in 1854. New agricultural projects triggered conflicts between upstream and downstream users in the Santa Cruz. The new Anglo developers won the dispute marking the decline of the traditional irrigation system. During next decades, 33 new ditches in addition to the three main canals were built by corporations and entrepreneurs. As the competition for river flows intensified, ditches were dug deeper to be able to divert the diminishing water shares. In 1887, a large flood eroded the riverbed down to the water table level, disconnecting all the diversion canals from the river. Thereinafter, wells were opened to maintain agriculture, although it was not until the beginning of the twentieth century that electricity enabled massive groundwater withdrawals. The Santa Cruz River used to flow in Southeastern-Northwestern direction (Figure I2.2 a), as also did the groundwater flow of the underlying aquifer, until aquifer overdraft in the region caused water table depletion and drying up of the river in the second half of the twentieth century.

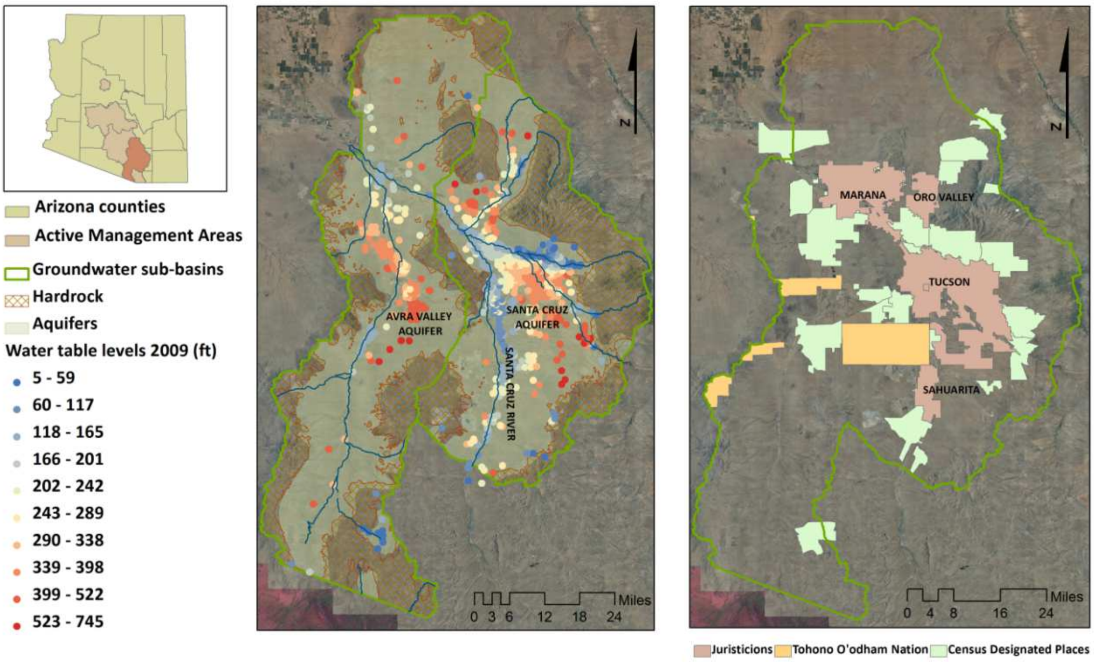

Figure I2.2 a - Tucson basin location and groundwater levels; b - Urban areas

Perspectives about water management challenges

In light of the transition from the third to the fourth MP, several dialogue processes with stakeholders were held in the TAMA with the aim of contributing to the development of the plan. The processes were led by the Water Resources Research Center (Medgal et al. 2008, Megdal and Lien 2008), the PIMA Association of Government and The City of Tucson (WISPS 2010) and the Regional Water Assessment Task Force (Kiser et al. 2011). The most ambitious work was the Water and Wastewater Infrastructure, Supply and Planning Study (WISPS) that gathered 124 stakeholders from different typologies in a two years process of dialogue that finally anchored a five years action plan for 2011-2015. The outcome reports from these efforts gather the different perspectives existing within the TAMA water community, their points of consensus and divergence. Kiser et al. 2011 (pp. 8) tailored the following grand goal from hundreds of comments received, as a point of departure for a collaborative regional water planning: “it is essential to ensure the region has a safe, reliable and sufficient water supply to meet the current and future needs of people, the environment and the economy”. Within this umbrella, water management needs are pinpointed in a similar inclusive discourse (Box 1) in a vast effort of synthesis of multiple perspectives into areas of concurrence.

- There needs to be more collaboration and cooperation in managing water resources at a regional scale.
- Current water resources should be fully utilized, including CAP water, effluent and rainwater/storm water.
- New water supplies need to be acquired/developed.
- Conservation initiatives and education should be implemented at a regional scale. The era of cheap water is over. Rates will need to be increased to build new infrastructure, meet water quality standards, acquire new supplies, and improve allocation of water resources.
- Regional water policy should be consistent with the natural limits of the region and should consider evolving climate conditions

Box I1.1 - Water management needs pinpointed during the Regional Water Assessment Task Force meetings (source Kiser et al. 2010)

There is a repetitive accord along the reports from those workshops on the need for establishing a framework for regional collaborative water planning, opened to participation of multiple stakeholders. However, the views on how to arrange this process greatly vary from those conceiving participation as ‘having a seat’ at the decision table (assuming a limited number of seats) to those advocating for open inclusive processes to deal with “conflicts between the environment and growth; between existing residents and new residents; between core city residents and suburban residents; between urban and rural residents” (Barry 2011 pp. 34).

Another common concern is the claim for achieving sustainability, albeit as it is usually the case, perceptions over what sustainability means diverge. While environmental stakeholders clearly link sustainability with a distributed achievement of safe yield that takes into account environmental needs, many other stakeholders perceive sustainability as the increment of water supply to meet increasing demands. Overall, there is a clear polarization on the key sustainability issue in Arizona: urban growth. Barry (2011) shows how the contrasting perspectives about growth drive most of the statements on how water should be managed, and lie at the bottom of the complexity of how to organize regional water planning. He classifies these perspectives over the continuum: growth as a desirable outcome, simply inevitable (but we need to be prepared and carefully plan for it), or a harmful outcome. In his view, these perceptions over growth are related to the defense of contrasting water management paradigms. The prevailing paradigm defended by growth as a good outcome or as most simply inevitable is the traditional supply-oriented approach based on a ‘sound management and technological expertise’. This is the narrative from water utilities which are in a more advantageous position to influence decisions than the rest. The challenger paradigm opposes to this view defending the priority of environmental needs as a constraint to growth, the uncertainties over the future of water supply and the focus on demand management and soft local infrastructures instead of very costly technologies. The term 'paradigm' is used here as a synonym of shared vision/perception. Remarkably, the IWRM paradigm is used by the business community as means to defend allocative efficiency as priority criterion for water management decisions (water allocated to the most profitable ends). Not in opposition but more aligned with the acknowledgement of uncertainties and the need to face them, the adaptive management paradigm was defended by some regional water managers. While repeatedly claimed as important sectors, agricultural interests[34], Indian nations and mining interests were not active in the processes.

Table I2.1 - Perspectives about water management from different stakeholders

Stakeholder type	Domain	Values about water management goals	Perception of growth
Regional water managers	Water system	Ensure enough supply for increasing demands; multilevel cooperation	Harmful outcome/ Simply inevitable
Municipal water and wastewater utilities	Water system	Ensure enough supply for increasing demands; regional cooperation	Simply inevitable
Jurisdictions managers	Political	Augment water supply; governance of private entities; regional cooperation; sustainability	Simply inevitable
Environmental stakeholders	Ecological	Environmental water needs; living within limits; soft-infrastructures & conservation; safe yield	Harmful outcome
Business stakeholders	Economic	Ensure long-term supplies for economic growth in the region; paradigm of economic rationality; IWRM; transparency and open participation	Good outcome
Elected officials	Political	Collaboration among multiple stakeholders, consensus; augment supply; infrastructures	Simply inevitable
Neighborhoods	Social	Open and inclusive participation; elites control politics; uncertainty; precautionary principle; water quality	Harmful outcome
Individual stakeholders	Environmental/ Social	Living within limits; soft-infrastructures; conservation; water quality; water-energy nexus	Harmful outcome
Agricultural interests	Economic	Flexible management to allow adaptation to economic markets; compensation for land conversion	Simply inevitable / Harmful outcome
Indian nations	Cultural/ Economic	?	NA
Mining interests	Economic	?	NA

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[34] The agricultural sector was interviewed by Megdal 2008a and Fleck 2013; relevant arguments from these works are summarized in Table 2.

Chapter 5. Water use and sustainability in the Tucson basin: Implications of a spatially neutral groundwater management

Arizona has developed strong regulatory mechanisms to ensure long-term sustainable water use and to integrate land and water use planning for the most populated areas (Jacobs 2009). The sustainability objective in Arizona's water policy is based on the concept of safe yield, that is, that the extraction of groundwater on a basin-wide and long-term basis is no more than is naturally and artificially recharged. As discussed in the introduction to the case study, this concept has been criticized by hydrologists because it can be interpreted as implying that by achieving a balance between recharge and pumping results there will be no detrimental impact on the aquifers and their dependent systems (Zhou 2009, Molle 2011). As sustainability objective the concept of safe yield may be considered as rather reductionist because it refers exclusively to the flows in and out of an aquifer, without taking into account other hydrogeological, socioeconomic and ecological criteria. Nevertheless, it is a challenging management goal that requires implementation strategies with ensuing evaluation systems.

Until the arrival of Colorado River water through the CAP in 1992, the city of Tucson and surrounding municipalities depended solely on groundwater for their water supply. As in other rapidly growing areas of Arizona, intensive groundwater pumping resulted in significant decreases in groundwater level and in consequent subsidence of areas of land. The approval of the 1980 GMA, and the resulting transformation of the institutional context for water management in Arizona, introduced changes in the way groundwater was managed and used in the Tucson basin. These included restrictions in water use patterns for municipal, industrial and agricultural users through binding conservation programs. The arrival of CAP water brought a new water source to the region that helped to substitute for diminishing groundwater resources. The recharge and recovery program was created to manage the new “renewable resources”[35] that came with the CAP, thereby allowing the region to optimize water allocation by storing large volumes of Colorado River water in overexploited aquifers. The Tucson basin is now recognized as a reference for its conservation practices to curb demand and its innovative groundwater management system (Jacobs and Holway 2004, Megdal et al. 2014). However, these practices are not exempt from critical assessment, since the techno-social fixes they present avoid facing the core challenge of uncontrolled urban growth head-on (Hirt et al. 2008, Akhter et al. 2010). There are two elements of Tucson's water management system have not yet been evaluated: a) the impact of water conservation programs on overall demand and b) the spatial dynamics of the groundwater management system.

The objective of this chapter is to delve into the debates about sustainability of water management in the TAMA, with the aim of providing insights on the limitations and challenges of the current management strategies to achieve the safe yield goal. Specifically, I look at three relevant questions formulated in collaboration with local stakeholders: How has the water

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[35] The Arizona water community uses the term "renewable resources" to refer to the inflow of Colorado River water through the CAP. However, the consideration of Colorado water as renewable is questionable given the serious impacts that this interbasin transfer, coupled with all the other ones that the Colorado suffers, causes in the donor river basin, the severe drought-related variability of water availability, the uncertainty surrounding climate change predictions and the amount of energy required to pump Colorado water all the way to the Tucson basin.

metabolism evolved since the approval of the GMA and the arrival of the CAP to the Tucson Basin? Is water demand decreasing as an effect of conservation programs? How does the spatially neutral approach to groundwater management shape vulnerabilities in the socio-hydrological system?

The chapter is organized in three sections. After this introduction I present the methods in section 5.1, in which I adapt the WMSES framework to the case study, depicting the region as a coupled water-human system. The quantitative analysis of water metabolism is complemented with a thorough review of academic literature and water planning reports, interviews with local experts and participant observation of water planning meetings. Research was conducted in two phases, between February and July of 2013, and between November 2014 and March 2015. Section 5.2 contains the results structured in i) a historical perspective on water use and planning; ii) a description of the evolution of societal metabolism of water after CAP arrival; iii) a discussion of the interplay between conservation programs and water demand; and iv) a spatial analysis of groundwater management. A discussion of the effectiveness of current water management strategies to cope with long-term and spatially equitable[36] sustainability is further presented in section 5.3 followed by the conclusions.

5.1 Methods

The Tucson Basin as a coupled Water-Human System

The water management system in the Tucson basin is extraordinarily complex; there is likely no way to depict it in simple terms. Multiple layers of institutional reforms, governance networks, technological fixes and contested interests are entangled, framed by the particular political culture of the USA. Figure 5.1 shows the multi-axes representation of relevant analytical levels in the Tucson basin. On the eco-hydrological axis, the basin is part of the huge Colorado River Basin, whose water is the main source for the region. Relevant groundwater dependent ecosystems are riparian areas rooted in shallow water tables along mountain range canyons. On the societal axis, there are three noteworthy markets influencing regional socio-economic functioning: agricultural commodities, housing and copper, which is main mineral extracted in the area (*s+1*). Socio-economic sectors using water to maintain their functioning are classified in urban, agriculture, industrial and Indian Nations at *s-1,* and subsectors at *s-2* (Figure 5.2). The governance levels were thoroughly presented in the institutional framework in the case study introduction.

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[36] Equity implies a social or political consensus about the 'fairness' or 'justice' of the distribution of costs and benefits of a policy or program. Yet achieving a consensus concerning the fairness of a particular distribution is almost impossible. Thus, equity is a complex and value-laden concept (Truelove, 1992). However, the notion of 'spatial equity' enjoys a long tradition in spatial planning practice. In a physical sense, spatial equity can be understood as the equitable development of land use. In a socio-economic sense it can refer to the equitable flow of goods and services from one spatial arena to another. In both senses, spatial equity is a parameter for sustainable development and can be defined as both a process and an outcome. As process, it involves the redistribution of the overall resources and development opportunities and/or the optimization of locally existing resources and development opportunities of an area. As an outcome, it envisions a region or area where such redistribution or optimization is achieved and sustained (Buhangin 2013, Kunzmann 1998).

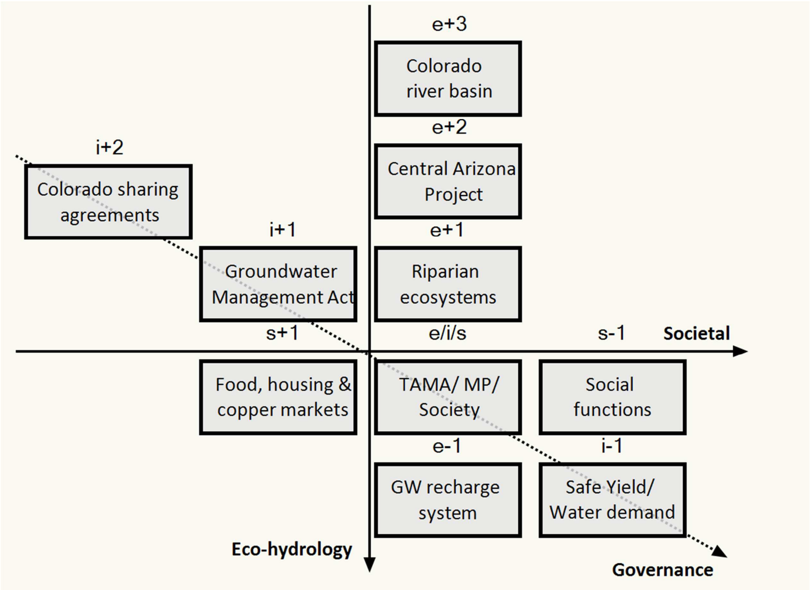

Figure 5.1 – Multi-axes representation of holarchies in the Tucson basin. GW = Groundwater; MP= Management plan

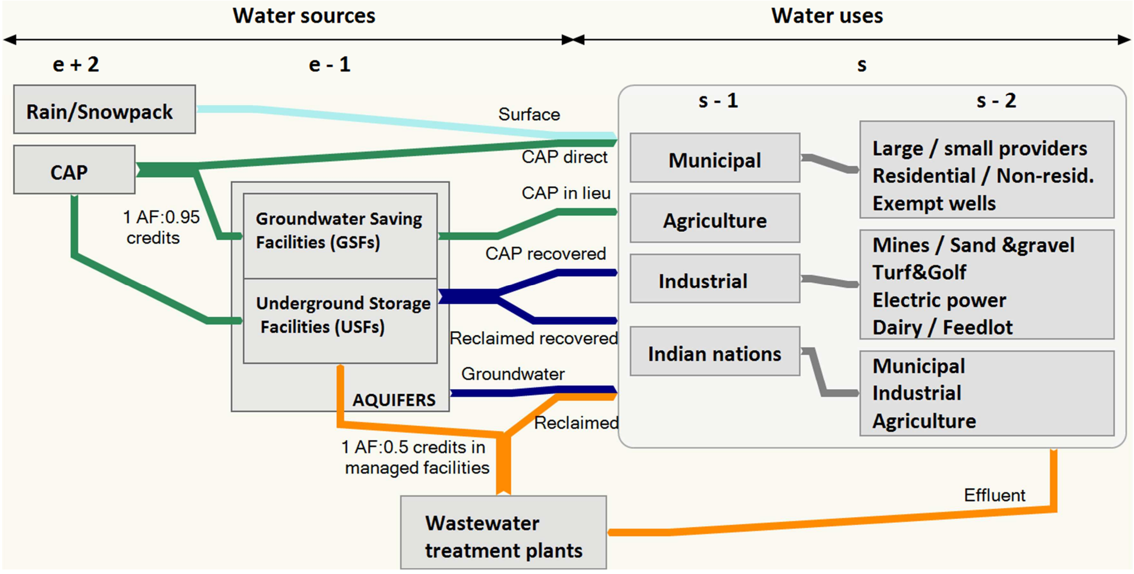

Figure 5.2 - Water metabolism in the Tucson basin

Figure 5.2 shows a dendrogram depicting the regional water management system. Arrows are not quantified; they qualify the different water flows. CAP water can be used directly, instead of groundwater (CAP in-lieu) or recharged and then pumped again (CAP recovered). Reclaimed water is also directly reused or recharged and recovered. Each acre-foot recharged generates groundwater credits that can be recovered in the future, through two types of mechanisms:

- Underground Storage Facilities (USFs) are areas where CAP or reclaimed water is physically recharged, either through *constructed* injection wells or recharge basins, or other *managed* recharge mechanisms, by a diversity of private and public operators. This water can then be recovered (pumped) in the form known as CAP/reclaim-recovered water.
- Groundwater Saving Facilities (GSFs), also called in-lieu or indirect recharge, are locations where CAP water or effluent is used by irrigation districts instead of their irrigation

groundwater rights. The surface water provider gets a groundwater credit for the amount of water that would have otherwise been pumped.

The recharge and recovery program distinguishes between water stored for recovery in the same calendar year (recovered water or short-term credits) or in a later year (long-term storage credits). In the latter case, 5% of each acre-foot of CAP water recharged or not extracted is considered the 'cut to the aquifer', devoted to overdraft recovery. In the case of reclaimed water the cut to the aquifer is 50% if it is recharged in a managed facility, whereas reclaimed recharge from constructed facilities has no cuts.

Grammar

The methodology for quantitative analysis was deployed in four steps. I first analyzed the evolution of water flows in the TAMA water budget, using a 25 year long data series for the period from 1985 to 2009-10, disaggregated per source and sector for the whole basin. The series were plotted combining water sources per sector in an interactive visualization type Icicle tree[37] in the Quadrigram software (www.quadrigram.com). Table 5.1 describes the semantic categories of the variables used and Table 5.2 lists the data sources. Water flows typologies are established according to the TAMA water budget sources and end-uses, maintaining the same nomenclature.

Next, to address structural changes after recharged CAP water started to be recovered, I analyzed the evolution of societal metabolism of water between 2000/01 and 2010/11. The analysis includes societal funds, land use and human activity, and water flows per end use sector. Land use and cover categories were aggregated from those of the 2001 and 2011 National Land Cover Databases. Human activity has been calculated from demographic, economic and employment data from the American Census for 2000 and 2010. It should be noted that the methodology followed in both censuses differs, in that the former is an extensive one year inventory of the entire population while the latter provides the average variables of surveys to population samples during different years. Data for 2010 are averages of 5 years. Water uses per sector were averaged for the previous decade (1990-99 and 2000-09) in order to compare tendencies.

In the third stage, I analyzed the evolution of water conservation targets for the municipal and agricultural sectors. The different components of municipal demand were included in the water budget alongside the population served by these subcomponents (large municipal residential and none residential, small municipal and exempt wells). Gallons per capita per day were calculated by simple division of those variables. Agricultural demand wais contrasted with precipitation and crop prices seriesdata. Precipitation time series for the weather station in the city of Tucson were obtained from the National Weather Service Forecast Office. Data for evolution of crop patterns and prices were obtained from the National Agricultural Statistics Service (available starting in 1996).

Finally, I conducted a spatial assessment of groundwater management. Available GIS data for groundwater recharge and recovery sites was analysed, as well as location of groundwater users and the changes in aquifer levels between 2000 and 2010. The latter were interpolated via point measurements with Inverse Distance Weighting using ArcGIS 10.1. Long-term

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[37] https://philogb.github.io/jit/static/v20/Jit/Examples/Icicle/example2.html

groundwater storage credit data for each recharge area is only available for the AWBA credits. The long-term storage credits held by other institutions (about 50% of all long term credits) were inferred by combining the ADWR total accounting per owner updated in February 2015 (ADWR 2015b), the annual status report of the TAMA recharge plan (ADWR 2007) and data from CAP recharge sites (CAP 2015). T Being based on a series of assumptions, the estimates cannot be considered to be fully accurate, but can be deemed sufficiently good for the purpose of establishing a spatial reference regarding where the water is being stored.

Table 5.1 - Water grammar for the Tucson basin

Role	**Extensive variables**	**Unit**	**Description**
FLOW	**Available water sources**	**AF/ Mm^3**	
	CAP direct		Water from CAP that is directly used without previous recharge
	Groundwater in-lieu		Water from CAP that is used instead of pumping groundwater
	CAP recovered		Water pumped from aquifers in exchange of previously recharged CAP water
	Reclaimed		Wastewater effluent directly reused after treatment
	Reclaimed recovered		Water pumped from aquifers in exchange of previously recharged wastewater effluent
	Groundwater		Water pumped from aquifer
STOCK	**Overdraft**		Difference between total water pumped from aquifers and natural + artificial recharge. Calculated in the water budget on a basin wide basis
FLOW	**Water use**		Sum of total gross water use per each of the sectors
	Municipal		Water supplied by municipal providers for residential and non-residential use. It is composed by large provider's residential, large non-residential (Other urban services), lost and unaccounted, small providers, exempt wells and deliveries to individual. Exempt wells are estimated as 1 AF of annual demand per every four wells
	Mining		Water withdraw by mines
	Other economic sectors		Water used by economic sectors outside the municipal supply network: dairy and feedlot; sand and gravel extraction; electric power generation; golf and turf facilities; other
	Agriculture		Water used by agricultural sector
	Indian nations		Water used by Tohono D'Oham nation and Pascua Yaqui tribes
FUND	**Human activity**	**Hours**	Population in a given year per 365 days per 24 hours
	Households		Hours of non-paid activities, calculated as the difference between paid work hours and total human activity. The required data to disaggregate this sector are the Time Use Surveys which are only available in the United States at the national level but not at the state level.
	Paid Work		Hours employed in paid work activities. Calculated as the

			sum of employment in each sector per average
	Land uses and covers	**Miles/ acres/ hectares**	
	Forest		Sum of deciduous and evergreen forest surface categories of the National Land Cover Databased (NLCD)
	Shrubs		Shrub category of the NLCD
	Water bodies		Sum of water bodies, woody wetlands and herbaceous wetlands of the NLCD
	Barren land		Barren land category of the NLCD – mines area
	Cattle grassland		Sum of grassland and pastures categories of the NLCD
	Mining		Digitalized over orthophoto 2014
	Urban		Sum of high, medium and low density and open space categories of the NLCD
	Crops		Crop category of the NLCD
	Intensive variables		
FUND/ FUND	Employment	%	Hours in each economic sector out of total working hours in a year
	Dependency ratio	%	Hours of unpaid activities (households) out of total hours in a year
	Land occupation ratio	%	Land employed in productive human activities out of total land minus hard rock (not available land)
	Housing units density	Housing number/mile^2	Number of houses per land unit
FLOW/ FUND	Income per capita	$/capita	Gross income per capita in a year
	Gallons per capita day	Gallons/cap*day	Municipal daily water demand divided by total population served
	Water use density	Acre-feet/acre	Water use per acre of land used
	Water use intensity	Gallon/ hour	Water use per hour of total human activity

Table 5.2 - Data sources

Data Type	Sources	Links (Accessed February 2015)
Rainfall	National Weather Service Forecast Office	http://www.wrh.noaa.gov/twc/climate/reports.php
Shallow groundwater areas	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Water table levels	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Wells inventory	Arizona Water Resources Department	https://gisweb.azwater.gov/waterresourcedata/WellRegistry.aspx
Artificial recharge	Arizona Water Resources Department	http://gisdata.azwater.opendata.arcgis.com/
Long-Term Storage	Arizona Water Banking	http://www.azwaterbank.gov/Ledger/defaultIntrasta

credits	Authority	te.aspx
	Arizona Water Resources Department	http://www.azwater.gov/azdwr/WaterManagement/Recharge/default.htm
	Central Arizona Project	http://www.cap-az.com/index.php/departments/recharge-program
Water accounting areas	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Water budget	Arizona Water Resources Department	http://www.azwater.gov/AzDWR/Watermanagement/AMAs/TucsonAMA/TAMAOverview.htm#waterbudget
Demography, housing, income& employment	American Census FactFinder	http://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t#
Land covers	Multi-Resolution Land Characteristics Consortium	http://www.mrlc.gov/
Crops and prices	National Agricultural Statistics Service	http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS

Collaborative research and participant observation. Literature, management and planning reports review

As explained in the introduction, in the sake of a transdisciplinary research experience, this research was conducted through collaborative interaction with stakeholders in Tucson. Pereira and Funtowicz (2006) define transdisciplinary “as a specific form of interdisciplinarity in which boundaries between and beyond disciplines are transcended and knowledge and perspectives from different scientific disciplines as well as non-scientific sources are integrated”. In this view, the common idea about the existence of “complex problems in society that need a combined effort of researchers of different disciplines and stakeholders from society, policy and industry” (Merkx et al. 2007) is understood not just as a practical need, but as a epistemological challenge, that could be expressed through the contraposition between ‘public participation’ and ‘going beyond the academy’.

The research process started with the definition and validation of research questions (Appendix 4), but continued through the establishment of a more permanent dialogue with the Sustainable Environment Program of the Pima Association of Governments[38] in terms of exchanging data and producing relevant information to their work and that of the Safe Yield Task Force. The outcome of this dialogue was a report on multi-criteria analysis of sustainability indicators for seven different sub-regions in the TAMA named Water Accounting Areas. The indicators were agreed with the stakeholders and gathered in a geodatabase for future sharing and reuse. The report is presented in Appendix 5 and has supported the interpretation of results and discussion in this chapter.

The main part of the research has been conducted during two research stays at the University of Arizona from March to July 2013 and from November 2014 to March 2015. During the second time, two regional water management meetings were attended as participant observant, the Safe Yield Task Force meeting January 23rd and the Groundwater Users Advisory

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[38] http://www.pagregion.com/tabid/76/default.aspx

Committee of February 28th, 2015. Discussions on how regional planning is moving forward to face identified management challenges were held in those meetings. Preliminary observations were discussed with local experts from the University of Arizona and the ADWR during two interviews conducted in January and February 2015.

In order to draw the institutional framework, the following water management and planning documents were reviewed:

- Arizona Department of Water Resources 1999, Third Tucson AMA Management Plan.
- Arizona Department of Water Resources 2010, Draft Demand and Supply Assessment. (Preliminary document of the 4th Management Plan).
- Tucson AMA Institutional and Policy Advisory Group 1998, Regional recharge plan.
- Medgal. S.B., Smith Z.A., Lien A. M. 2008. Evolution and Evaluation of the Active Management Area Management Plans. Report of the Water Resources Research Center.
- Arizona Water Banking Authority 2012, Annual plan of operation.
- Arizona Water Banking Authority 2014, Recovery of water stored by the AWBA. A Join plan of AWBA, ADWR and CAP.

5.2 Results

Evolution of water use

This section explores the evolution of the TAMA as a socio-hydrological system since the approval of the GMA, linking changes in the institutional context to those in water use. The information presented is extracted from a thorough review of water planning reports (ADWR 1999, 2008 and 2010a; AWBA 2012 and 2014; Megdal et al. 2008; and TAMA 1998) in combination with data from the last update of the TAMA water budget until 2010. The data are presented using the Icicle visualization[39] in Figure 5.3. It illustrates the evolution of the different sources of water used in the whole Tucson basin (big upper square) and per sector (four small lower squares) in 1990, 2000 and 2009 (different colors are used each water source). In addition, Figures 5.4 and 5.5 show the temporal evolution of the data.

1980-1990: Responding to challenges. While the CAP was being constructed, the first TAMA MP boosted water conservation programs by setting conservation goals for each sector. The target of 140 gallons per capita day (GPCD) was set for the municipal sector. The Base Conservation Program (BCP) was approved for the agricultural sector establishing groundwater allotments based on irrigation efficiency targets[40], water duties[41] and water duty acres for the reference period of 1975 to 1979. Specific programs were developed for each type of industrial use permit. Mandatory water use reporting requirements were set and water accounting started in 1985. As Figure 5.3 - a illustrates, during this period all sectors relied almost exclusively on groundwater, with the exception of some reclaimed water used by the municipal and agricultural sectors. Indian nations represented a small share of total water

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[39] The interactive visualization will be available until August 2016 at https://violetacabello.quadrigram.com/space/#/vzy/TAMA4

[40] Efficiency defined as final water uptake per water delivered

[41] Calculated for each farm unit as irrigation requirements divided by total acres planted from 1975 to 1979 and multiplied by irrigation efficiency target.

demand (1%) while mining was already relevant (Figure 5.5). The municipal sector was already the biggest water consumer, steadily growing from 41 to 48% of total water demand during this period, while agriculture fell from 42 to 32% of overall water demand as a result of the gradual reduction in irrigated acres (see Figure 5.4).

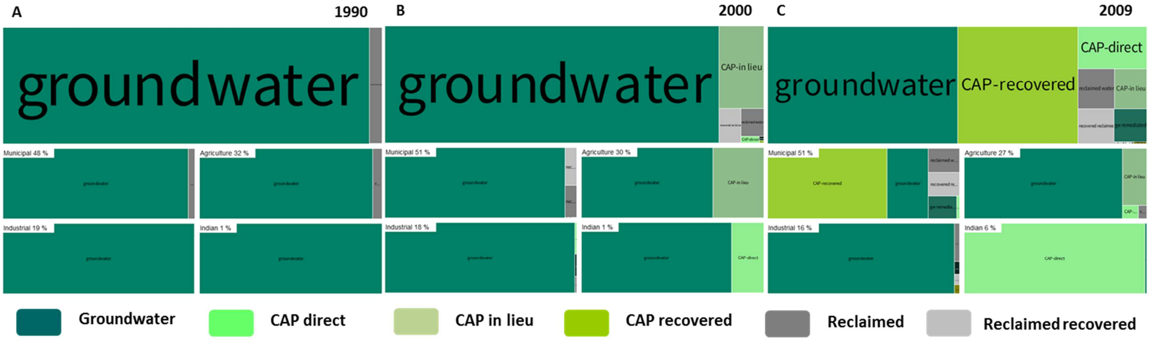

Figure 5.3 - Sources of water used for the TAMA (upper half of the figure) and per sector (lower half) in 1990 (A), 2000 (B) and 2009 (C)

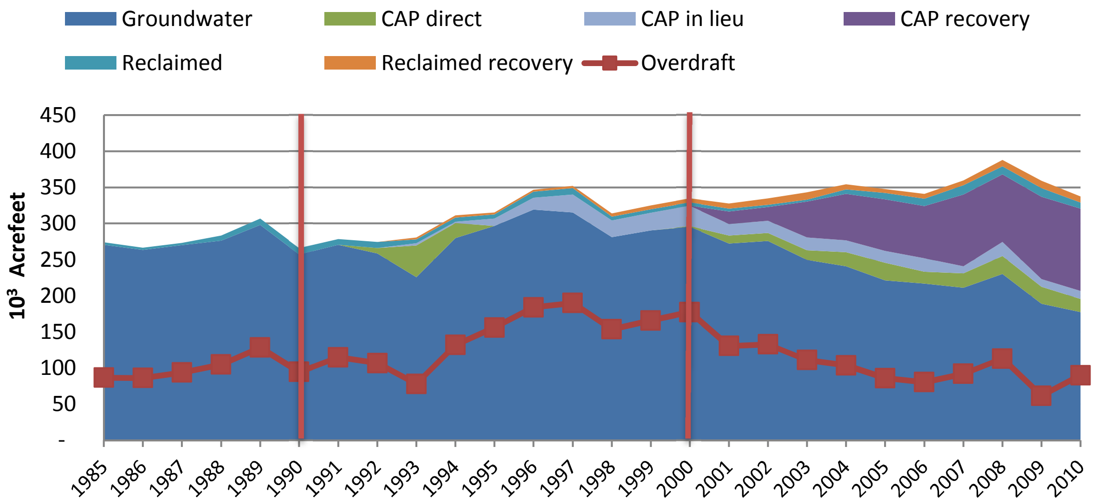

Figure 5.4 - Evolution of water use per source and groundwater overdraft

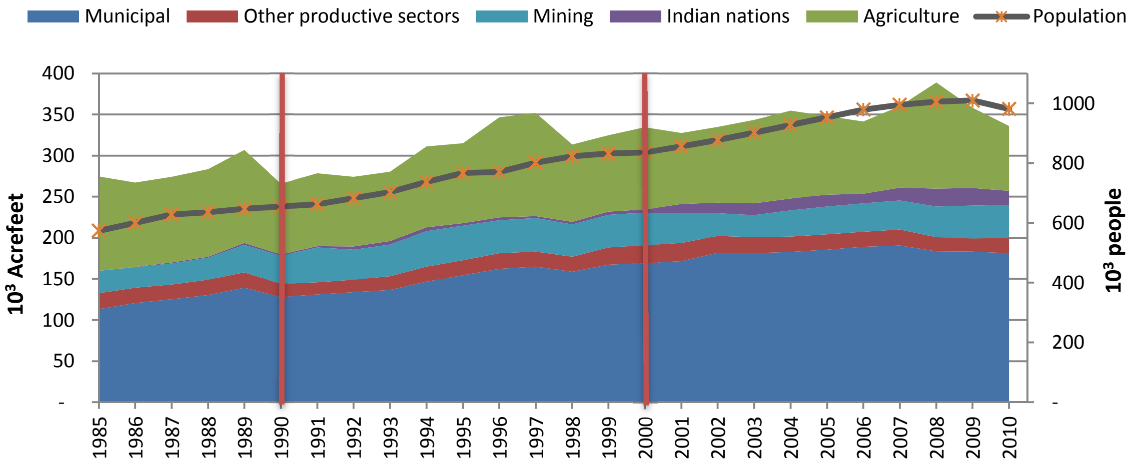

Figure 5.5 – Evolution of water use per sector

1990-2000: Adapting. CAP water arrived to Tucson in 1992 (Figure 5.4). One of the main objectives of the 2nd MP was overcoming legal, institutional and structural barriers for utilization of new supplies from CAP and reclaimed water (Megdal et al. 2008 pp. 90-91). Most of the laws, programs and institutions in place to firm CAP water (for instance AWBA or CAGRD) were created during this period. In the TAMA, the regional recharge plan was enacted as the new device for the achievement of the safe yield goal by storing excess CAP water underground (IPAG 1998). While the second MP renewed conservation programs it also introduced flexibility measures in both the agricultural sector—in order to facilitate adaptation to the evolution of market for agricultural products—, and in the municipal sector for small providers who had encountered difficulties achieving the 140 GPCD target. The highly controversial efficiency target for agriculture was set at 85% in this period. In addition, if farmers did not use their entire groundwater allotment in one year, they were allowed to "bank" this water which became ‘flexibility credits’ for future recovery (Fleck 2013).

CAP water started being used for the city of Tucson municipal supply in 1993. It was treated to drinking standards and delivered through the water distribution system that had only conveyed groundwater in the past. Due to the different nature of CAP water (chemical composition, pH), it dissolved and re-mobilized mineral concretions that had accumulated inside the pipes over the years. This resulted in brown and unappealing water coming out of the taps. The consumer protests that ensued led to the abandonment of its direct municipal use after less than two years. Tucson had to revert to groundwater use while alternative solutions were developed to indirectly use CAP water for the city's water supply.

Groundwater use by the mining sector significantly increased in 1991 in 8449 AF (10 Mm^3), remaining constant the rest of the decade. According to the TAMA water budget, the groundwater in-lieu program started in 1992, redirecting direct CAP use to agricultural production (albeit not in a significant share until 1998), in exchange for the accumulation of long-term storage credits. Municipal providers subsidized the cost of part of this CAP water to farmers accruing the generated LTCS in exchange for municipal groundwater pumping for residential water supply. The result of all these parallel processes was groundwater annual overdraft dropping down in 1993 but increasing again a year later and peaking at 189,916 AF (154 Mm^3) in 1997 (Figure 5.4).

2000-2010: complexifying. The 3rd MP inaugurates the decade of groundwater storage and recovery. Between 2001 and 2010 there were 7 different sources of water used in the Tucson AMA: groundwater, direct use of CAP, CAP in-lieu, CAP recovered, reclaimed, reclaimed recovered as well as small quantities of surface water or low quality groundwater. While all water sectors diversified their sources of water, the greatest change throughout this period was observed in the municipal sector, which by 2009 was using 60% of recovered CAP water as well as water from five different other sources. The recharge infrastructures and the institutional framework created in the previous decade permitted increasing municipal demands to be met while simultaneously replacing direct groundwater use with CAP recovered water. Annual groundwater overdraft started to decrease significantly (Figure 5.4). Another noteworthy change was the reallocation of CAP water to the Indian nations and tribes following the Arizona Water Settlements Act of 2004. As observed in Figure 5.5, the agricultural sector is the one driving overall variability in demand and, in turn, instability of annual groundwater withdrawals. In addition, conservation programs were substantially softened during the 3rd MP, substituting conservation targets with the Best Management Practices program that tailors the set of improvements towards conservation to each end-user instead of setting a common goal.

Evolution of societal metabolism

With the aim of widening the discussion to other relevant dimensions of sustainability, this section compares two snapshots of the societal metabolism of water (for 2000 and 2010). Table 5.3 shows societal funds and moving average water flows for the two decades, alongside some metabolic indicators (intensive variables). Indian nations demand has been disaggregated and added to final subsectors (municipal, agriculture, other economic sectors).

During this period, the land occupation ratio increased by two points, driven mainly by the urbanization of shrubland areas with an average annual growth ratio of 3.3%. In addition, the housing density rose from 1 to 1.2 houses per square mile. A significant fact is that the small surface devoted to agriculture is surpassed by large-scale mines. Conifers forested area decreased by 11.7%, mostly in the Northwest Catalina peaks. A positive environmental change was the increase in surface area of water bodies by 40%, especially wetlands, partially because of the groundwater recharge sites but also due to riparian restoration projects. In regards to human activity, the ratio of total working hours to total human activity increased despite increased unemployment in many urban areas, especially for those with lower incomes such as South Tucson, Summit, Three Points and Drexel Heights. This was compensated for by jobs generated in new urban areas, resulting in an overall employment rise of 13%. The economic model of Arizona has been based on the services sector coupled to urban growth (Jacobs 2009). Indeed, the services sector grew more in terms of employment generation, particularly in education, health, professional science, recreation and food services. This unveils the role of the University of Arizona as an important economic driver for the region. In addition, Arizona is famous as being a destination for winter seasonal retirees who help to boost the services economy. The demographic evolution shows two clear trends: a process of ageing and a permanent domination of the group aged between 18 and 25. On the other hand, the building and real estate sectors lost importance in regards to fraction of the total economy, although both grew in absolute terms. Agriculture and mining are smaller, but yet increasing sectors. The overall income per capita increased by 27%.

Most water uses are positively correlated with the evolution of the employment pattern. For instance the sand and gravel water use decreased with the declining weight of the building sector in the overall economy. Main water use increases were observed in residential and urban economic activities (non-residential municipal), in parallel to the growth of the services sector and the expansion of urban areas. Mining is the only activity that grew in employment without mirroring increments in water flows, thus becoming more efficient per hour of human activity. On the other hand, agriculture augmented its average consumption by 13% during this decade. Overall water efficiency improved per hour but decreased per acre (from 2032 m3/ha in 2000 to 3432 m3/ha in 2010) linked to the process of densification of urban areas.

Table 5.3 - Societal metabolism evolution during the 3rd MP

		Land use (miles^2)			Human activity (10^6 hr)			Water use (10^3 AFY)	
		2000	**2010**		**2000**	**2010**		**2000**	**2009**
e+1	Forest	162	145						
	Shrubs	3235	3216						
	Water bodies	7	10						
	Barren land	17	16						
s	Land occupation	451	486	Total human activity	6810	7990	Gross water use	306	346
s-1				Paid Work	501	657	Economic sectors	197	209
s-2	Crops	42	43	Agriculture	1.4	2.3	Irrigation	97	110
	Grassland	52	53				Dairy & feedlot	0.07	0.1
	Mining	NA	50	Mining	2.5	4.4	Mining	39	34
	Urban & developed	307	340	Building	38.7	40	Sand & gravel	4.1	3.9
				Manufacturing &Retail	140	163	Electric power	2.1	3.5
				Real State & financial	29	35	Golf & turf facilities	7.4	8.4
				Other urban services	254	362	Other urban services	39	43.5
				Government & military	35	50	Other	7.2	5.3
s-1				Households	6308	7333	Residential	109	136
s	Land occupation ratio (%)	0.19	0.21	Dependency ratio (%)	93%	91%	Water use density (AF/acre)	1.06	1.11
	Housing units density (houses/ mile^2)	1.0	1.2	Income ($/cap)	19,959	25,454	Water use intensity (Gallon/hour)	14.67	14.11

From a sustainability perspective, it is important to point out that the TAMA water management system depends on two external resources: i) Imports of practically 100% of food requirements since agricultural production is mainly devoted to cotton and cattle-feeding products. ii) Low-cost energy from the Colorado dams, and the availability of the Navajo Generating Station used for pumping CAP water and is lifting it 2900 feet from the Colorado to South Tucson city. Regarding the latter, the CAP is the major single energy consumer in Arizona, with an annual consumption of 2.8 million megawatt-hours (CAP 2010). Ninety percent of this electricity is supplied by the Navajo Generating Station coal-fired power plant in Page, which also supplies energy to the Tucson Electric Power Company. According to Eden et al. (2011), the estimated energy intensity of CAP water when it reaches Tucson is 3,140 KWh/AF (2.54 KWh/m^3), which is four times bigger than the average for groundwater pumping.), which is four times larger than the average for groundwater pumping. Interestingly, the current (2014) rate for CAP water is only 140 $/AF (0.11 $/m3), thanks to good energy efficiency management and the revenues obtained from sales of surplus NGS energy (Eden et al. 2011). As shown in Table 5.3, water used for electric power generation within the Tucson basin is a small but increasing share of the overall budget. Increasing regulations over emissions and shortage predictions in the Colorado River basin are pinpointed as vulnerabilities of the system to an increase in energy prices (Cullom 2014).

Is water conservation curbing demand?

As described in the institutional framework, the use of water conservation programs was a core management device during the first three MPs, because such was specifically required by the GMA. Nevertheless, MP goals and requirements have evolved towards increasing flexibility and adaptability for each individual end-user, to the point that their effectiveness is currently being questioned (Megdal et al. 2008, Fleck 2013). The general accepted view is that demand is decreasing because of a reduction in the GPCD in the municipal sector. In what follows I examine available data from the TAMA water budget. The data are given for entire sectors, and are only disaggregated for municipal demand into the categories shown in Figure 5.6. Data for agricultural uses only indicates overall demand and irrigable acres, but does not identify actually irrigated land. The problem with this data format is that it does not allow distinguishing the effects of conservation programs on demand evolution from other drivers like climate, landing use or market changes (Megdal et al. 2008).

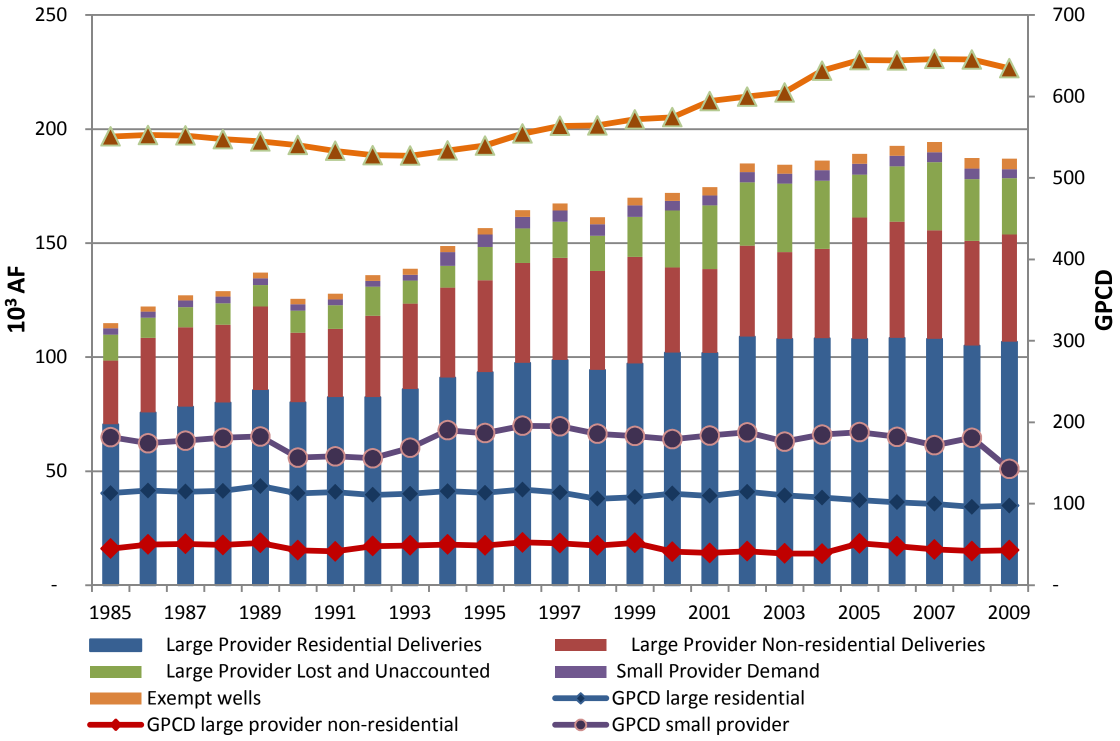

Figure 5.6 - Evolution of total municipal water demand, identifying demand categories and GPCD

As observed in Figure 5.6, 58% percent of municipal demand is residential supplied by large water providers within what are called service areas. This demand grew continuously until

2002 when it stabilized. From 2007 to 2009, overall large provider residential demand decreased by 1223 AF (1 Mm^3) and the GPCD also decreased to 97 GPCD (370 lpcd) in 2009 (down from 122 GPCD in 1989). On the other hand, large-provider non-residential deliveries and lost and unaccounted increased in the last decade regarding the previous one. Small providers and exempt wells[42] are a very small share of the total municipal demand but have very high GPCD (181 and 645 GPCD per capita in 2009 respectively). Between 2000 and 2009, the population in the TAMA region increased in 173,864 people, but decreased in 2010 for the first time on record. The increase did not mirror increases in large-scale domestic demand. Updated data presented by the ADWR at the GUAC meeting of February 2015 confirmed the decreasing tendency in domestic demand, both in absolute and relative terms.

The agricultural sector is a different and very complex reality. The GMA limited the possibility of increasing irrigable acres. Since 1995, these have remained relatively stable at around 36,200 acres (14,500 has, 1% of the total TAMA area), when 6210 acres of irrigation grandfathered rights were bought by Tucson water and transformed into non-irrigation rights (ADWR 2015a). There is no available data on actual irrigated acres per year per irrigation district, nor of the evolution of irrigation systems that could allow an assessment of the effects of conservation programs on agricultural demand. According to the ADWR (2015), average agricultural efficiency has increased from 50% to 80-90% as a result of the BMP program. Nonetheless, the literature is skeptic in regards to these results (Wilson and Needham 2006; Bautista et al. 2010). A very generous water allotment from the beginning and the introduction of flexibility accounts are pointed out as primary causes for ineffectiveness. According to these authors, conservation programs for the agricultural sector are so flexible that most farmers did not even change to the purportedly more flexible BMP program but, rather, remained in the initial Base Conservation Program.

Wilson and Needham (2006) and Fleck (2013) show rather than the conservation programs of the GMA, it is commodity prices (especially for cotton and alfalfa, which are water intensive crops) and rain that are the main explanatory factors driving agricultural water demand variability in central Arizona. Figures 5.7 and 5.8 show the evolution of agricultural water use, precipitation and the prices of the three main crops planted in the Tucson basin (cotton, hay and wheat). Agricultural demand is highly variable on a year-to-year basis, but fluctuates around a rather stable average. Until 1998, demand had a negative correlation with precipitation (Pearson -0.63) but since then, this relation is much less obvious. The 1996 Federal Agricultural and Improvement Reform Act decoupled crop prices and government subsidies from production, and increased planting flexibility (Frisvold 2007). Separating out the composite effect of this legislation from the evolution of crop prices and precipitation would require an econometric model that is outside the scope of this paper. Nevertheless, Figures 5.7 and 5.8 show that from 1996 onwards, the peaks in prices (especially for cotton) mirror peaks in water demand even when precipitation is not below the mean (Pearson 0.45 for cotton price, 0.3 for wheat, 0.44 for hay and -0.2 for precipitation). In 2008 peak water demand for the decade coincided with both lower precipitation and peak prices for all crops.

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[42] Estimated as 1 AF of annual demand per every four wells.

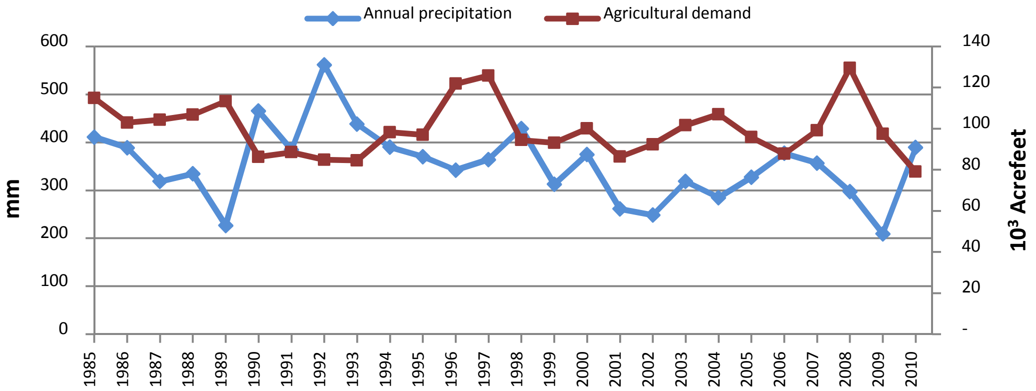

Figure 5.7 – Evolution of agricultural demand and precipitation

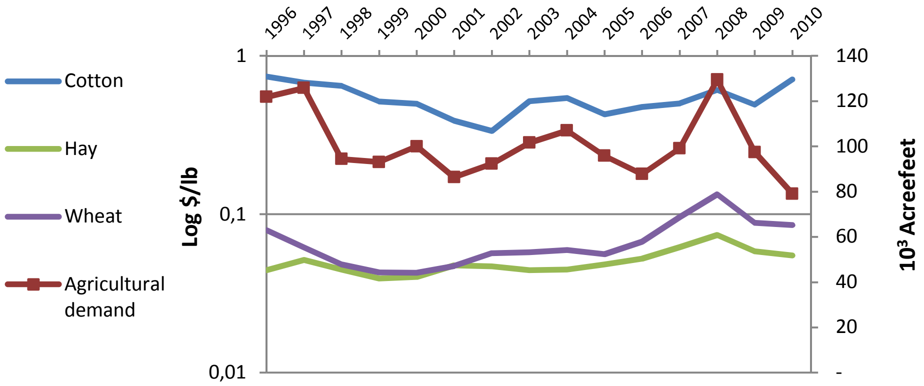

Figure 5.8 – Evolution of agricultural demand and crop prices

The analysis in the previous sections shows that: i) Overall water demand trend in the Tucson basin has continued to increase over the past 25 years although the pace of increase has slowed down by one third in the last decade (with respect to 1990-2000); ii) large municipal providers are making progress both in terms of cutting domestic demand as well as reducing groundwater overdraft; iii) for the other water use sectors analyzed, conservation has not been very effective as a demand reduction strategy; and iv) agriculture, being highly affected by crop prices and precipitation, drives annual variability of overall Tucson basin demand and groundwater use. The capacity to continue curbing demand in the future by increasing conservation is considered small (Megdal 2015, ADWR 2015a). Instead, the ADWR plans to turn the core management strategy for the forthcoming 4th MP to supporting regional cooperation towards achieving safe yield during the next 10 years (ADWR 2015a).

Table 5.4 - Water resources (AFY)

1908-2010	**Funds**	Precipitation (mm)	209 – 670
		Average	379
		Average natural recharge	81,964
2009	**Flows**	CAP inflow	197,289
		Reclamation	50,904
		Artificial recharge (CAP + reclaimed)	202,201
	Stocks	Recovery	124,118
		Long-Term Credits	798,844
		USF-CAP	630,545
		USF-Effluent	89,583
		GSF	78,716

Undoubtedly, the main management strategy for achieving the TAMA goal of safe yield is the substitution of groundwater overdraft by other resources. Taken together, the total volume of CAP water and wastewater is three times the groundwater available through natural recharge. From 1993 to 2009, an average of 53% of total artificial recharge was recovered annually for municipal and industrial uses, 1.6% lost through evaporation in recharge sites, 7.4% remained as cut to the aquifer and the rest was stored as LTSC. The continuous increase of recharge capacity coupled with the renaming of most municipal groundwater withdrawals as recovered water, propelled a technical achievement of safe yield on a basin-wide scale (SYTF 2015). However, the spatial distribution of this achievement is not homogenous.

As depicted in Figure 5.9 - A, there are 12 USF sites in the Tucson AMA — 7 recharging reclaimed water and 5 recharging CAP water — plus 6 GSF located in agricultural sites. Most of the recharge occurs in the Avra Valley and Pima mine road CAWCD sites using CAP water. Most of the recharge occurs in the Avra Valley and Pima mine road CAWCD sites, and uses CAP water. Most of the recharge of effluent takes place north of Tucson city. Groundwater recovery is mostly done by Tucson Water in the area of influence of the Avra Valley (CAP) and Sweetwater (effluent) recharge sites and delivered to the city (ADWR 2010 pp. 52). However, 90% of recovery and withdrawal wells are scattered throughout the municipal service area, with an important concentration in the large Mission and Sierrita Mine sites (located in southeastern Pima County), which are spatially disconnected from recharge areas (Figure 5.9 - A and B).

Arizona statutes require that groundwater recovery for municipal providers be located either within one mile of a USF site or in areas where groundwater decline is less than 4 ft/year (1.22 m/year). This limitation does not apply to those municipal users that join the CAGRD to meet the AWS requirements and can withdraw groundwater anywhere within their service or member lands (ML) areas. This was seen by municipal providers to be a major equity problem in the region (Megdal et al. 2008 pp. 24). Indeed, many of these providers have transferred their LTSCs to the CAGRD to enjoy the same advantages (ADWR 2010a pp. 55). As observed in Figure 5.9 - B, the CAGRD service area embraces all municipal providers while new member lands have three hotspots in northwest Catalina Mountains, eastern Vail and south Green Valley, all primary development areas within the TAMA. In 2009, 50% of groundwater (not recovered) pumping for municipal use was allocated to new developments, 37% as groundwater allowed under the AWS rules and 13% as excess groundwater that has to be replenished by the CAGRD.

The last piece of this complex puzzle is the LTSC system. The most recent update of credits accrued in 2014 showed a total of 1.4 M AF (1129 Mm^3, nearly four times total water demand in 2010), an increase of 80% since 2009 (Table 5.4). During the AWBA has been especially focused on recharge within the Tucson basin, accounting for 50% of the total LTSC. Other major owners are Tucson Water (15.6%), CAGRD (8.6%), Tohono O'odham Nation (6.2%), the Bureau of Reclamation (5%) and the Rosemont mine company Augusta Corporation (3%) (ADWR 2015b). In addition, there are 18 other entities owning less than 2% of the credits including small municipal providers (Marana, Oro Valley, Vail, Metrowater) and one irrigation district. As observed in Figure 5.9 C and D, the accumulation of credits is responsible for the recovery of aquifer levels in Avra valley and along Pima mine road. The rate of annual recovery of LTSC is around 1%. These credits can be recovered from anywhere within an AMA as long as consistency with management plan goals is maintained, and the recovery is inside or within three miles of the service area of a municipal provider or irrigation district. The credits owned by AWBA have the purpose of assisting municipal and industrial uses in case of shortage, meeting Indian water rights and fulfilling management goals; they have a specific recovery plan (AWBA 2014).

There is no available spatial data online that provides an exact accounting of recovery and pumping. Nevertheless, water table levels are monitored and their evolution from 2000-2010 is displayed in Fig 5.9 D[43]. It can be seen that the areas where groundwater credits are being accrued are those undergoing water table rises of up to 60 feet (18 meters). Groundwater levels in the central part of the city of Tucson have also been rising, since the recovery in Avra Valley enabled Tucson Water to turn off its central well (that was driving the major cone of depression and land subsidence in the TAMA). On the other hand, few areas of water table decline remain. Peak declines of up to 71 feet (21.6 meters) are observed in north-east Oro Valley area were the major use sector is urban. The second relevant drawdown area is the southern Green Valley where some of the largest mines coincide with new developments and a large irrigated area, all of which rely mainly on groundwater. In addition, the eastern area of Vail has experienced similar average decreases of 44 feet (13 meters) in the last ten years. As can be seen in Figure 5.9 D, the mountain ranges around the Santa Cruz valley are home to the largest riparian ecosystems in what are known as shallow groundwater areas (SGWA, PAG 2012). These are sustained by natural recharge over high bedrock but many connect to areas of the aquifer with declining levels. Within the Tucson basin there are 20,537 acres of SGWA connected to wider systems (Figure 5.9 D), 46% of which overlap with areas of the aquifer having declining levels. It is noteworthy that there have been very few areas showing declines over 40 feet during the ten years monitored and in which recovery was forbidden.

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[43] The figure shows interpolated data for monitored wells between September 2009 and March 2010. For a detailed visualization of wells location and levels visit the interactive map of Pima Association of Government http://gismaps.pagnet.org/subbasins/#/MapUser

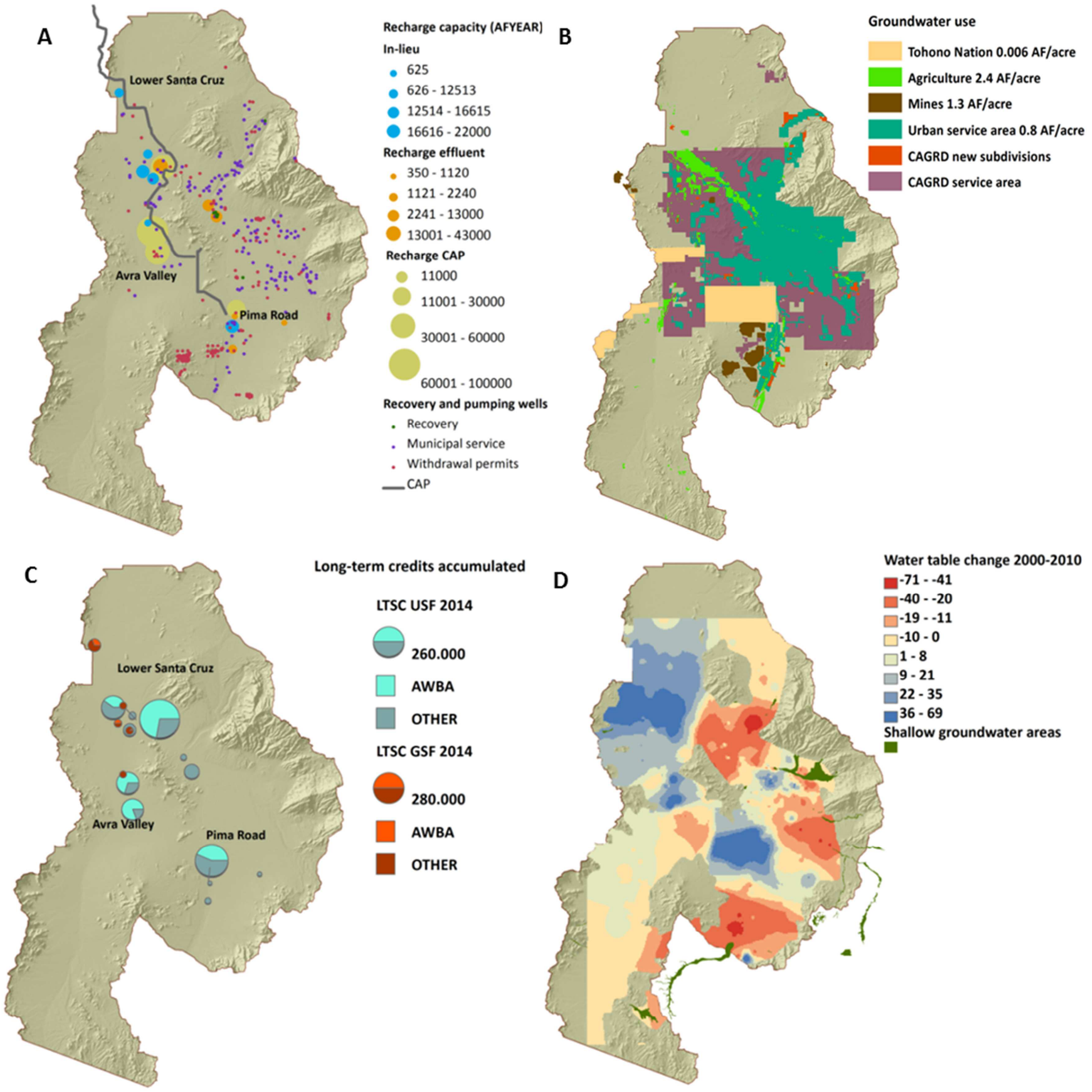

Figure 5.9 A- Recharge sites and capacity; B- water users location; C- accrued LTSC per site; D- groundwater levels change from 2000-2010 (feet) and shallow groundwater areas

In 2013, the ADWR launched a public consultation regarding a proposal named Enhanced Aquifer Management (ADWR 2013) that aimed to encourage groundwater recovery nearby recharge sites. It consisted on a calibration of percentage cuts to the aquifers depending on the distance to the recharge site: 0% within one mile buffer, 10% after the first mile but within the AMA, 20% outside of the AMA. All comments to the proposal were negative arguing that any disincentive to use CAP water would turn users towards groundwater again, resulting in increased water costs to customers or negatively affecting the emerging LTSC market (Tucson Water 2013, Brooks 2013). Alternative proposals included limiting pumping in areas with declining groundwater levels, limiting the allowable declining rate, or setting a tax based on observation of impacts in declining areas (Brooks 2013). The final outcome of the discussion was twofold: i) a requirement to improve information of the water budget, and ii) a proposal to project more pipes to allow CAP water to reach more areas within the TAMA. On one hand, the SYTF has recently proposed subdividing the Tucson basin into seven water accounting areas as a tool to improve water planning (ADWR 2015a). On the other hand, water providers are also working on cooperative Wheeling Programs with the aim of building the infrastructures required to deliver CAP water to all urban service areas experiencing declining water tables[44].

5.3 Discussion: Growth, sustainability and spatially neutral groundwater management

This chapter has examined the evolution of water metabolism with particular focus on the changes induced by the arrival of CAP water to the TAMA, and with the aim of contributing to the debate regarding water management strategies to achievement sustainability objectives in the Tucson basin. The goal of safe yield imposed by the Groundwater Management Act has been pursued by a combination of i) reducing demand for existing uses through conservation practices (i.e. improving efficiency), ii) limiting the expansion of new demands and iii) bringing new resources to the region to substitute for the use of groundwater. Dissecting the effect of each of these strategies is a difficult task, since multiple interconnected layers of regulations have been overlaid during the past 30 years without a discrete assessment being carried out. Here, I have analyzed available data and pinpointed limitations in information.

The construction of the CAP was a tipping point in the water metabolism of the area, in the sense that it brought a drastic reconfiguration and diversification of water sources for the different sectors, while fueling the economy. This was enabled by increasing infrastructural and institutional complexity to make full use of what are deemed renewable resources from the Colorado River. Infrastructural complexity was deployed through a system of new facilities for recharge and storage, and by constructing new wells and pipelines to transport recovered water to the denser urbanized Tucson area. Institutional complexity was achieved through a series of new laws, programs, institutions and cooperative agreements that multiplied the decision-making nodes of a decentralized governance network.

Regarding the control of water demand, I have shown that, despite population growth, large municipal providers have managed to stabilize urban demand by reducing demand per capita. Therefore, if not reducing overall demand, at least the sector is now balancing savings against new demand. Other municipal components do not seem to be making significant progress and the apparent slight reductions in total municipal demand are mainly due to a change in accounting rules. Further, conservation programs for agriculture seem to not seem to be having the foreseen impact. On an annual basis, irrigation demand varies about a rather stable average, driving peaks in both the total Tucson basin demand and groundwater pumping on dry years and/or periods of high commodity prices. Since 2000, the Indian Nations have become significant players in the overall budget. Total water demand in the Tucson basin has grown continuously, although a slowdown in the pace of growth was observed from 2000 to 2010, in comparison with the previous decade. CAP water has partially replaced groundwater withdrawals, therefore contributing to overdraft reduction.

In regards growth limiting measures, the binding non-expansion rule for agriculture has been effective in controlling demand. Mines and other economic sectors have no limits imposed on their permits. The data indicate that mines have become more efficient in water use, but that

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[44] http://www.azwater.gov/azdwr/WaterManagement/AMAs/documents/SAWUA_TW_EAMPresentation06042014.pdf

their local impacts on water table levels are still very significant. Water uses are in general coupled to the trajectory of evolution of the economic sectors with a clear predominance of urban services. The Achilles heel of Arizona water problems is that of limiting growth in the urban sector, since the dominant economic model is tied to urban expansion (Akhter et al. 2010). All attempts to set constraints regarding groundwater overdraft that might affect development have been systematically thwarted. From 2000 to 2010 the development sector lost weight in the economy, but this is perceived as associated with the volatility of the housing market after 2008. According to the CAGRD Operation Plan 2014, the annual rate of membership drastically dropped since 2009, and so did their replenishment obligations. Most land lots have not been built upon and current projections show construction increasing over the next 10 years and peaking in 2021. Coupled with this, municipal water demand in the TAMA is projected to grow until 2045 (CAGRD 2014 pp. 49-51) by nearly 29.000 AF (35 Mm^3). It is however the lowest of the projections for the three CAGRD AMAs.

The lack of spatial disaggregation of the water budget makes it difficult to assess the extent to which improvements in efficiency in some urban areas are enabling growth in others. This 'spatial neutrality' in the accounting has a long tradition in USA since the Bureau of Reclamation started to pool the cost-benefits analysis of large infrastructure projects for whole river basins as means to justify their economic viability (Reinser 1993). What seems clear is that there is a disconnection between recharge and recovery in some areas, and that local impacts over the water table are still significant. The technical achievement of safe yield at a basin level is spatially uneven and there are wide areas in which overdraft continues, especially in new developments and large mines loci. Larger biodiversity hotspots are dependent on shallow groundwater and some of them partially overlap areas with declining aquifer levels from 2000 to 2010.

The new category of *recovered water* enables continued mining of groundwater without being properly accounted for in the overdraft equation. A proper accounting should reflect which part of the recovered water is actually CAP, which is reclaimed water (for instance the water that Tucson Water transports from Avra Valley to the city), and which is not (all the water recovered outside the area of impact of the recharge site), and should split the accounting of safe yield into different sub-regions according to that. The water accounting areas project is a good step in this direction. The regional network for water governance is aware of the impacts of the ill-defined spatial management strategy and is negotiating solutions. While it was initially proposed to constraint recovery near recharge, it seems instead that the final bet is for bringing recharge close to recovery through an expansion of the CAP infrastructure to reach more areas within the TAMA. Some have argued this is a straightforward solution to the current depletion problems (Tucson Water 2013), but at the same time this view may not properly account for the expected shortage of Colorado water acknowledged by CAP managers. Regional inequities are one of the main arguments leading to what has been termed 'river basins overbuilding' (Molle 2006). This term is used to name the vicious cycle between water scarcity and development of new resources, usually entailing critical impacts on ecosystems and increasing vulnerability of water users to variability in supply.

The AWBA recovery scenarios until 2024 show that municipal, industrial and Indian demands can be largely met with 66% of its actual storage (AWBA 2014 pp. 46). The main recovery mechanism that has been proposed is the exchange of short-term annual credits of municipal providers for LTSCs accumulated near recharge sites (AWBA 2014 pp. 55). Agriculture has low priority access to CAP water and thus it is the most vulnerable sector to potential Colorado water shortages. Nevertheless, it has grandfathered rights that could again increase the pressure in regards to use of groundwater. The AWBA recovery plan does not mention safe yield at all and so far there is no assessment of how recovery by other different owners would impact the management goal.

Conclusions

The problem of how to reconcile the positive and negative impacts of urban growth remains the eternally unresolved debate in the Tucson basin and in the American south-west. Questions regarding potential physical, socio-economic or environmental limits to growth are not even on the discussion table in Arizona. Water scarcity imposes a key limiting factor on the current urban growth-based economic model. However, an increasingly sophisticated governance regime has been devised to try to overcome this limitation.

Safe yield is a laudable management goal that has triggered important changes in the water metabolism of the TAMA. Management strategies of conservation, non-expansion of irrigation rights and new resources have been effective in progressing towards the achievement of safe yield, partially thanks to an intense cooperation among regional stakeholders. The municipal sector has been the most adaptive one in reducing overdraft and stabilizing demand through conservation, yet it is responsible for the largest share of the overall demand which will likely keep on incrementing with new infrastructures. The agricultural sector will be key in future responses to drought since it drives inter-annual overdraft variability.

Yet, the discourse regarding CAP as a renewable resource, and the use of creative accounting devices veil an unequal distribution of impacts and vulnerabilities derived from the spatially neutral approach to groundwater management. Mines and new development areas count with privileged withdrawal permits that are causing important local impacts over water tables with potential effects over riparian ecosystems. How this spatial inequity is resolved appears the main sustainability debate of the next ten years when the GMA is to be assessed. Achievement of safe yield might be possible in most areas if new pipes are constructed to deliver CAP water to those locations, as long as no severe shortage in the Colorado River occurs. Whether this is a resilient or a ceteris paribus strategy that increases vulnerability will be seen over the course of the next decade.

PART IV

Conclusions

Summary of conceptual and methodological contributions

This dissertation offers a complex systems perspective on water resources management through the operationalization of the WMSES framework (Madrid 2014, Madrid and Giampietro 2015) for the purpose of the integrated assessment of water policies at basin scale. The framework builds on the concept of social-ecological systems, or coupled human-water systems, and a definition of water use that deals with epistemological issues of complexity such as the existence of multiple perceptions of nature, the multi-scale organization of living systems, and circular causality as the main type of relationship maintaining this organization. In order to address the research objective, two relevant conceptual advances have been introduced into the framework alongside several concomitant methodological contributions.

First of all, this is the first implementation of the WMSES at the scale of water basins, either surface or groundwater, that are depicted as open, holarchical and autopoietic SES/WHS. The conceptualization of watersheds as SES is a key development that allows a comprehensive assessment of how social and eco-hydrological systems, and the multi-scale relationships between them, change as a result of the implementation of policies. This assessment requires the combination of different bodies of knowledge and analytical tools, such as human geography, ecological economics, eco-hydrology or institutional analysis. Thereby, I hope it contributes to the new interdisciplinary currents in water science.

I advanced this methodological integration through the link between the analysis of societal metabolism and that of the ecosystem metabolism of water on a spatially explicit basis, using GIS for the integration of an eco-hydrological model in the flow-fund accounting system. By doing so, I could operationalize the WMSES framework, and formalize relationships between the ecosystem and society interfaces, and between their respective structures and water supply and demand. The analysis of the ecosystem metabolism of water was approached through the eco-hydrological processes that control water resource renewability (supply-side sustainability), the impacts caused on ecosystem health (sink-side sustainability) and the boundary concepts of water availability and ecosystem water requirements. This operationalization allows addressing the feedback loop "water supply->societal uses/discharges->impacts on ecosystems->impacts on supply". Thereby, social-ecological patterns of water can be described through the characterization of this loop in WHS, which can be defined through the combination of criteria from the watershed and problemshed perspectives. These criteria used to define the boundaries and analytical levels of the SES/WHS should be made explicit, as well as the mismatches and losses of information associated with the pre-analytical decisions. This type of integrated representation is something that water plans in both case studies lack, because they only apply a watershed criterion in their delimitation of management units. However, the possibility of considering socio-economic criteria is foreseen in the Spanish Instruction for Hydrological Planning, and it has recently been applied in other basins to subdivide groundwater bodies.

In the Tucson basin case study, I also combined water metabolism accounting with the spatial analysis of groundwater management (location of sources, users, and groundwater storage, and impact on aquifer levels and their dependent riparian ecosystems). This combination is particularly suitable for understanding how the metabolic functioning of the system is geographically displayed, and shapes spatially differentiated vulnerabilities and inequity.

In addition, I have made progress in the integration of GIS techniques in MuSIASEM by designing a conceptual data model for data structuring and management in water metabolism studies. This model has been further developed through three logical models adapted to the analytical extents and objectives of the different chapters. The logical models have in turn been implemented in several geodatabases in open reusable formats with the aim of contributing to the transparency and reproducibility of this research.

Second, this is the first application of the WMSES in the appraisal of the outcomes of the implementation of water policies. MuSIASEM is usually employed to assess the sustainability of future pathways related to possible political decisions. However, ex-post analyses of how political decisions have shaped metabolic patterns are not very common. The concept of the holon is particularly useful to this purpose because it embraces the idea of emergent properties as the outcome of both the interactions among parts at lower levels that cannot be obtained by their mere aggregation, and the boundary conditions posed by upper levels. Therefore, the question turns into "What are the cross-holon interactions that are driving the observed metabolic patterns and their associated water management challenges?" In addition, the conceptualization of the holon as a dual physical rate-dependent and a constructed, informational, rate-independent entity enables the bridging of quantitative biophysical and qualitative policy analysis. Following other frameworks for SES that address feedback relationships between societal and ecological systems, the core conceptual contribution of this dissertation is this bridge between water metabolism and water governance.

On a conceptual level, this connection materialized through the following processes: i) the addition of a third axis to the multi-axes holarchic representation of SES, with the *infoshed* referring to the policies and regulations driving metabolic change and mediating relationships between societal and eco-hydrological holons; ii) the formalization of this axis within the general WMSES framework as a boundary area on the societies/ecosystems interface; iii) a discussion of water availability as a normative boundary category that depends on infrastructural, technical, sociocultural and eco-hydrological factors at the same time, and the calculation of which requires the explicit recognition of underlying assumptions; and iv) the development of the concepts of the semiotic process and semantic closure of the water management cycle (Allen and Giampietro 2014, Diaz-Maurin and Kovacic 2015), integrating Hajer’s (1995) concepts of problem closure, social accommodation and discursive closure. These checks pose questions that in turn have been used to operationalize the policy assessment criteria of effectiveness, efficacy and pertinence.

On a methodological level, this connection has been operationalized through the combination of quantitative and qualitative analysis tools. Regarding quantitative analyses, three water grammars have been tailored to the specific analytical objectives of the case studies. The grammars have been formalized through different models and statistical sources, and depicted for the integrated analysis of metabolic patterns in dendrograms, radar graphs or tree-icicle visualizations. The integrated analysis of metabolic patterns provides insights into the lower-level socioeconomic drivers of change in the water metabolism, the biophysical outcomes resulting from the implementation of policies, and the trade-offs associated with management decisions. With this latter aim, Chapter 3 presents a scenarios exercise that compares RBMP scenarios with alternative ones. The elaboration of this exercise required a normative definition of the alternative scenarios with different decisions that were biased towards what I aimed at showing. Ideally, these decisions would not have been made by me as an analyst but by stakeholders in participatory processes.

Discourse analysis has been a key tool for understanding the diversity of perceptions about water management and dominant discourses permeating decision making, allowing researchers to tackle the question of the "how and why" of metabolic patterns of water. This question of "”how and why" complements those of "what the system is" and "what the system does", which are normally addressed with MuSIASEM. The production and evolution of hydro-social landscapes is filled with a variegated set of social agents set against each other with changing and more or less acute conflicts and struggles. Fund and flow configurations are invariably filtered by social dreams and fantasies, and are politically managed or reimagined through shifting governance arrangements. The diverse and changing attributes of water, together with the contentious uses, demands and imaginaries surrounding it, are always mediated through political institutions and policy networks and regimes, which include those through which access to or ownership of resources, and the tools for its distribution are organized.

Finally, regarding the post-normal science framework in which MuSIASEM is situated and the more extended transdisciplinary practices, I endeavored to collaborate with stakeholders in both case studies within my time and resource constraints, and some reflections on these experiences are summarized. I hope that the proposed framework contributes to the bridging of some of the current science-policy gaps, such as the need for multi-scale analysis, the targeting of collaboration with practitioners and the opening up of scientific knowledge (Jarvis et al. 2015).

Conclusions about challenges in water governance in case-studies

This dissertation follows the implementation of sustainability objectives in water policies in two water basins in Spain and Arizona. The two areas share similar semi-arid conditions, sun-driven economic models, acute human pressures on water bodies, and techno-managerial water governance models. Both basins face situations in which over-abstraction of resources propelled aquifer degradation as a core problem driving water policies and management strategies. In addition, they also share an ideological background of hydraulic mission (Sauri and del Moral 2001, Molle 2006), culturally anchored for over a century through stout epistemic communities brandishing long-lasting claims such as "not one drop should be lost in the sea", and large engineering works to cope with snowballing water scarcity.

The water policies regulating management in the two case studies are rather dissimilar[45], partly because between one and the other there has been an important evolution in the dominant water management paradigm towards IWRM. The GMA in Arizona was enacted in 1980 in response to major aquifer depletion over the course of previous decades. It delimited management extents based on aquifer limits for the most populated areas, and set management goals for each of them. In the Tucson basin, the management goal is safe yield achievement by 2025, which is calculated as a zero sum between outflows and inflows for the whole basin as a black box. This differs substantially from the European WFD released in 2000

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[45] Appendix 6 shows a table with a comparison of the main features of both regulations.

that focusses on the quality of aquatic ecosystems. The directive embraces the principles of IWRM, such as river basins as management units, economic instruments for decision making and public participation in water planning. Management goals are established for every surface and groundwater body as a horizon for the achievement of status, to be restored to purportedly pristine condition (Bouleau and Pont 2015).

Water management in the Andarax river basin appears to be in a situation of institutional lock-in that responds to several entwined external and internal multi-level causes. Regarding external drivers, at an international and European level, the continuous negotiations among contested interests surrounding agricultural production, rural development and ecosystem conservation have been framed by the inclusive discourse of sustainable development. This is reflected in the win-win-win rhetoric of policy goals linking social equity and ecological quality to economic growth. However, agricultural discourses are biased towards the market function of agriculture, whereas water discourses are biased towards ecosystem integrity. At a national level, the principles of the WFD encountered an old institutional inertia managed by powerful coalitions formed by the central government, old RBAs, large agricultural and hydroelectric lobbies, and civil-engineering corporations, which was focused almost exclusively on river regulation and inter-basin transfers. As expected, these coalitions struggled to adapt to the new framework, and in many cases hampered the possibilities of shifting management priorities. At a regional level, significant steps have been taken towards a rigorous normative development of the WFD and the integration within agricultural policies. However, this integration has been pursued through strategical win-win bridges between political agendas, these bridges essentially being based on technological interventions to generate additional resources. In addition, the implementation of the resulting standards is subjected to infringements of the law, not in an incidental but in a structural atmosphere of deviance or non-compliance with legal norms (Sampedro and del Moral 2014), within a substantially waned and unstable water administration in terms of both budgetary allocation and decision-making capacity.

Regarding internal drivers, the Andarax river basin is a genuine complex SES due to its outstanding biophysical, cultural and institutional diversity, which can be observed in a range of evolving hydro-social landscapes. Agriculture is the main driver of change in water metabolism, with very different agricultural metabolic patterns coexisting with, and sometimes competing for, water bodies in different situations of impact. These patterns go from upper rural areas with low-productive agriculture adapted to their ecosystem water metabolism, to intensive techno-boosted greenhouse vegetable production and stock-groundwater-fueled olive monoculture. The city of Almeria is another key player, not only as a major water user and producer, but also through the intricate rural-urban relationships influencing the socioeconomic transition of rural areas from the agricultural to the services sector. The degradation of water bodies responds not only to the entanglement of multiple direct causes, such as an excess of withdrawals during summer periods and wastewater discharges, but also to other long-term processes like the abandonment of traditional agriculture and erosion, lax land planning, and an absence of monitoring of and control over abstractions that adds to the great uncertainty regarding the insufficient knowledge about impacts on aquifers and their dependent systems.

The challenges posed by EO are related to the impossibility of reducing pressures and impacts on water bodies without effectively reducing withdrawals and discharges. This would require the re-addressing of land uses and water rights, the integration of water and land management in a format of comprehensive planning, and, especially, an acute monitoring of pressures and transparency in decisions. In other words, the achievement of EO requires a reconfiguration of the power balance among water users and among different sections of the regional administration. Far from facing up to this conundrum, regional management decisions in Almeria strove for a techno-social fix to attend to both EO and agricultural demands by applying the following strategies: i) restricting the expansion of irrigable land but enabling irrigated land to reach the irrigable ceiling; ii) incrementing the technical efficiency of irrigation; and iii) augmenting the desalination and reclamation capacity. The required infrastructural investment was aided by European funds channeled through several national and regional programs.

Underlying these decisions there is a dominant water discourse that combines deep-ecology justifications and problem structuring with ambiguous efficiency arguments from IWRM biased towards incrementing supply, and with the traditional supply-oriented demands for more infrastructures to cope with "structural deficit". Contesting narratives unveil a social-ecological perception of the livelihood of rural communities, eco-integrative proposals for reorienting the economic model as well as critical claims about the institutional and political performance of water administration bodies. These perceptions are either accommodated through techno-social fixes, prompting coalitions among otherwise contested narratives, or directly rejected as "outside the scope of water management".

The chosen strategies entail important trade-offs that were overlooked in the water planning process. First of all, water accounting in management scenarios anticipated a rebound effect in water use patterns, at the same time as compulsory e-flows were disregarded. This is related to the fact that efficiency increment is deemed a supply-augmentation and not a demand-control measure in the RBMP. Secondly, the significant intensification of energy, and thus monetary, costs associated with desalination was neither accounted for in the economic analysis of the RBMP nor negotiated with farmers taking into account the cost-recovery mandate of the WFD. The problem posed by water was simply solved by increasing the problem posed by energy. Thirdly, the installation of drip irrigation implies an alteration in well-integrated social-ecological patterns in rural areas. Flood irrigation systems are part of the traditional adaptive practices of the Mediterranean region, existing within an integrated management system of surface, subsurface and soil flows. The low technical efficiency of irrigation has represented a buffer when adapting to drought periods in semi-arid areas by increasing efficiency. Water losses due to low technical efficiency are returned to the environment, and benefit third parties when flowing out in lower springs. Therefore, their reduction might lead to important social and ecological impacts that need to be carefully considered. The potential trade-offs of phasing out traditional infrastructures and institutions are emphasized by the communities in question. These communities extend the debate on water management problems from the basic RBMP idea of flow augmentation to more complex ideas about the structural drivers of metabolic change such as demographic ageing, rural exodus and landscape desertification. The long-term social-ecological evolution of water metabolism in these areas challenges the ecosystems integrity goal of the WFD.

At the end of the first water management cycle (2015), the outcomes of the chosen strategies proved highly cost-ineffective in the new context of financial austerity, unraveling the premises under which the RBMP was designed. The great recession from 2010 onwards stalled economic growth and large-scale developments, thus the expansion of demands. In spite of that, progress towards EO is almost inexistent since the RBMP was never implemented at all. Moreover, there is the patent problem of insufficient information, transparency and justification of decisions, as well as of ineffective communication, all of which has been downplayed during the management cycle. As a result, local resistance to implementing measures and fostering cooperation among actors has emerged, alongside a generalized mistrust of the water administration body, which is deemed incapable of dealing with perceived problems.

The Tucson basin has already gone through three management cycles, with the much more significant outcomes resulting from the GMA implementation. The main management strategies are not far removed from those employed in the Andarax basin: new supplies, an improvement in efficiency and non-expansion of irrigable land. However, the way they were applied in the Tucson basin was substantially different, essentially because there was a real commitment to controlling demand and to devoting new supplies to the retrieval of groundwater overdraft. A remarkable attempt at integrating land and water planning was the subjection of new developments to the demonstration of a hundred years of assured water supply. In addition, the compulsory annual reporting of withdrawals and uses provides the ADWR with key water budget information for assessment and planning.

Since the year 2000, there has been an observed decreasing trend in the annual groundwater overdraft that has recently been approaching zero. The tipping point for this shift was the effective alliance between CAP construction and the recharge, storage and recovery system, this alliance eliciting a drastic reconfiguration of water metabolism with a plethora of new water sources. This infrastructural investment was accompanied by a range of new regulations, institutions and cooperative programs among the multiple nodes of a decentralized governance regime.

The municipal sector has been the most adaptive in reducing overdraft by replacing more than half of its groundwater consumption with CAP-recovered water, and by stabilizing its demand through conservation per capita. However, a thorough understanding of the effect of urban development stagnation and the potential effects of the reactivation of the sector would be worthwhile. The expectations of growth for this sector remain unaltered; they have simply been postponed for the next ten years. The agricultural sector drives inter-annual variability in overall water demand and overdraft in the TAMA, mirroring weather and agricultural market vagaries. The partial substitution of groundwater by CAP in lieu is the most vulnerable to droughts in the Colorado basin. An issue that requires further attention is the role of the existing agricultural systems in both local economies and the USA's societal metabolism. The Indian Nations are an increasingly important player in the overall water budget and their role in the emerging LTSC market is another issue to be looked at. Finally, mines are causing significant local impacts on aquifers, and their qualitative long-term effects are not fully understood.

Basin-pooling water accounting conceals an uneven distribution of the technical safe yield achievement. The spatial disconnection between recharge and recovery is obscured by the label of "CAP-recovered", a category that is suppressed in the overdraft equation. This spatial neutrality of groundwater management provides the ADWR with the flexibility to negotiate with regional stakeholders, but at the same time overlooks equity issues regarding the privileged situation of large mining sites and developers that are members of the CAGRD, all of whom can continue to mine groundwater anywhere in the basin. The sub-regional breakdown of the water budget into water accounting areas should enable a better assessment of social-ecological vulnerabilities associated with the continuous decrease of water tables in some areas. However, it is noteworthy that this spatial inequity is the core argument used by regional utilities for increasing infrastructural complexity in the basin over the coming years.

Besides the accepted premise of Colorado River water as a renewable resource, pinpointing a dominant water discourse in the Tucson basin is not easy because the decentralization of decision making makes the power network more leveled than in the Andarax basin. However, clearly polarized narratives reflect perceptions surrounding the economic model based on urban growth. These range from developers defending the economic argument of the allocative efficiency of IWRM, to the denouncement of growth as detrimental to local people's quality of life and regional resilience. Water utilities are clearly strategic players in this network and defend the sound techno-managerial expertise of water decisions. In light of the transition to the fourth management cycle for 2010-2020, these contrasting narratives were accommodated through intense regional multi-stakeholder cooperation, participatory processes and grand consensual objectives of water for the present and the future, and for the economy and the environment. However, the economic recession did also significantly impact the ADWR budget and resources, and the fourth MP has accumulated five years of delay and increasing challenges in the achievement of a spatially equal, environmentally sound and durable safe yield in the next decade.

Like most environmental governance regimes, water management in both study sites mirrors the ecological modernization discourse of sustainable development. Nevertheless, the practical reach of IWRM principles has been inchoate or partial. One reason is the dispute with pre-existing values, institutions and coalitions. Another is the double edge of the ambiguity of integration as a discursive strategy that propels narrative coalitions among truly opposing meanings. But the main underlying reason is the limits imposed by the actual impossibility of thinking outside the box of economic growth as the ultimate political goal of our time. These are the limits of sustainable development itself as a global ‘grand narrative’ to guide political action to face up to the challenges of humanity[46]. Both basins could be considered to be in a situation of overbuilding or social scarcity. In this type of situation, a positive feedback loop is established when the over-commitment of resources generates social-ecological impacts, bringing about new infrastructures that fuel growth and demand, in turn generating new scarcity (Molle 2006). This vicious cycle of artificial scarcity is what the Andalusian government terms “structural deficit”, something that cannot be broken by repeating the same courses of action over and over.

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[46] I am finishing this writing on the same day that global leaders are meeting at the UN Sustainable Development Summit 2015 to discuss and approve the new Sustainable Development Goals. From reading the proposal for these goals, it appears clear that the limitations of sustainable development discussed in this dissertation are reinforced in the new agenda, which will guide global action for the next fifteen years.

I would like to insert a note of caution on efficiency as the new mainstream global discursive strategy for water management. Efficiency can be defined and measured in different ways (such as technical, productive and allocative) and thus its meaning needs to be made explicit. Augmenting technical efficiency (increasing the ratio net/gross resource use) requires the increment of structural complexity and the reduction of adaptive capacity and resilience. Productive efficiency is a synonym of increasing productivity or getting more end-use per unit of resource (lower intensive ratios of liter or kilogram per capita or kilogram). While this is generally celebrated as an avenue for reducing resource consumption, careful attention should be paid to offsets in overall demand. Increments in productivity lower the prices of the resource, which in turn fosters new uses. The same thing occurs with allocative efficiency, which demands the assignation of resources to the most profitable activity (more €/liter), this generating new expectations that attract new investors. This is the so-called Jevons paradox, which demonstrates that improvements in efficiency lead to an increase in the structural size of the system in the long run and thus in the overall demand for resources. So far, this paradox has not been refuted in the field of water management, although there is an intense ongoing academic debate with regard to the conditions necessary to avoid rebound effects in the improvement of the technical efficiency of irrigation (Sampedro and del Moral 2014, Berbel et al. 2015). In addition, structural trade-offs of augmenting efficiency are not properly taken into account in water planning. Accountability and evaluation mechanisms to ensure that efficiency, in any of its forms, is a conducive strategy to be used for controlling demand and not for contributing to the scarcity loop, are a clear research and management challenge.

A final general reflection is that the dominant techno-managerial vision on how water should be managed continues to seek, or claims to seek, win-win-win solutions to complex environmental problems. It might be wise to start acknowledging that most of the time these ‘solutions’ end up becoming win-lose-lose realities (Scheidel 2013), either among dimensions of sustainability, either among the members of the same hydrological system or from different ones. Critical evaluations of the trade-offs and outcomes of political strategies are essential in order to foster social learning and improve adaptive capacity. I hope to have contributed to this challenge with the case studies presented. Furthermore, I would like to call for a politically wise recognition of the need to open transdisciplinary debates about when enough is enough (Molle, 2006).

To end this section, I will outline the main lessons learned from what in my opinion works in each region that could contribute to the enhancement of management in the other. I think that Arizona water policy has a lot to learn from the European WFD in terms of more ambitious policy goals, a better territorialization of management boundaries that includes all basins, and more environmentally sound management that could help to deal with emerging challenges surrounding groundwater-dependent ecosystems. Setting management goals at the level of water bodies facilitates a better sub-regional understanding of social-ecological patterns and helps to avoid the flaws of basin-pooling accounting devices. Regarding the Andarax basin, the main positive to be taken from Arizona is clearly the significantly greater trust in water managers and decision makers. From my observations of what takes place there, this trust is built on an effective control and monitoring of withdrawals, compulsory water accounting as a basis for evaluation and learning, the exemplary transparency of public agencies, the existence of accountability mechanisms for decision makers, and the much more effective regional public participation. Finally, I think that both policies could benefit from a vision of social-ecological systems to address problem solving in a more integrated, complex and hopefully useful way.

Reflections on the inter and transdisciplinary experiences in this research process

In my view, interdisciplinarity is a pathway that will take many years to be walked. Despite having strived to integrate different analytical frameworks and tools from different research disciplines, it is obvious that I am not an expert in all of them or even in any of them. Having a multi-disciplinary educational background, it is relatively easy for me to understand different scientific narratives and constructions about a reality, and I feel comfortable navigating, translating and finding relationships among them. However, there are times when I clearly lose methodological accuracy and enter into fuzzy areas of eclecticism. Therefore, my aim is to work within truly interdisciplinary teams in which can be found effective avenues for dialogue among different areas of expertise and epistemological backgrounds.

My experience within the group of students in the SWAN project has provided some lessons for future projects regarding the challenges involved in interdisciplinary work, which are not that far removed from those involved in the work of any group of diverse humans trying to achieve objectives collaboratively. First of all, it is important to say that interdisciplinarity within a common framework with explicit analytical rules, like societal metabolism or ecosystem services, is much less challenging than if each of the team members apply a different framework. This is because integrating methodologies is easier than integrating mental constructions and epistemologies from the realism-constructivism continuum. In the case of the SWAN group, each of us was applying its own framework.

In this type of interdisciplinary group, the process of conceptual modeling, and consequently its outcomes, certainly follows different avenues depending on which are the backgrounds sitting at the table and who leads the discussion. Because the group was more weighted towards quantitative approaches, at the beginning we found ourselves more comfortable talking about the integration of variables and models than about power or conflicts, which took longer to be understood. Because each concept meant something different to each of us, discussions about consensual definition could take hours, sometimes with unsatisfactory results. There is a degree of irreducible incommensurability that has to be accepted and, I would say, generously embraced. Indeed, the points of disagreement were those that pushed discussions towards more thoughtful and creative areas.

After four months, we had failed to develop an integrated conceptual framework, basically because of these irreducible epistemological differences. Our decision was then to opt for a common case-study, in which we aimed to generate feedback from the abstract to the empirical and then back to the abstract. The outcomes of that decision will be seen when we complete the process in 2016, but they will surely be different from those we had imagined, because the group has evolved. Academic groups change all the time, with new people coming in and others leaving, and each researcher having individual personal interests and constraints. Therefore setting common goals that require long-term thinking and collaboration can be daunting.

The question of our role as researchers is at the core of the difficulty in moving towards transdisciplinary collaboration with actors outside the academic arena. There is a challenging balance to be found between being consistent with your individual interests and making your results understandable, useful and ready for actual use by stakeholders. Furthermore, there is a clear tension involved in working on real-world problems and using the results to produce cutting edge scientific publications in top ranking journals, because the academic world is to a great extent disconnected from societal needs. Participation processes are complex, difficult to arrange and often frustrating. Proper facilitation is essential in order to ensure leveled participation and deal with micro-political issues. In addition, ethical issues like who will participate and for what reason and purpose should be seriously addressed, acknowledging that participants are not subjects of the study but active members of the process. I would like to add a call for humility in the academic realm when working with people who have their own needs, desires and dreams, the fulfilment of which is not your research objective. Taking these issues seriously when designing research projects requires some pre-funding work, what can be especially challenging in precarious research groups.

Regarding my transdisciplinary experiences in the two case studies, in the Tucson basin interactions with stakeholders were more fruitful than in the Andarax basin because in the former I had a whole research project supporting me from the beginning. In addition, the culture of dialogue and cooperation in the USA is much more intense and extended among practitioners. Stakeholders were more open to attending meetings, discussing questions and giving me feedback on my work there. Spain’s poor deliberative culture hampers a more meaningful collaboration. In general, I experienced difficulties in explaining complex concepts to non-academics and trying to bridge abstract theoretical knowledge and day-to-day problem-solving empirical knowledge. In both case studies, I conducted exercises of quantifying indicators and multi-criteria analysis of sustainability (Appendices 3 and 5). This is something that practitioners on both study sites considered useful to their work. However, the outcomes of these processes were not those expected due to a lack of resources, a lack of experience in facilitation and/or timing constraints. Therefore, very demanding activities did not produce publishable academic results, but they definitely gave me a very thorough perspective on what was happening.

In conclusion, despite the many challenges and flaws of my transdisciplinary endeavors in this research, it has been an extraordinary mind-opening experience that has reinforced my determination to make science useful for the solving of real-life problems. My impression is that I have simply opened small windows onto an immense ocean, and that the long voyage of discovery will require commitment and research funding. Janice Dickinson from the Cornell Ornithology Laboratory asked during the discussion at a SWAN project conference, "By becoming a researcher without a specialty, how do you expect to get a job in the academic market?" I answered that the valuing of inter- and transdisciplinary expertise might provide the only chance we have of coping with environmental problems.

Outlook for future research

Future research on the Water Metabolism of Social-Ecological Systems

The WMSES is a very recent analytical framework that has not yet been sufficiently tested. Being semantically open provides the framework with flexibility and robustness, as well as adaptability to new developments, but at the same time requires an effort for a minimum degree of methodological normalization. There is still a need for coordinated case studies in the future in order to move towards this standardization.

An avenue opened in this dissertation that still needs to be developed significantly is the integration of eco-hydrology into MuSIASEM accounting on a spatially explicit basis. BalanceMed allows the splitting of productive and non-productive soil water (transpiration and evaporation), but does not yet deal with other relevant processes such as erosion or water pollution. Other integrative models, like SWAT or WIMMed, could contribute in this sense. Some questions derived from the modeling explained in Chapter 2 involve the exploration of the following issues: *the combined effect of climate change and drought periods, of the collapse of traditional agricultural production and of land-cover evolution on water funds and aquatic systems; or the impacts on the aquifers and dependent systems of the improvement of irrigation efficiency*. These questions can be approached through scenario building, integrating eco-hydrological forecasting, and MuSIASEM water-energy-land-food nexus assessment.

The integrated spatial analysis of societal and ecosystem metabolic patterns of water is to be further explored. Regarding ecosystems as priority criteria for the establishment of focal analytical holons, I think that water in Europe provides a particularly suitable arena in which to advance in this direction because of the systems for the monitoring of ecological integrity of water bodies. From a problemshed perspective, analysis at lower eco-hydrological levels than the water could be integrated with that of rural systems that has been well developed using MuSIASEM. This type of connection could enable accurate assessments of the desirability, viability and feasibility of metabolic patterns. The connection of metabolic analysis at higher grains to water governance would deal with the challenge of upscaling to the basin level. *Which is the suitable scale for defining accurate social-ecological patterns of water metabolism? How should the spatial relations among social-ecological patterns of water be characterized? How can the analysis of rural systems and of water metabolism be integrated on a spatially explicit basis? How can this analysis be scaled up to generate useful information for water planning?*

Because the WMSES is a complex theoretical framework, there is still a need for the proper operationalization of some fuzzy conceptual areas. One of these areas is the impredicative definition of water resources through the identification of both relevant attributes and the range of useful values for those attributes. As I was working with normative water data, I assumed that those flows were supplied in desirable conditions, and the approach followed was a top-down disaggregation of total water demand for different sectors. However, other forms of normative definition of useful water resources can be explored, for instance through public participation. This would enable a bottom-up definition of water flows that could, for example, be adapted to a more accurate definition of societal functions or societal needs, and then contrasted with official water-planning definitions of flows. *What are the useful characteristics of water according to water users? What is the desirable quality, timing of supply and location of water? How can water flows and their services based on these attributes be defined? What are the desirable flows that current water management does not supply?* Another interesting conceptual area to be explored is the analysis of non-productive societal uses of water funds, which is being developed in studies of cultural ecosystem services. This would facilitate, for instance, a move towards more complex definitions of water productivity that incorporate aesthetic values that are core to the current shift towards service economies in high mountain rural areas. *How can non-consumptive societal uses of water funds be identified, qualified and quantified? Does the ecosystem services framework offer useful* *methodological approaches for this purpose? What is the "value" of water funds?*

Regarding the application of the framework to the assessment of water management strategies, I think that the standardization of methodologies for appraising each typology of strategy (supply augmentation, improvement of efficiencies, growth control, etc.) could enable a better understanding of their interplay when observing outcomes. I think that the MuSIASEM Sudoku-effect could be very useful for building robust frames for an integrated assessment of this interplay that could be tailored to the specificities of policies and regional management and applied to both an anticipatory and an ex-post analysis of trade-offs and outcomes. *Can the Sudoku effect help to dissect the effects of multiple overlaid management strategies?* The ability to answer this question requires the resolution of a prior issue, which is, *How can water accounting in water planning be arranged to allow this assessment?*

Finally, I think that the framework still needs a lot of "translation work" in order to be useful in participatory processes. The heavy conceptual load requires more effective means of communication and the tools for integrated analysis need useful visualizations that are accessible to non-academics. *How can metabolic patterns be visualized in order to facilitate transdisciplinary discussions?* I think that GIS visual tools offer clear advantages in the facilitation of common understanding of environmental problems and thus have a promising future in metabolic studies.

Future research on water governance

Within the SWAN project, the team from the University of Seville opened a new research line around data, information and knowledge for water governance in the networked society that, in my opinion, goes straight to the heart of some important challenges in the field. Some of the research questions that have been raised are the following: *What are the conditions for deliberative mechanisms in water planning necessary to ensure more leveled participation and decision making? Can ICTs play a role in improving the democratic quality of decision making in water resources management?* In addition, progress is required in integrated water information systems, open water-data and visualization platforms. As discussed in this dissertation, transparency in water information is a core issue not only in Spain, but also in many other countries, partly because of the traditional inertia of engineers and water managers who think that water information is too complex to be understood by non-technicians. This era of "the guardians of the truth" is over, and water administration bodies are slowly moving towards more open information standards. Citizens' organizations play a key role in controlling the quality of the information used for making decisions and evaluating their outcomes. Improving the quality and accessibility to data can galvanize progress towards an integrated assessment of water governance.

The emerging practices of citizen science are very promising for a push in this direction, through collaborative scientific projects involving practitioners, stakeholders, communities, activists or the general public. The effective inclusion of non-academics in the research process is not only creating unprecedented opportunities for the scaling up of research by, for example, facilitating the application of big-data analysis techniques, but is also opening new avenues for transdisciplinary dialogue and external quality control of the research process. *How can citizen science help to bridge science-policy gaps in water governance?*

Regarding discourse analysis, I am aware that the methodology I used in this research was not the most rigorous considering the recent developments in specific software like Atlas.ti and Envivo, and that great improvements can be made in this sense. A particular research pathway that I would like to explore in near future is the analysis of the use of social media in environmental conflicts or activist campaigns, through a combination of quantitative network analysis and discourse analysis. I am already involved in a collaborative research project that aims to answer the question *What kind of social capital do social networks reinforce?*

Finally, there are two important black boxes in this dissertation that I hope to open in the future: institutions and power. Even if they were mentioned and recognized as essential for the shaping of social-ecological relations, I specifically addressed neither institutional arrangements nor power relations, partly because I lack the educational background to do so. I think that a huge challenge, not only in water governance but also in most public realms right now, is the effective scaling up of citizen participation. Because participation usually works at local levels around common resource management, but ICTs and the Internet have opened up opportunities for improving democratic management and decision making at all levels, the following questions are yet to be responded: *What kinds of institutional arrangements can make bottom-up participation effective and improve the legitimacy of water management decisions? How could an open multi-scale social-ecological governance system be envisaged? Could such a system help to overcome current post-political regimes or would it instead reinforce them?*

CONCLUSIONES

Resumen de contribuciones conceptuales y metodológicas

Esta tesis ofrece una perspectiva de sistemas complejos sobre la gestión del agua a través de la operacionalización del marco de análisis WMSES (Madrid 2014, Madrid and Giampietro 2015) para la evaluación integrada de políticas del agua a escala de cuenca. Este marco se basa en el concepto de sistema socio-ecológico, o sistema socio-hidrológico, así como en una definición de usos del agua que responde a los retos epistemológicos de la complejidad como son la existencia de múltiples percepciones sobre la naturaleza, la organización multi-escalar de los sistemas vivos o la causalidad circular como el principal tipo de relación que mantiene dicha organización. Para abordar el objetivo de investigación se introducen dos avances conceptuales relevantes en este marco, así como varias contribuciones metodológicas asociadas.

En primer lugar, esta es la primera implementación de este marco teórico a la escala de cuencas hidrográficas, ya sean superficiales o subterráneas, que son representadas como sistemas socio-ecológicos abiertos, holárquicos y autopoiéticos. Esta representación de la cuenca como sistema socio-ecológico es una propuesta conceptual clave en esta tesis, que requiere la combinación de diferentes áreas de conocimiento y herramientas de análisis tales como la geografía humana, la economía ecológica, la eco-hidrología o el análisis institucional. De esta forma espero contribuir a las nuevas corrientes interdisciplinares en investigación del agua.

En esta tesis he avanzado esta integración metodológica ligando el análisis del metabolismo social y ecosistémico del agua de manera espacialmente explícita, a través del uso de SIGs para la integración de un modelo eco-hidrológico en el sistema de contabilidad de flujos y fondos de MuSIASEM. De esta forma pude operacionalizar el marco conceptual del metabolismo hídrico, formalizando relaciones cuantitativas en las interfaces sociedades-ecosistemas, así como entre sus respectivas estructuras y la demanda y provisión de agua. Para el objetivo y escala de análisis de esta tesis, se propone una aproximación al metabolismo hídrico de los ecosistemas a través del análisis de los procesos eco-hidrológicos que determinan la provisión de recursos hídricos, los impactos causados sobre la salud de los ecosistemas, y los conceptos frontera de disponibilidad del agua y requerimientos hídricos de los ecosistemas. Esta operacionalización permite analizar la retroalimentación entre 'provisión de agua -> usos/vertidos -> impactos sobre los ecosistemas -> impactos sobre la provisión'. Caracterizando estos links se pueden describir patrones socio-ecológicos de metabolismo hídrico en sistemas hidro-sociales, los cuales se pueden definir a través de diferentes criterios que combinen la 'cuenca del agua' con la 'cuenca de problemas'. Los criterios para definir los límites y niveles analíticos del sistema tienen que hacerse explícitos, así como las incompatibilidades resultantes entre diferentes tipologías de límites de gestión y las consecuentes pérdidas de información relevante asociadas a estas decisiones pre-analíticas. La planificación hidrológica en los dos casos de estudio de esta tesis carece de esta visión integrada puesto que solamente aplican criterios hidrológicos para delimitar las unidades de gestión. La Instrucción Española de Planificación Hidrológica prevé la posibilidad de incorporar otros criterios además de los hidrogeológicos, lo cual se ha aplicado ya para subdividir las masas de agua subterránea en algunas cuencas españolas.

En el caso de estudio de la cuenca de Tucson, combiné el análisis del metabolismo hídrico con el análisis espacial de la gestión del agua subterránea (localización de fuentes, usuarios, almacenamiento de agua subterránea e impacto sobre niveles de acuíferos y ecosistemas de rivera dependientes). Esta combinación es particularmente útil para entender cómo se despliega geográficamente el funcionamiento metabólico del sistema y moldea diferentes vulnerabilidades e inequidad espacial.

También he avanzado la integración de las técnicas de SIG en MuSIASEM a través del diseño de un modelo conceptual para la estructuración y gestión de datos para el análisis del metabolismo hídrico. Este modelo lo he aplicado después a dos modelos lógicos adaptados a las particularidades de cada caso de estudio, implementados a su vez en varias bases de datos geográficas con formatos abiertos con el objetivo de contribuir a la transparencia y reproducibilidad de esta investigación.

En segundo lugar, esta es la primera aplicación del marco teórico del metabolismo hídrico para la evaluación de resultados de la planificación hidrológica. MuSIASEM se ha aplicado comúnmente para acompañar un proceso de decisión entre diferentes alternativas de gestión, evaluando la sostenibilidad de posibles escenarios. Sin embargo, análisis de cómo han influido las decisiones políticas en la evolución de patrones metabólicos no son tan abundantes. El concepto de holon es especialmente útil en este sentido, pues introduce la idea de propiedades emergentes como resultado de las interacciones entre las partes del sistema en niveles inferiores, que no se puede predecir por mera agregación de las mismas, y de las condiciones de contorno impuestas por niveles superiores. De esta forma, la cuestión relevante es cuáles son las interacciones entre holons que conducen a los patrones metabólicos observados y los retos de gestión del agua asociados a dichos patrones. Además, la conceptualización de un holon como algo dual que es a la vez material, dominado por leyes físicas, y construido y narrado a través de la creación de significado, facilita ligar el análisis biofísico cuantitativo y el análisis cualitativo de políticas del agua. Siguiendo los marcos de análisis de sistemas socio-ecológicos que abordan retroalimentaciones entre sistemas sociales y ecológicos, la principal contribución conceptual de esta disertación es ese puente entre el metabolismo hídrico y la gobernanza del agua.

A nivel conceptual, esta conexión se materializa a través de: i) un nuevo eje en la representación holárquica de los socio-ecosistemas referido a la ‘cuenca de información’, esto es, a las políticas y regulaciones que actúan como motor de cambio metabólico y median las relaciones entre holons sociales y eco-hidrológicos; ii) la formalización de este eje en el marco de análisis general como un área en la interfaz sociedades/ecosistemas; iii) una discusión sobre la disponibilidad del agua como una categoría frontera normativa que depende a la vez de factores infraestructurales, técnicos, socio-culturales y eco-hidrológicos, y cuyo cálculo tiene que hacerse explícito reconociendo las asunciones que hay en el mismo; iv) el concepto de proceso semiótico y cierre semántico del ciclo de gestión del agua (Allen y Giampietro 2014, Diaz-Maurin y Kovacic 2015), integrando a su vez los conceptos de cierre del problema, acomodación social y cierre discursivo de Hajer (1995). Estos conceptos plantean cuestiones que a su vez las aplico para operacionalizar lo criterios de evaluación de políticas públicas de eficacia, eficiencia y pertinencia.

A nivel metodológico, esta conexión se operacionaliza a través de la integración de herramientas de análisis cuantitativo y cualitativo. Los análisis cuantitativos se han estructurado a través del desarrollo de gramáticas específicas para los objetivos de análisis de cada caso de estudio. Éstas se han formalizado con distintos modelos y fuentes estadísticas de datos y representadas para el análisis integrado de patrones metabólicos en dendrogramas, gráficos de araña y una visualización en árbol tipo Icicle. Este análisis integrado permite profundizar en los factores socio-económicos que condicionan la transformación del metabolismo hídrico, así como en el impacto biofísico de la implementación de políticas públicas y en los costes asociados a las decisiones de gestión. Con este último objetivo, el Capítulo 3 aborda un ejercicio que compara los escenarios de la planificación hidrológica con otros escenarios alternativos establecidos en base a decisiones diferentes que están sesgadas respecto a lo que pretendía mostrar. Idealmente este tipo de decisiones tendrían que tomarlas actores sociales en procesos participativos.

El análisis del discurso ha sido una herramienta fundamental para entender la diversidad de percepciones sobre gestión del agua y los discursos dominantes que permean las decisiones, permitiendo abordar la cuestión del “cómo y por qué” de los patrones de uso del agua. Esta cuestión complementa otras que se abordan normalmente en MuSIASEM: “qué es el sistema” y “qué hace el sistema”. La producción y evolución de paisajes hidro-sociales está repleta de una gran variedad de actores sociales, enfrentados entre ellos y con conflictos y disputas cambiantes más o menos afilados. Las configuraciones de flujos y fondos están invariablemente filtradas por los sueños y fantasías sociales que son gestionados políticamente o re-imaginados a través de regímenes de gobernanza en constante evolución. La diversidad de atributos cambiantes del agua, junto con sus usos contenciosos, demandas e imaginarios a su alrededor están siempre mediados por instituciones y redes políticas, que incluyen aquellos a través de los cuales se organiza el acceso y la propiedad de los recursos y las herramientas para su distribución.

Finalmente, con respecto al marco de la ciencia post-normal en el que MuSIASEM se sitúa, y más extensamente a las prácticas transdisciplinares, he realizado un esfuerzo en colaborar con actores locales en los dos casos de estudio, dentro de mis límites de tiempo y recursos. Más adelante incluyo algunas reflexiones sobre estas experiencias. Espero que el marco propuesto pueda contribuir a minorar algunas de las brechas que existen hoy día entre la ciencia y la política, como la necesidad de análisis multi-escalares, que busquen la colaboración con gestores y que abran el conocimiento científico más allá del ámbito académico (Jarvis et al. 2015).

Conclusiones sobre los retos en la gobernanza del agua en los casos de estudio

Esta tesis realiza un seguimiento a la implementación de objetivos de sostenibilidad en políticas de agua en dos cuencas en España y Arizona. Ambas áreas comparten un clima semi-árido, modelos económicos en torno al sol que generan presiones agudas sobre las masas de agua, y modelos de gobernanza tecno-gerenciales. Además, ambas cuencas comparten situaciones de sobreexplotación de recursos hídricos que han conducido a la degradación de los acuíferos como problema fundamental al que la política de aguas y las estrategias de gestión intentan responder. Otra característica común en ambas regiones es una cultura ideológica de paradigma o misión hidráulica (Sauri y del Moral 2001, Molle 2006), anclada durante más de un siglo por firmes comunidades epistémicas abanderando expresiones de tipo “ninguna gota de río perdida en el mar”, y con grandes infraestructuras hidráulicas como única solución a una escasez de agua en continuo aumento.

A pesar de estas características similares, las políticas de aguas que regulan la gestión en ambos casos de estudio son muy diferentes, en parte porque entre ambas hubo una importante evolución en los paradigmas de gestión dominante hacia la Gestión Integrada de Recursos Hídricos. El Acta de Gestión del Agua Subterránea en Arizona se aprobó en 1980 en respuesta a la sobreexplotación de acuíferos en décadas anteriores. El Acta estableció el ámbito de la gestión en torno a los límites de acuíferos en las zonas más pobladas y un objetivo de gestión para cada una de ellas. En la cuenca de Tucson, el objetivo es alcanzar la extracción segura para el año 2025, calculada como la suma cero entre flujos entrantes y salientes de la cuenca entera entendida como una caja negra. Esto difiere sustancialmente de la Directiva Marco del Agua en Europa aprobada en el año 2000, que se enfoca en la calidad de los ecosistemas acuáticos. La directiva abraza los principios de la gestión integrada de los recursos hídricos (GIRH) como son la cuenca hidrográfica como unidad de gestión, los criterios económicos como prioritarios para la toma de decisiones y la participación pública en el proceso de planificación. Los objetivos de gestión se establecen para cada masa de agua superficial y subterránea de manera similar: como horizontes de recuperación del estado de la masas de agua a unas supuestas buenas condiciones de referencia (Bouleau and Pont 2015).

La gestión del agua en la cuenca del Andarax se encuentra en una cierta situación de bloqueo institucional que responde a varios factores tanto externos como internos entrelazados a diferentes escalas. En lo que se refiere a los factores externos, las continuas negociaciones a nivel europeo entre múltiples intereses enfrentados en producción agraria, desarrollo rural y conservación de ecosistemas se enmarcan en el discurso inclusivo del desarrollo sostenible. Esto se refleja en la retórica gana-gana-gana de los objetivos políticos que ligan la equidad social y la calidad ecológica al crecimiento económico. Sin embargo, los discursos en agricultura están sesgados hacia la función de mercado de la misma, mientras que en agua lo están hacia la integridad de los ecosistemas. A nivel nacional, los principios de la Directiva Marco encontraron una inercia institucional antigua, gestionada por fuertes coaliciones entre el gobierno central, las Confederaciones Hidrográficas, grandes grupos de presión de intereses agrícolas e hidroeléctricos y empresas de ingeniería y construcción, enfocados casi exclusivamente en la regulación superficial y las transferencias entre cuencas. Como era de esperar, estas coaliciones han puesto resistencias para adaptarse al nuevo marco regulador y en muchos casos han limitado las posibilidades de cambiar las prioridades de gestión. A nivel regional, se llevaron a cabo esfuerzos significativos en una trasposición de la normativa Europea rigurosa y en la integración dentro de las políticas agrarias. Sin embargo, esta integración se ha promovido a través de puentes estratégicos gana-gana entre agendas políticas, basados fundamentalmente en intervenciones tecnológicas para generar recursos adicionales. Además, la implementación de estas agendas se ven sometidas a infracciones continuas de las normas, en una atmósfera no incidental sino más bien estructural de desviación o incumplimiento de leyes (Sampedro and del Moral 2014), con una administración del agua notablemente debilitada e inestable, tanto en presupuesto como en capacidad de decisión.

En lo que se refiere a los factores internos, la cuenca del río Andarax es un genuino y complejo sistema socio-ecológico debido a su espectacular diversidad biofísica, cultural e institucional, la cual se observa en una variedad de paisajes hidro-sociales en evolución. La agricultura es el principal sector consumidor de agua con diferentes patrones metabólicos coexistiendo con, y a veces compitiendo por, masas de agua en diferentes situaciones de impacto. Desde zonas rurales de alta montaña con agricultura de baja productividad adaptada al metabolismo hídrico de sus ecosistemas, a cultivos intensivos en invernaderos tecnológicamente sostenidos y al monocultivo de olivar intensivo alimentado con stocks de aguas subterráneas no renovables. La ciudad de Almería es también un actor importante en el metabolismo hídrico de la cuenca, no sólo como consumidor y productor de recursos hídricos, sino también a través de las relaciones rural-urbano que influencian la transición socio-ecológica en áreas rurales hacia el sector servicios. La degradación de las masas de agua responde al entrecruzamiento de varias causas directas como el exceso de extracciones en períodos de verano o los vertidos de aguas residuales no tratadas, pero también a procesos estructurales de largo recorrido como el abandono agrícola y la erosión, una planificación territorial bastante laxa, la ausencia de monitorización y control sobre las extracciones que se añaden a la gran incertidumbre asociada a la alteración de los acuíferos y sistemas dependientes.

Los retos que plantean los objetivos ambientales de la Directiva están relacionados con la imposibilidad de reducir las presiones e impactos sobre las masas de agua sin reducir las extracciones y los vertidos. Esto requeriría una reasignación de usos del suelo y concesiones de agua, integrando la gestión hidrológica y territorial en una planificación integrada y, especialmente, una monitorización efectiva de las presiones existentes y transparencia en las decisiones. En otras palabras, estos retos requieren una reconfiguración del balance de poder entre usuarios del agua y entre secciones de la administración regional. Lejos de enfrentarlos, las decisiones regionales apostaron por un ajuste tecno-social entre objetivos ambientales y atención a nuevas demandas agrícolas a través de: i) la restricción de la expansión del regadío al techo impuesto por lo que estaba catalogado como tierra irrigable; ii) el aumento de la eficiencia de riego; y iii) aumentar la desalinización y la reutilización. La inversión infraestructural necesaria fue subvencionada con fondos europeos canalizados a través de diversos programas nacionales y regionales.

Detrás de estas decisiones se encuentra un discurso dominante que combina justificaciones y diagnóstico de problemas de ecología profunda, con argumentos ambiguos de eficiencia de la GIRH sesgados hacia el incremento de la oferta, y con declaraciones tradicionales de gestión de la oferta a través de infraestructuras para resolver el “déficit estructural”. Narrativas alternativas desvelan percepciones en torno a la sostenibilidad socio-ecológica de la comunidad rural, propuestas eco-integradoras para reorientar el modelo económico, así como afirmaciones críticas sobre el funcionamiento político e institucional de la administración hídrica. Estas percepciones o bien son acomodadas a través de los mencionados ajustes tecno-sociales (desalinización, riego por goteo), favoreciendo coaliciones entre narrativas antagonistas, o son directamente ignoradas y catalogadas como “fuera del ámbito de la gestión del agua”.

Las estrategias elegidas implican costes importantes que no han sido contemplados durante el proceso de planificación. En primer lugar, la contabilidad del agua en los escenarios anticipaba un efecto rebote sobre en el uso del agua en la agricultura, a la vez que los caudales ambientales quedaban desatendidos. Esto está relacionado con el hecho de que el aumento de la eficiencia se considera una medida de incremento de la oferta y no de control de la demanda en la planificación hidrológica andaluza. En segundo lugar, la introducción de la desalinización para la agricultura conlleva una intensificación importante en el coste energético del abastecimiento de agua, y por tanto en el monetario. Esto no ha sido considerado en el análisis económico del plan, ni negociado con los agricultores que debían pagar por los costes de la misma. El problema del agua se resuelve simplemente empeorando el problema de la energía. En tercer lugar, la instalación del riego por goteo plantea una alteración de patrones socio-ecológicos bien integrados en zonas rurales. Los sistemas de irrigación por manta en zonas semi-áridas han supuesto buffers de adaptación en períodos de sequía a través del aumento de la eficiencia. Las pérdidas por baja eficiencia son retornos al sistema que benefician a terceras partes cuando surgen por manantiales a menor cota. Por lo tanto, su reducción puede conllevar impactos ecológicos y sociales que deberían ser analizados con detenimiento. Estas comunidades enfatizan los costes potenciales de desfasar las prácticas e instituciones locales tradicionales, ampliando el debate sobre los problemas del agua desde la ampliación de los flujos a los factores estructurales de cambio metabólico como el envejecimiento de la población, el éxodo rural y la desertificación del paisaje. La larga evolución socio-ecológica del metabolismo hídrico en estas áreas reta al objetivo de integridad ecológica de la Directiva Marco del Agua.

Al final del primer ciclo de gestión (2015), los resultados obtenidos a través de las mencionadas estrategias han sido bastante coste-inefectivos en el nuevo contexto de austeridad financiera, desmontando las asunciones sobre las que el plan fue diseñado. La recesión a partir del año 2010 estancó el crecimiento económico y las grandes intervenciones. Sin embargo, el progreso hacia los objetivos ambientales ha sido prácticamente inexistente puesto que el plan apenas se ha implementado. Por otra parte, existe un problema patente de insuficiente información, transparencia y justificación de las decisiones tomadas, además de comunicación poco efectiva, que se ha dejado de lado durante el ciclo de planificación. Como resultado, han emergido resistencias locales a aplicar las medidas y promover la cooperación entre grupos sociales, además de una generalizada falta de confianza hacia la administración del agua que es considerada incapaz de resolver los problemas.

La cuenca de Tucson ha atravesado ya tres ciclos de gestión con resultados mucho más significativos de la implementación de Ley de Gestión del Agua Subterránea. Los principales mecanismos de gestión no están muy lejos de los del Andarax: aumentar la oferta, mejorar la eficiencia y no expandir el regadío. Sin embargo, el despliegue de estas estrategias se ha realizado de forma notablemente diferente, fundamentalmente porque ha existido una voluntad real de control de la demanda a través de la limitación del crecimiento y de prácticas de conservación, así como del uso de los nuevos recursos para acabar con la sobreexplotación de los acuíferos. Un notable esfuerzo por integrar la gestión del agua y la ordenación del territorio fue la subordinación de la construcción de nuevas urbanizaciones a la demostración de cien años de abastecimiento de agua asegurado. Además, la obligatoriedad de reportar las extracciones y consumos anuales genera una información muy valiosa para la planificación y evaluación del progreso hacia los objetivos políticos.

Desde el año 2000 se observa una tendencia decreciente en la tasa de sobreexplotación anual que está aproximándose a cero. La alianza efectiva entre la construcción del CAP y el sistema de recarga, almacenamiento y recuperación de los nuevos recursos supuso un claro punto de inflexión que provocó una reconfiguración drástica del metabolismo hídrico con una batería de nuevas fuentes de agua. Esta inversión infraestructural fue acompañada por una serie de nuevas regulaciones, instituciones y programas de cooperación ente los múltiples nodos de una red de gobernanza descentralizada.

El sector municipal ha sido el más adaptativo en la reducción de la sobreexplotación sustituyendo más de la mitad de su consumo de agua subterránea por agua recuperada del CAP y estabilizando su demanda a través de esfuerzos en conservación por habitante. Sin embargo, sería oportuno comprender en profundidad cuál es el efecto del estancamiento del desarrollo urbano sobre dicha estabilización y cuáles son los impactos potenciales de su reactivación en los próximos años. Las perspectivas de crecimiento por parte de este sector no han cambiado, simplemente se han pospuesto a los próximos años. El sector agrario es el que condiciona la variabilidad interanual en la demanda y la sobreexplotación, en función de la variabilidad climática y la deriva de los mercados. La sustitución parcial del bombeo por agua del CAP es la más vulnerable a un episodio de sequía en el Colorado. Una cuestión que requiere más atención es el papel de estos sistemas agrícolas tanto para las economías locales como dentro del metabolismo social de Estados Unidos. Las Naciones Indias son un actor cada vez más importante en el balance de agua y su papel dentro del mercado de créditos de agua es otro tema a analizar. Finalmente, las minas están causando impactos locales sobre los acuíferos importantes cuyos efectos cualitativos a largo plazo no se conocen.

El sistema de contabilidad del agua de tipo caja negra corre un velo sobre la distribución desigual del alcance técnico de la extracción segura del acuífero. La desconexión espacial entre la recarga y la recuperación queda difuminada bajo la etiqueta de CAP-recuperada, categoría que es eliminada de la ecuación de cálculo de la sobreexplotación. Esta neutralidad espacial de la gestión del agua subterránea permite al Departamento de Recursos Hídricos de Arizona contar con cierta flexibilidad para negociar con los actores regionales, pero también pasar por alto el debate sobre inequidad respecto a la situación privilegiada de las grandes minas y de los promotores y constructores urbanos que pueden seguir sobreexplotando los acuíferos en cualquier punto de la cuenca. La regionalización espacial del balance hídrico en varias sub-áreas de contabilidad debería permitir una mejor evaluación de la vulnerabilidad socio-ecológica asociada a la bajada continua del nivel freático. Sin embargo, es importante resaltar que esta inequidad espacial es precisamente el argumento central utilizado por las empresas de agua urbana para incrementar aún más la complejidad infraestructural en la cuenca durante los próximos años.

Aparte de la premisa aceptada de que el agua del Río Colorado es un recurso renovable, no es fácil señalar un discurso dominante en la cuenca de Tucson puesto que la descentralización en la toma de decisiones hace que las relaciones de poder estén algo más niveladas que en el Andarax. Sin embargo, narrativas claramente polarizadas reflejan percepciones contrastantes respecto al modelo económico basado en el crecimiento urbano. Desde los promotores defendiendo el argumento del GIRH de eficiencia económica en la asignación de recursos, hasta denuncias contundentes del crecimiento como dañino para la calidad de vida de los habitantes de la cuenca y la resiliencia regional. Las empresas de abastecimiento urbano son actores estratégicos en esta red, defendiendo que la gestión se base en la racionalidad y experiencia técnica. A la luz del cuarto ciclo de gestión 2010-2020, estás narrativas divergentes fueron acomodadas a través de varios acuerdos de cooperación, intensos procesos participativos y objetivos políticos amplios consensuados, con agua para el presente y para el futuro, para la economía y para el medioambiente. Sin embargo, la recesión económica también impactó de manera significativa al presupuesto y los recursos de la administración del agua en Arizona, y el cuarto plan de gestión acumula cinco años de retraso y retos crecientes para alcanzar una extracción segura en la próxima década que sea espacialmente equitativa, ecológicamente sostenible y perdurable en el tiempo.

Como la mayoría de los regímenes de gobernanza ambiental, la gestión del agua en ambos casos de estudio refleja el discurso de la modernización ecológica del desarrollo sostenible. Sin embargo, en la práctica, el alcance de los principios de la GIRH ha sido bastante incipiente o parcial. Una razón de esto es la disputa con los valores, instituciones y coaliciones preexistentes. Otro motivo es el doble filo de la ambigüedad del concepto de integración como estrategia discursiva que provoca coaliciones narrativas entre significados antagonistas. Pero quizás la principal razón subyacente sean los límites de la imposibilidad real de pensar más allá del crecimiento económico como el último objetivo político de nuestro tiempo. Esto es, los límites del desarrollo sostenible como la gran narrativa global para guiar la acción política capaz de resolver los restos de la humanidad[47]. Las dos cuencas estudiadas se encuentran en una situación de sobre-construcción o escasez social. Estos conceptos hacen referencia al establecimiento de un círculo de retroalimentación positiva en el que la sobreexplotación de recursos genera impactos socio-ecológicos que se solucionan con más infraestructuras que alimentan el crecimiento y la demanda, generando a su vez nueva escasez (Molle 2006). Este círculo vicioso de la escasez artificial es lo que el gobierno andaluz llama “déficit estructural”, algo que no se puede arreglar repitiendo las mismas acciones una y otra vez.

Me gustaría añadir una nota de cautela sobre la eficiencia como la nueva estrategia discursiva global para la gestión del agua. La eficiencia se define y calcula de diferentes maneras (eficiencia técnica, productiva, de asignación) y esto hay que hacerlo explícito. El aumento de la eficiencia técnica del riego o el abastecimiento (aumentando el ratio de uso neto respecto al bruto) requiere aumentar la complejidad infraestructural, reduciendo la capacidad adaptativa y la resiliencia. La eficiencia productiva es un sinónimo del aumento de la productividad o abastecer a más usuarios por unidad de recurso (menores ratios de uso per cápita o kilo). Si bien esto es generalmente celebrado como una forma de reducir el consumo de recursos, debería prestarse más atención a la compensación de ahorros con nuevas demandas. Los aumentos de productividad provocan una bajada de precios del recurso que a su vez atrae a nuevos inversores. Lo mismo ocurre con la eficiencia en la asignación que pide que los recursos se adjudiquen a las actividades económicamente más beneficiosas (más € por litro), lo que genera nuevas expectativas que alimentan la expansión de dichas actividades. Esto es lo que explica la famosa paradoja de Jevons: las mejoras en la eficiencia conducen a largo plazo al aumento del tamaño estructural del sistema y por lo tanto al incremento de la demanda total. Hasta el momento, esta paradoja no ha sido rebatida en gestión del agua aunque existe un intenso debate académico respecto a las condiciones para evitar el efecto rebote en el aumento de la eficiencia del regadío (Sampedro y del Moral 2014, Berbel et al. 2015). Además,

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[47] Estoy terminando de escribir esta tesis justo el mismo día que los líderes del mundo se reúnen en la Conferencia de Desarrollo Sostenible de Naciones Unidas de 2015 para aprobar los nuevos Objetivos de Desarrollo Sostenible. Leyendo la propuesta que hay sobre la mesa, parece que los límites que he discutido son reforzados en la nueva agenda que guiará la acción de desarrollo global en los próximos quince años.

los costes estructurales asociados al aumento de la eficiencia que no se consideran en la planificación. En definitiva, un claro reto actual tanto de investigación como de gestión es el desarrollo de mecanismos de contabilidad, evaluación y rendición de cuentas para asegurar que la eficiencia, en cualquiera de sus formas, sea una estrategia eficaz para el propósito de controlar la demanda y no para contribuir al círculo vicioso de la escasez.

Una reflexión general final es que la visión dominante tecnocrática de la gestión del agua continúa buscando, o pretendiendo buscar, soluciones gana-gana-gana a problemas ambientales complejos. Puede que sea razonable empezar a reconocer que la mayoría de las veces éstas terminan siendo realidades gana-pierde-pierde (Scheidel 2013), ya sea entre dimensiones de la sostenibilidad, o entre los miembros de un mismo sistema hidrológico, o de diferentes sistemas. Evaluaciones críticas de los costes y resultados de estrategias políticas son fundamentales para aprender y mejorar la capacidad adaptativa. Es más, reclamaría un sabio reconocimiento político de la necesidad de abrir debates transdisciplinares sobre cuándo suficiente es suficiente (Molle 2006).

Para terminar esta sección, me gustaría proponer las principales lecciones de lo que, en mi opinión, funciona en cada región estudiada que podría contribuir a mejorar la gestión en la otra. Creo que la política de agua en Arizona puede aprender de la Directiva Marco Europea en lo que se refiere a objetivos políticos más ambiciosos, una mejor demarcación de las unidades de gestión incluyendo todo el territorio y una gestión ambientalmente más racional que podría ayudar a abordar retos emergentes sobre los ecosistemas dependientes del agua subterránea. Establecer los objetivos de gestión a la escala de masa de agua permite una mejor caracterización subregional de patrones socio-ecológicos y escapar del reduccionismo de la contabilidad de caja negra. En lo que respecta al Andarax, el principal aprendizaje es la drástica diferencia en la confianza hacia los gestores y tomadores de decisiones. Por mis observaciones allí, esta confianza se ha construido sobre un control y monitorización efectivos de las extracciones, una contabilidad real obligatoria como base para evaluar y planificar, una transparencia ejemplar de las agencias públicas, la existencia de mecanismos de rendición de cuenta para los tomadores de decisiones, y una participación pública mucho más efectiva. Finalmente, creo que ambas políticas de agua podrían beneficiarse de una visión socio-ecológica integrada que contribuiría a diagnosticar y resolver problemas de una forma más compleja y espero que útil.

Reflexiones sobre las experiencias inter y transdisciplinares de esta investigación

La interdisciplinariedad, en mi opinión, es un camino en curso que tardaremos muchos años en recorrer. A pesar de mis esfuerzos por integrar marcos y herramientas analíticas provenientes de distintas disciplinas científicas, es obvio que no soy experta en todas ellas, o incluso en ninguna de ellas. Teniendo una formación multi-disciplinar, me resulta relativamente sencillo entender diferentes narrativas científicas y sus construcciones sobre una misma realidad, y me encuentro cómoda navegándolas, traduciéndolas y encontrando relaciones entre ellas. Sin embargo, también pierdo rigor metodológico y entro en pantanosas áreas de eclecticismo. Mi objetivo es formar parte de equipos interdisciplinares en los que poder encontrar vías para el diálogo efectivo entre áreas de conocimiento y posiciones epistemológicas.

Mi experiencia dentro del grupo de estudiantes del proyecto SWAN me ha permitido aprender algunas lecciones para el futuro con respecto a los retos del trabajo interdisciplinar, que no están muy lejos de los que enfrentan cualquier grupo diverso de humanos que intentan trabajar de manera colaborativa. Antes de nada merece la pena enfatizar que trabajar en grupos interdisciplinares con un marco de análisis común, como el metabolismo social o los servicios ecosistémicos, es mucho menos complicado que si cada miembro del grupo aplica su propio marco. Esto se debe a que integrar metodologías es mucho más fácil que integrar construcciones mentales y epistemologías en el continuo realismo-constructivismo. Este segundo caso más complejo era precisamente el del grupo SWAN.

En este tipo de grupo interdisciplinar, el proceso de modelado conceptual, y por lo tanto sus resultados, obviamente seguirá diferentes caminos en función de cuáles son las disciplinas sentadas en la mesa y de quién lidere la discusión. Puesto que el peso del grupo estaba más en las aproximaciones cuantitativas, al principio nos encontramos más cómodos hablando de integración de variables y modelos que de poder o conflictos, los cuales tardaron más en ser entendidos. Puesto que los conceptos tenían significados diferentes para cada uno de nosotros, las discusiones sobre definiciones de consenso podían llevar horas, a veces sin demasiado éxito. Existe una inconmensurabilidad irreducible que tiene que ser asumida y, añadiría, abrazada de forma generosa. De hecho, los puntos de desacuerdo eran precisamente aquellos que empujaban las discusiones a llegar a mayor profundidad y creatividad.

Después de cuatro meses de reuniones, no habíamos sido capaces de elaborar un marco conceptual integrado, básicamente debido a estas diferencias epistemológicas irreductibles. Nuestra decisión entonces fue optar por un caso de estudio común en el que intentar generar una retroalimentación de lo abstracto a lo empírico y después retorno a lo abstracto. Los resultados de aquella decisión están aún por llegar cuando completemos el proceso en 2016, pero seguramente serán diferentes a lo que habíamos imaginado pues el grupo ha evolucionado. Los grupos de investigación cambian continuamente, con nuevas personas incorporándose y otras marchándose, y con ellas sus intereses y limitaciones personales. Establecer objetivos comunes que requieren pensamiento colectivo y colaboración a largo plazo puede resultar una tarea muy complicada.

La pregunta sobre cuál es nuestro papel como investigadores es una de las claves que subyacen a la dificultad en avanzar hacia colaboraciones transdisciplinares con actores fuera de la academia. El balance entre ser coherente con tus intereses individuales y hacer que tus resultados sean inteligibles, útiles y utilizados por grupos o actores sociales es delicado. Es más, existe una clara tensión entre trabajar de manera orientada a problemas y producir artículos científicos punteros en revistas de alto impacto porque el mundo académico está en su mayoría bastante desconectado de las necesidades sociales. Los procesos participativos son complejos, difíciles de organizar y muchas veces frustrantes. La facilitación es esencial para asegurar una participación equilibrada y lidiar con los temas micro-políticos. Además, hay que tener muy en cuenta cuestiones éticas en cuanto a participación de quién y con qué propósito, reconociendo que los participantes no son sujetos de estudio sino miembros activos del proceso científico. Me gustaría añadir una llamada a la humildad en el ámbito académico cuando trabajamos con personas que tienen sus necesidades, deseos y sueños, cuyo cumplimiento no es el objetivo de nuestra investigación. Tomarse estas cuestiones seriamente cuando diseñamos un proyecto de investigación requiere hacer trabajo previo a la obtención de fondos, lo es difícil sobre todo en grupos de investigación precarios.

En cuanto a mis experiencias transdiciplinares en los dos casos de estudio, en la cuenca de Tucson la interacción con actores fue mucho más fructífera que en el Andarax porque tenía un proyecto de investigación que me apoyaba desde el principio. Además, la cultura de diálogo y cooperación en Estados Unidos es mucho más intensa y está más extendida entre los gestores públicos, los cuales estuvieron muy abiertos a venir a reuniones, discutir nuestras preguntas y darme opiniones y sugerencias sobre mi trabajo allí. La pobre tradición deliberativa de España dificulta claramente una colaboración más provechosa entre investigadores y gestores. Por mi parte encontré grandes dificultades en traducir conceptos complejos a personas que trabajan fuera del ámbito académico y en intentar conectar el conocimiento teórico abstracto con el empírico de la resolución diaria de problemas. En ambos casos realicé ejercicios de cuantificación de indicadores y análisis multi-criterio de la sostenibilidad (Apéndice 3 y 5). Esto es algo que los gestores en las dos áreas encontraron útil para su trabajo. Sin embargo, los resultados de dichos ejercicios no fueron los esperados debido a la falta de recursos, de experiencia en facilitación o a limitaciones de tiempo. Por lo tanto, actividades que requirieron mucho trabajo no produjeron resultados académicos publicables, aunque sí me facilitaron una perspectiva mucho más profunda de la gestión del agua en ambas regiones.

En conclusión, a pesar de los múltiples retos y errores cometidos en mis intentos transdisciplinares durante el desarrollo de esta tesis, han sido experiencias de apertura mental extraordinarias que han reforzado aún más mi determinación en hacer del conocimiento científico algo útil para problemas reales. Mi impresión es que apenas he abierto pequeñas ventanas a un inmenso océano y que el largo viaje de navegación requerirá compromiso y financiación. Janice Dickinson del Laboratorio de Ornitología de Cornell nos preguntó en una conferencia de SWAN "¿Cómo pretendéis obtener un trabajo en el mercado académico si os convertís en investigadores sin especialidad?" Mi respuesta fue que valorar la experiencia inter y transdisciplinar puede que sea la única oportunidad que tenemos de resolver los problemas ambientales.

Ideas para futuras investigaciones

Investigación sobre el metabolismo hídrico de sistemas socio-ecológicos

El marco de análisis del metabolismo hídrico es bastante reciente y aún no ha sido suficientemente testado. El ser semánticamente abierto aporta flexibilidad y robustez a este marco, así como la capacidad de incorporar continuamente nuevos desarrollos, pero también requiere un esfuerzo para llegar a un grado mínimo de normalización metodológica. Para avanzar hacia esta estandarización son aún necesarios más casos de estudio coordinados.

Un camino abierto en esta tesis que requiere de mayor desarrollo es la integración de modelos eco-hidrológicos en el esquema de contabilidad de MuSIASEM de manera espacialmente explícita. BalanceMed permite separar el agua productiva del suelo de la no productiva (transpiración de evaporación) pero no modela de momento otros procesos importantes como la erosión o la contaminación del agua. Para estos propósitos existen otros modelos integrados como SWAT o WIMMed. Algunas cuestiones derivadas de la modelización en el capítulo 2 son la exploración del *efecto combinado sobre los fondos de agua y los ecosistemas acuáticos del cambio climático/períodos de sequía, el colapso de los usos del suelo tradicionales y la evolución de las coberturas vegetales, o los impactos sobre los acuíferos y sistemas dependientes del aumento de la eficiencia del regadío.* Estas preguntas se pueden analizar a través de la construcción de escenarios integrando predicción eco-hidrológica y la evaluación del nexo entre agua-energía-tierra-comida de MuSIASEM.

La integración del análisis espacial del metabolismo social y ecológico del agua requiere también una mayor exploración. El agua en Europa ofrece un ámbito particularmente apropiado para avanzar para avanzar en análisis que usen los ecosistemas como criterio prioritario para establecer el nivel focal del sistema socio-ecológico debido a los sistemas de monitorización de la integridad de los ecosistemas acuáticos que se están desplegando para cada masa de agua. Desde una perspectiva de 'cuenca de problemas', el análisis a niveles eco-hidrológicos menores que la cuenca podría integrarse con el análisis de sistemas rurales que está bien desarrollado con MuSIASEM, permitiendo una evaluación bastante afinada de la deseabilidad, viabilidad y factibilidad de patrones metabólicos. La conexión de estos análisis metabólicos a resoluciones más finas con la gobernanza del agua tendría que abordar el reto de cómo ampliarlo hasta la cuenca. *¿Cuál es la escala más apropiada para la definición integrada de patrones socio-ecológicos de metabolismo hídrico? ¿Cómo caracterizar las relaciones espaciales entre estos patrones? ¿Cómo se pueden integrar el análisis espacial de sistemas rurales y del metabolismo hídrico? ¿Cómo escalar este análisis para generar información útil para la planificación hidrológica?*

Puesto que el WMSES es un marco teórico complejo, aún hace falta operacionalizar de manera apropiada algunos aspectos conceptuales. Uno de ellos es la definición impredicativa de recursos hídricos a través de la identificación de atributos relevantes y del rango útil de valores de dichos atributos. Puesto que los datos con los que he trabajado son normativos, asumí que esos flujos se proveen con una calidad deseable y el proceso seguido fue la desagregación de arriba a abajo de la demanda total de agua para los diferentes sectores. Sin embargo, sería interesante explorar otras formas de definición normativa de recursos hídricos útiles, por ejemplo a través de participación social *¿Cuáles son las características que hacen el agua útil de acuerdo con los usuarios? ¿Cuáles son la calidad, frecuencia y localización deseables para proveer diferentes tipos de servicios? ¿Cómo definir flujos de agua en función de estos atributos? ¿Cuáles son los flujos deseables que la gestión actual no provee?* Otra área conceptual interesante a explorar es el análisis de usos sociales no productivos de los fondos de agua, como se está haciendo en el análisis de servicios culturales de los ecosistemas. Esto permitiría por ejemplo avanzar a definiciones más complejas de productividad del agua incorporando valores estéticos que son clave en la actual evolución hacia el sector servicios en áreas rurales de alta montaña. *¿Cómo identificar, cualificar, y cuantificar los usos sociales de los fondos de agua? ¿Cuáles es el valor de los fondos de agua? ¿Existen metodologías útiles para este propósito en el marco de los servicios ecosistémicos?*

Con respecto a la aplicación del marco del metabolismo hídrico a la evaluación de las estrategias de gestión del agua, creo que la estandarización de metodologías para evaluar cada tipología de estrategia (aumento del recurso, mejora de cada tipo de eficiencia, control del crecimiento, etc.) permitiría entender con más profundidad el efecto de cada una de ellas sobre los resultados observados. El análisis del Efecto-Sudoku en MuSIASEM puede ser muy útil para construir marcos de evaluación integrada de esta interacción que puedan ser adaptados a las especificidades de cada tipo de política y gestión regional, y aplicados tanto en el análisis previo de escenarios y costes para tomar decisiones, como con posterioridad para evaluar resultados *¿Cómo aplicar el Efecto-Sudoku para diseccionar los efectos de diferentes* *estrategias de gestión?* Esto requeriría resolver un problema anterior que es el de *cómo organizar la contabilidad del agua para permitir esta evaluación.*

Finalmente, creo que aún se necesita bastante trabajo de 'traducción' del marco del metabolismo hídrico para que sea útil en procesos participativos. La pesada carga conceptual requiere formas de comunicación efectivas y las herramientas de análisis integrado necesitan visualizaciones útiles accesibles para un público no académico *¿Cómo visualizar patrones metabólicos para facilitar discusiones transdisciplinares?* En este sentido creo que los visores SIG tienen muchas ventajas a la hora de facilitar un entendimiento común de los problemas ambientales y por ello tienen un futuro prometedor en los estudios de metabolismo.

Investigación sobre gobernanza del agua

En el marco del proyecto SWAN, el equipo de investigación de la Universidad de Sevilla desarrolló una línea de investigación sobre datos, información y conocimiento para la gobernanza del agua en la sociedad red que, en mi opinión, da en el clavo de algunos retos importantes del sector. Algunas preguntas de investigación abiertas son *¿Cuáles son las condiciones para que los mecanismos de participación y deliberación en la planificación hidrológica aseguren una participación y capacidad de decisión equilibrada? ¿Pueden las TICs jugar un papel más importante en mejorar la calidad democrática de la toma de decisiones en la gestión del agua?* En mi opinión, es necesario avanzar hacia sistemas de información del agua integrados, datos abiertos y plataformas de visualización y descarga. Como he discutido en esta disertación, la transparencia en la información del agua es un tema clave en España, pero también lo es en muchos otros países, debido sobre todo a las viejas inercias de ingenieros y gestores que consideran que la información del agua es demasiado compleja para ser entendida por no expertos. Esta era de 'guardianes de la verdad' se ha terminado, y las administraciones públicas poco a poco empiezan a moverse hacia estándares abiertos. Las organizaciones ciudadanas juegan un papel fundamental en controlar la calidad de la información que se utiliza para tomar decisiones y evaluar sus resultados. Mejorar la calidad y accesibilidad de los datos puede por tanto impulsar el progreso hacia la evaluación integrada de la gobernanza del agua.

Las prácticas emergentes de ciencia ciudadana son bastante prometedoras para empujar en esta dirección a través de la colaboración entre investigadores, gestores, usuarios y comunidades locales, activistas o el público en general. La inclusión efectiva de actores no académicos en el proceso de investigación está creando no sólo oportunidades de investigar a escalas antes imposibles, permitiendo la aplicación de técnicas de análisis big-data, sino también abriendo nuevas vías para el diálogo transdisciplinar y para el control externo del proceso científico *¿Cómo puede la ciencia ciudadana ayudar a suturar las brechas entre ciencia y gobernanza del agua?*

En cuanto al análisis de discurso, soy consciente de que la metodología utilizada en tesis no es la más rigurosa considerando los avances con softwares específicos como Atlas.ti o Envivo, y que se puede mejorar bastante en este sentido. Una línea de investigación que me gustaría explorar próximamente es el uso de las redes sociales en conflictos ambientales o campañas activistas relacionadas, combinando el análisis de redes con el del discurso. Para ello estoy colaborando en un artículo con el objetivo de responder a la pregunta *¿Qué tipo de capital social refuerzan las redes sociales?*

Por último, hay dos cajas negras importantes que no he abierto en esta tesis pero que espero poder abordar en el futuro: instituciones y poder. Aunque mencionadas y reconocidas como esenciales condicionantes de las relaciones socio-ecológicas, no he analizado en detalle las organizaciones institucionales específicas, ni tampoco las relaciones de poder entre actores, en parte porque carezco de formación para ello. Creo que un reto urgente no sólo para la gestión del agua sino para la mayoría de los ámbitos de la gestión pública es cómo escalar de manera efectiva la participación ciudadana desde lo local a escalas superiores. Puesto que la participación normalmente funciona bien en la escala comunitaria de gestión de recursos comunes, pero las TICs e internet han abierto nuevas oportunidades para una gestión y toma de decisiones democrática a todos los niveles, *¿Qué tipo de organización institucional puede hacer la participación de abajo-arriba eficaz y mejorar la legitimidad de las decisiones en gestión del agua? ¿Cómo se puede concebir un régimen institucional de gobernanza socio-ecológica multi-escalar y abierta? ¿Ayudaría este diseño a superar los regímenes post-políticos actuales o correría el riesgo de reforzarlos?*

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Appendix 1

Table A1.1 - Characterization of WMSES as a framework for SES analysis according to the criteria of Binder et al. 2013

Contextual criteria		**Structural criteria**	
Acronym	WMSES	*Social system*	
Disciplinary origin	Complexity Science, Sustainability Science, Bioeconomics, Systems Ecology	Scales	Multiple levels of societal organization, from whole social-ecological systems to functional compartments; semantically open definition of analytical levels and scales according to case study
Theoretical origin	Complex systems theory, hierarchy theory, Rosen's modelling theory, autopoiesis, evolutionary theory, flow-fund model, Post-Normal Science, Multi-Scale Analysis of Societal and Ecosystem Metabolism	Conceptualization and dynamics	Holarchy. Interactions intra and inter-holons. Impredicative loops. Processes and structures characterized through flow-fund model of Georgescu-Roegen 1971
Application fields	Sustainability analysis, rural systems analysis, water use, analysis water-energy-food-land nexus, assessment of water management	*Ecological system*	
Analytical purposes	Multi-scale and multi-dimensional analysis of resources use; integrated assessment of sustainability	Scales	Multiple levels of eco-hydrological organization; semantically open definition of analytical levels and scales according to case study
Temporal scale	For societal systems: extent of one year, grain of hour. For ecological systems: extent of decades, grain of a year	Spatial scale	It has been applied at local, regional and national spatial extents and different grains. This dissertation focuses on the watershed extent and grains of water bodies and land uses and covers
Guidance/ operationalization	Guidance on operationalization is provided in several works depending on analytical purposes (Giampietro et al. 2014, Madrid 2014, Cabello et al. 2015)	Conceptualization and dynamics	Holarchy. Feedback relationships intra and inter-holons. Processes and structures characterized through eco-hydrological modeling and environmental impact assessment
		Socio-Ecological system	
		Conceptualization of interactions	Reciprocity between social systems and ecosystems characterized through four types of relationships describing the loop 'water supply->societal uses/discharges ->impacts on ecosystems->impacts on supply'.
		Degree of equal depth	So far more focus on the social system. This dissertation proposes the analysis of ecosystem metabolism of water through eco-hydrology and environmental impact assessment
		Analysis vs action oriented	So far analysis oriented but nexus applications evolving towards public policy design (see http://ceproec.iaen.edu.ec/curso-musiasem/)

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Appendix 2

This appendix has the purpose of extending the methodological description of Chapter 2, including detailed calculation of variables and modeling validation.

Scales

Figure A2.1 shows the temporal and spatial levels used for the Upper Andarax grammar according to these constraints. We run the BalanceMED model on temporal monthly and spatial Hydrological Units (HU) resolutions. Results were aggregated to the extents of one year and land uses and covers types. Socioeconomic data are available for a variety of grains (see Table 1). Human activity is mapped for whole urban areas (municipal level) and agricultural land uses for irrigation communities and rain-fed agriculture polygons. Note that we could do a municipal level analysis (comparing each municipality Land-Human activity budgets) but this would enlarge the amount of results and loose the purpose of the study: the operationalization of the SESWM framework for the analysis of water management at river basin scale. As Schneiel 2013 explains "every kind of data collection is always a 'heroic simplification' of a complex rural system and the issue is rather to find the adequate simplification, which allows answering some relevant research question". A more detailed hydrological resolution and, especially, temporal series of water use would clearly improve the method analytical potential.

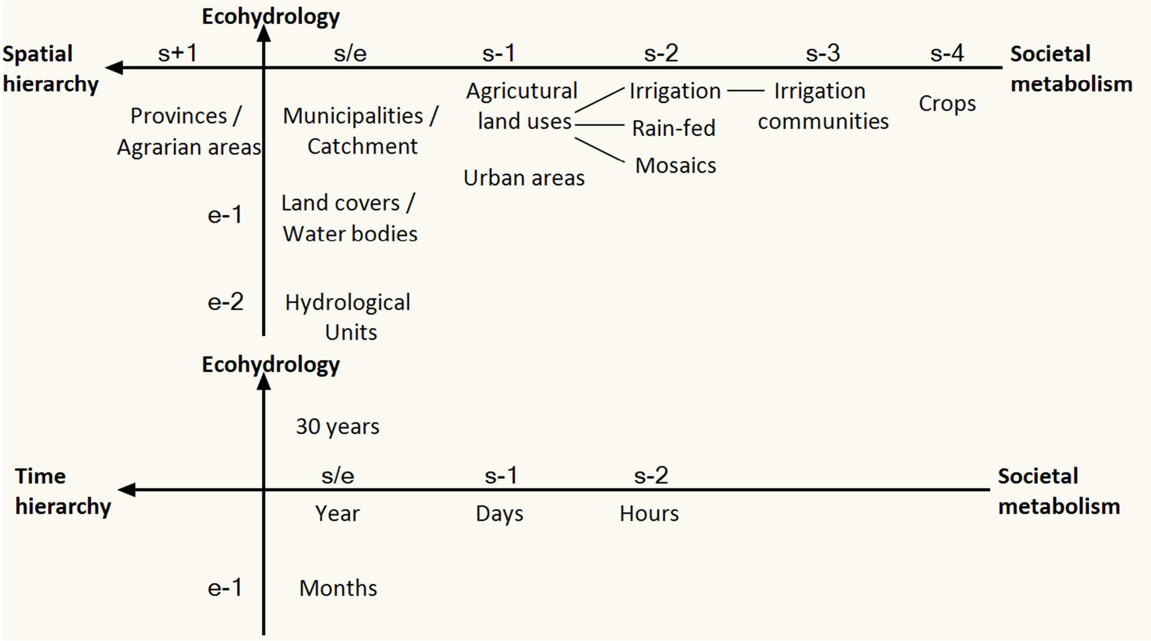

Figure A2.1- Temporal and spatial hierarchies in the Upper Andarax water grammar

Conceptual model and formal categories

The conceptual model for variables calculation is presented in Figure 2 and the formal categories of the grammar in Table 1. Codes and databases can be downloaded here:

https://www.dropbox.com/sh/45za6hqmnjelqoi/AAD-ObuilYtGzFwVKyJ_WzQ5a?dl=0

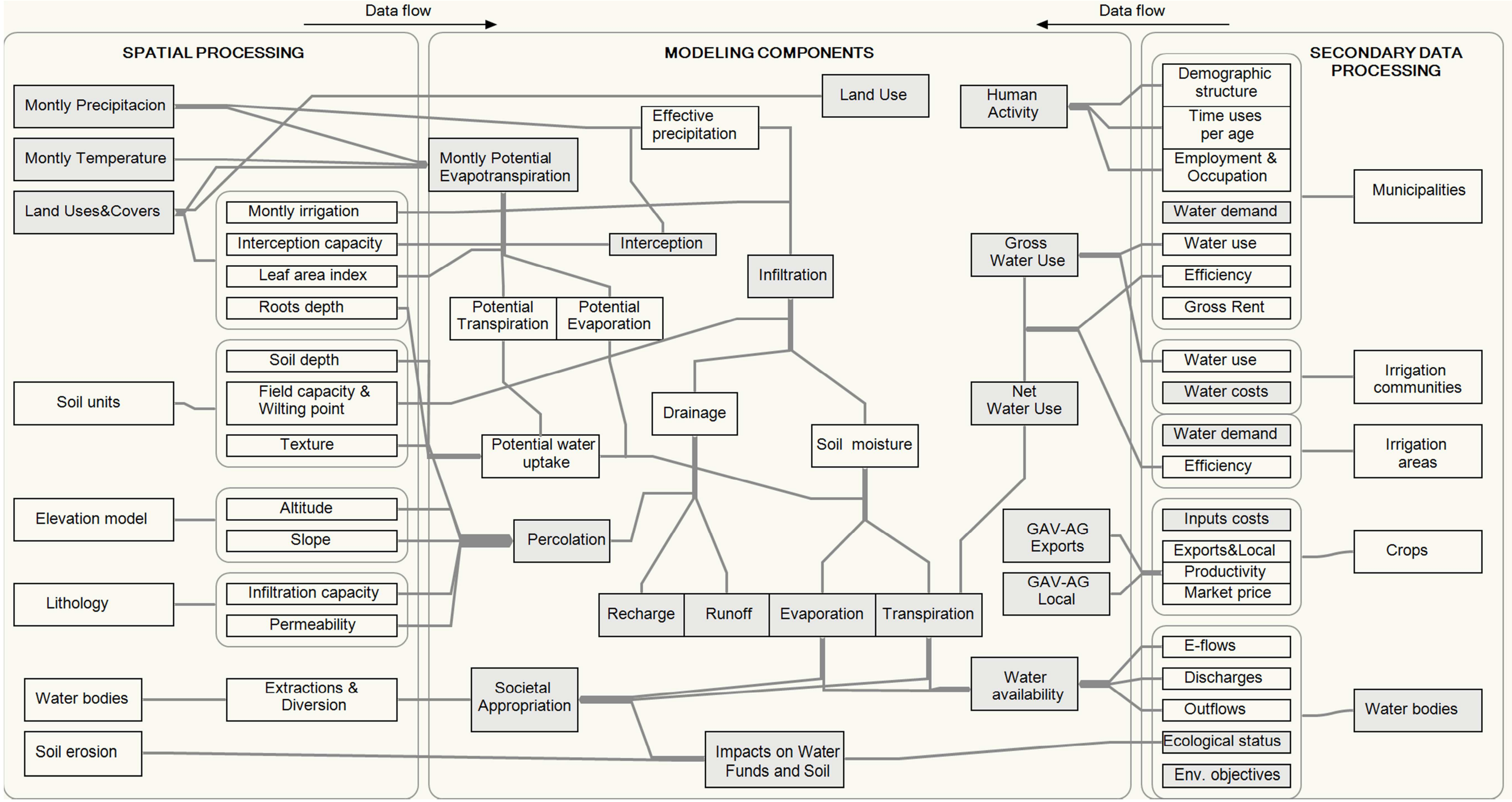

Figure A2.2- Conceptual scheme for water grammar formalization

Table A2.1- Formal categories of the water grammar

Semantic categories	**Types**	**Description**	**Units**	**Temporal resolution**	**Spatial resolution**	**Data sources**
Water exchange						
Climate	Precipitation	Average precipitation from the series 1970-71/2000-01	mm/Hm^3	Months	Raster 10 m	Secondary Climatic Stations National Network (8)
Water funds turnover	Runoff	Total runoff to surface water bodies	mm/ Hm^3		HU	BalanceMED
	Recharge	Infiltrated rain water that percolates to aquifers				BalanceMED, APPLIS recharge model
	Soil Infiltration	Infiltrated rain water that is evapotranspired or contributes to soil reserve				BalanceMED
Societal appropriation & Availability	Surface	Direct diversion from the river for human uses	Hm^3	Year	Municipalities &Irrigation communities	(1), (2), (3)
	Groundwater	Extractions from aquifer	Hm^3			
	Soil water	Soil moisture in land used by humans	mm/ Hm^3	Months	HU	BalanceMED
Gross water use	Withdrawn	Ground and surface water consumption	Hm^3	Months	Municipalities &Irrigation communities	(1), (2), (3)
	Soil	Evapotranspiration from land uses		Months	HU	BalanceMED
Net water use	Urban supply	Water supply*Efficiency in supply chain	Hm^3	Year	Municipalities	(1), (2)
	Food production	Water withdrawal for agriculture*Efficiency in supply chain*Efficiency of irrigation system + Transpiration from rain water		Months	Agricultural areas & Irrigation communities	(1), (4), (5)
	Forestry &*Esparto* gathering	Transpiration from rain water		Year	Land cover polygons	BalanceMED
	Cattle	Surface water requirements + transpiration from rain water		Year	Watershed, land cover	(1), BalanceMED
	Loses	Gross Water Use minus Net Water Use		Year	Municipalities& irrigation areas	(1), (2), (3)
Water demand		Deficit for irrigation purposes in the RBMP		Year	Irrigation areas	(1)

Water rights		Authorized withdrawals from each water body		Year	Water bodies	(1)
Organization						
Climate	Temperature	Average precipitation from the series 1970-2001	ºC	Months	Raster 10 m	Secondary Climatic Stations Network (8)
Water bodies	Rivers	Descriptive category: water bodies types considered in the RBMP	-	6 years	6 years	(1)
	Aquifers					
Land covers		Surface occupied by land cover types	Hectares	4 years	Land cover polygons	Map of Land Uses and Covers of Andalusia 2003 (9)
Managed land uses		Surface occupied by land uses types under managed land	Hectares	4 years	Land use polygons	
Human activity	Physiological overhead	Hours devoted to personal care, eating, sleeping and dependent people time	Hours	Hours	Municipalities	Time Use Survey of Almeria province 2002/03 (10) Spanish Population and Households Census 2001 (11) Local population census 2005 and 2011 (10)
	Social, Leisure &Education	Hours devoted to traveling, leisure activities, education and volunteering				
	Unpaid work	Hours devoted to households work				
	Paid Work	Hours devoted to each type of paid work sector by the working population				
Technical capital	Hydraulic infrastructures	% of surface of irrigation communities supplied by acequias	%	Year	Crop types	(3)
	Irrigation technology	% of surface of irrigation communities with drip irrigation				(3)
Monetary exchange	Agricultural inputs& Water costs	Total expenditures of irrigated agriculture on water and other inputs	€		Crops types & Irrigation communities	(3), (7)
	Gross Added Value	Total income from local and external markets			Crops types	(3), (6)

(1) CMAT 2012. Andalusia Mediterranean River Basins Management Plan 2009-2015. [online] URL:

http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnextoid=6d3173f2c746a310VgnVCM2000000624e50aRCRD&vgnextchannel=0bb66af68bb96310VgnVCM1000001325e50aRCRD

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(5) CA 2011. System of technical assistance to farmers of the Andalusian government. [online] URL: http://www.juntadeandalucia.es/agriculturaypesca/ifapa/sar

(6) CMAT 2006. Andalusia Multiterritorial Information System. [online] URL: http://www.juntadeandalucia.es/institutodeestadisticaycartografia/sima/index2.htm

(7) CA 2005. Annual statistics on agriculture and fishing of Andalusia. [online] URL: http://www.juntadeandalucia.es/agriculturaypesca/portal/servicios/estadisticas/estadisticas/agrarias/resumen-anual.html

(8) AEMET. Spanish State Agency of Meteorology. [online under payment] URL: http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos

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(11) INE. Spanish Statistical Office. [online] URL: http://www.ine.es/jaxi/menu.do?type=pcaxis&path=%2Ft20%2Fe242&file=inebase&L=0

BalanceMED

Precipitation and potential evapotranspiration

GIS raster layers of average monthly precipitation and potential evapotranspiration (PE) variables were obtained from the Andalusian Network for Environmental Information (REDIAM) for the period 1971-2000. Monthly scale reflects better the normal Mediterranean environmental conditions due to the usual lack of rainfall in finer time scales generated by long periods of water deficit. This source of information was chosen because it is the same used by the River Basin Authority for hydrological modeling. We found hydrological variables (runoff and recharge) were greatly overestimated using this data source. Mean values are usually not representative when dealing with very irregular regimes with skewed precipitation density functions such as the ones in the Andarax. In arid and semiarid climates, the median as central statistic measure is more robust. For this reason, median monthly values of were obtained at the closer 24 meteorological stations with available data for the 1971-2000 period (within a buffer of 10 km). These stations belong to the Spanish State Agency of Meteorology and only provide temperature and rainfall data. PE was estimated using an excel macro based on Thornthwaite method (HydroBio3, Camara and Martinez 2002). All data series where then spatialized using the Inverse Weighted Distance interpolation in ArcGIS 10.2 to obtain continuous information to be entered in the model. Results significantly improved making estimates closer to real conditions.

Hydrological units processing

Hydrological units are obtained from the intersection of soil and land cover GIS layers. Previously, several parameters were calculated for each of them. Roots depth, Leaf Area Index and interception capacity were gathered for vegetation species through literature review. Weighted means per number of species were obtained for each land cover unit. Soil parameters are wilting point, field capacity and soil depth. These are calculated from data on lime, clay and organic matter fractions extracted from the soil cartography of the Desertification Prevention in the Mediterranean Project (LUCDEME) of the Spanish Ministry of Agriculture.

Percolation

The APLIS equation was proposed by Andreo et al. 2004 for determining the average rate of recharge in carbonate aquifers. This rate is expressed in BalanceMED as a percentage of drainage for each hydrological unit and calculated as:

$$R(\%) = (A + S + 3L + 2I + S)/90$$

Where A is the Altitude, S is the Slope, L is the Lithology, I the preferential Infiltration layers and S the Soil. Punctuation categories are established for each variable between one (minimal influence in recharge) and ten (maximum influence). In our study, slope was corrected to zero for agricultural land uses in order to introduce the leveling effect of terraces. These parameters are averaged for HU grain.

Model calibration, validation and limitations

A detail description of BalanceMED can be found in Willaarts et al. 2012. For this study, the model was translated from a Microsoft Excel macro to an R script to gain flexibility for future implementations. Model calibration was done through standard hydrograph plot (Figure A2.3). Monthly volumetric runoff rates are recorded at the only one available gauging station in the basin for the time series 1971-2000. Mean-monthly values of observed runoff were contrasted against model runoff. The peak of runoff in April responds to the monthly precipitation pattern but is not observed in the gauging station likely because it is the month were irrigation starts and pools are filled with diversions from river.

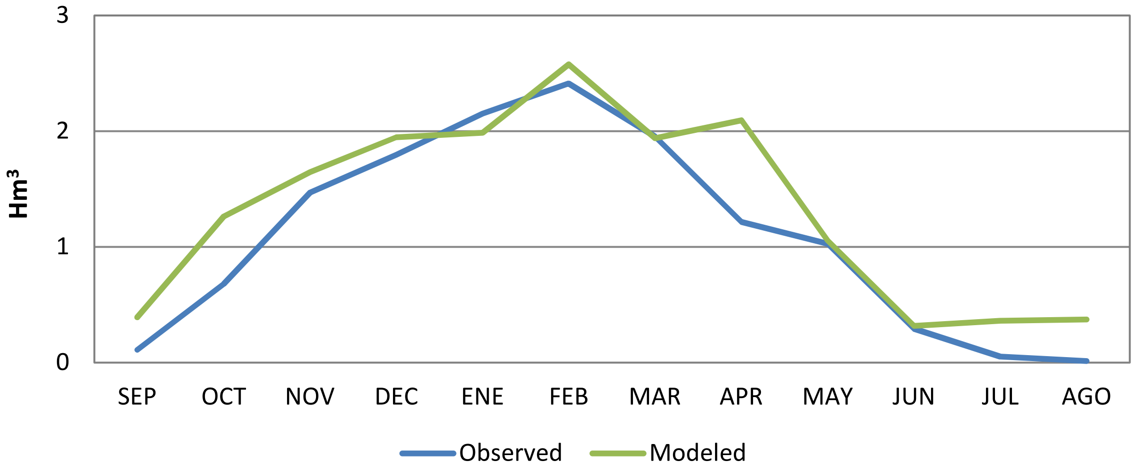

Figure A2.3- Plot of observed vs modeled runoff volumetric rates

In order to validate results, the evaluation statistics recommended by Moriari et al. 2007 were used: (i) the Nash-Sutcliffe efficiency (NSE) which indicates how well the plot of observed versus simulated data fits the 1:1 line, (ii) the Percent bias (PBIAS) which measures underestimation tendency of the model and (iii) the RMSE-observations standard deviation ratio (RSR), which is a standardized version of the root mean square error. The model performance can be judged as satisfactory according to these criteria (NSE > 0.50 and RSR < 0.70, and if PBIAS ≤25% for streamflow) (Table 2). The model efficiency shows a good plot fit between observed and simulated data. The PBIAS indicate a slight overestimation of runoff.

Table A2.2- Model evaluation of BalanceMED. Three metrics were calculated to validate modelresults: Nash-Sutcliffe efficiency (NSE) (range =−∞/1, optimum 1); Percent bias (PBIAS) (range =−∞/+∞, optimum 0); and RMSE-observations standard deviation ratio (RSR)(range =0/+∞, optimum 0).

Statistics	**Value**
NSE	0.80
PBIAS	12.00
RSR	0.44

Post processing water grammar variables

Main results from BalanceMED are the volumetric variables of recharge, runoff, soil infiltration, transpiration and evaporation on a monthly and HU resolution. Intensive variables (mm or m^3/ha) used for spatial analysis of ecosystems-water funds relation are obtained by weighted means per area for each type of LULC considered. Extensive volumetric variables (total Hm^3) were obtained by aggregation per HU area.

Societal metabolism

Human activity

A thorough description of human activity accounting can be found in Kovacic and Ramos-Martin 2014. The Total Human Activity in a given society is calculated in hours as:

$$THA_{year\ i} = 365 * 24 * Population_{year\ i}$$

This total is disaggregated in subsequent hierarchical levels according to case-study objectives. In our case, the categories considered are explained in Table 1 and the equation to valid is:

$$THA_{2005} = HA_{PO} + HA_{SLE} + HA_{UW} + HA_{PW}$$

Where *PO* is physiological overhead; *SLE* is social, leisure and education; *UW* is unpaid work; *PW* is paid work. These variables were calculated for each municipality with data on employment, occupation, education and demographic structure from Spanish Census of Population and Households 2001 and the Time Use Survey 2002-03 for Almeria province. This latter establishes shares of hours devoted to the different activities in a day per age ranges. Since that information is only available every ten years in Spain, the obtained human activity shares were then extrapolated to the population evolution until 2005. Considering there was not mayor societal changes those years (pre economic crisis 2008 scenario), it is a reasonable assumption. The new census 2011 collected data from 2011 to 2013 and did not reach the same detailed level of municipality for required data inputs. For this reason it is not possible to update the human activity budget.

Land uses

Two geographical layers were used for the land budget analysis: the Map of Land Uses and Covers of Andalusia 2003 (MLUCV03) and the Inventory and characterization of irrigation in Andalusia 2008 (ICIA08). This latter collected data through surveys to Irrigation Communities from 2002 to 2008 and is the baseline used for the RBMP. It contains crops surface per irrigation community. Categories of irrigated agriculture in the MLUCV03 were coerced to match those of the ICIA08. For the rest of land uses and covers, we broke the hierarchical structure of the MLUCV03 in order to group them in types and levels relevant our analysis. MLUCV03 was intersected with the parks boundaries to obtained categories of land management. For each type of LULC and protection category (High protection in the National Park, Medium protection in the Natural Park, no protection in the rest of the watershed) a land use ratio was assigned as shown in Table A2.3.

Table A2.3– Land and soil water use coefficients.

	High protection	Medium protection	Not protected	Water uses
Irrigated agriculture	1	1	1	Irrigated agriculture
Rainfed agriculture	1	1	1	Rainfed agriculture
Abandoned	0	0	0.2	Grazing
Quercus forest	0	0.1	0.2	Forestry
Pine plantations	0	0.1	0.2	Forestry
Riparian forest	0	0	0	
Shurbs	0	0.2	0.3	Grazing (2/3) and gathering (1/3)
Pastures	0	0.3	0.5	Grazing
Urban	0	1	1	Urban supply

Monetary flows and technical capital

Crops economic data and irrigation infrastructures were also double-sourced:

- Irrigated crops: Gross Added Value/ha, Working Days/ha, agriculture Inputs Costs/ha and Water Costs (cent €/m^3) were obtained from ICIA08. The type of trade (exports, local or self-consumption) and water supply and irrigation systems are also included in this database. Total extensive variables were obtained for each type of crop and trade.
- Rain-fed crops: production in Tons/ha per type of crops and prices received by farmers in €/100 kg were obtained from the annual statistics on agriculture and fishing of Andalusia 2005. Total Gross Added Value per crop was estimated based on the surface of rain-fed agriculture land uses.

There is no available data of added value for other economic activities than agriculture at municipal level. The total Gross Rent in the basin is calculated aggregating for each municipality rent per capita.

Water use

Water withdrawals and use were obtained from three sources:

- The Andalusia Mediterranean River Basins Management Plan 2009-2015, which includes extraction from different sources, water allocation to different uses and average irrigation efficiencies.
- The Inventory and characterization of irrigation in Andalusia 2008– ICIA08 contains data on gross water use for each irrigation community from different sources. Net water use was estimated by multiplying for the average efficiency in their area.
- The report from Martinez 2011 is the only data source with actual urban gross and net water use measured data for all municipalities in the Almeria province as well as water sources.

These variables are provided for one year. For seasonal analysis, monthly irrigation was estimated based on schedules from the technical assistance to farmers system of the Andalusian government and personal communication from farmers in the area. Multi-crops areas were averaged. Urban water was broken into equal monthly shares for residents and commercial uses and non-residential use was added to summer months. Water withdrawals were spatialized by splitting the river length in segments according to water withdrawal points by each municipality and irrigation community. Soil water use is calculated applying the same coefficients of land covers use and relating them to activities presented in Table 3. Gross water use is the total evapotranspiration and net water use is transpiration in those covers. The separation of transpiration from irrigation and from rain water was obtained by the difference between running the model with and without irrigation.

Environmental impacts

The assessment of the ecological status of water bodies is the baseline of the RBMP. Aquifers are evaluated on their quantitative (exploitation index) and qualitative (pollution) status. Rivers are evaluated on their biological (biodiversity), hydro-morphological and physic-chemical status. The information provided in the plan is rather dated (only one sampling campaign) and the final evaluation based on expert evaluation. We provide additional analysis of available secondary data to complement and discuss this assessment: erosion rates, water table levels and surface and groundwater quality.

The cartography of average erosion rates for the period 1992-2006 is available at the natural hazards section of the Andalusian Network of Environmental Information [Online] URL: http://www.juntadeandalucia.es/medioambiente/site/rediam/portada/. The calculation method used by the Andalusian Environment Agency is the Universal Soil Loss Equation (USLE) and the scale set by this institution by normalizing the range of average soil loses values in the region from low (<12 ton/ha yr) to high (>50 ton/ha yr). Water table levels change was also averaged for the available series from 1992-2006 from the network of piezometers of the Spanish Institute of Geology and Mining Water Database [Online] URL: http://info.igme.es/BDAguas/. There are more control piezometers but only 32 have data and 22 data for the selected period. Most series stop in 2004 and there is no data afterwards in this database. The Spanish Ministry of Environment has been monitoring only 9 of them from 2006 on. The decrease in water table monitoring points is therefore considerable. Groundwater and surface water quality variables have been download from the Andalusian River Basins Network for physic-chemical and biological control of water quality, which contains all the sampling campaigns from 2002 to 2013 [Online] URL: http://laboratoriorediam.cica.es/Visor_DMA/?urlFile=http://laboratoriorediam.cica.es/Visor_DMA/service_xml/capas_dma.xml]. Available series for this period for each control point were averaged.

Regarding ecosystems water requirements, land ecosystems transpiration is a result from BalanceMED, environmental flows for the river are proposed in the RBMP on a monthly volumetric rate and aquifer discharges to springs and other connected aquifers were estimated in the Hydrogeological Atlas of Andalusia 1980-1990 [Online] URL: http://aguas.igme.es/igme/publica/libros1_HR/libro110/Pdf/lib110/in_32.pdf.

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Appendix 3

Synthesis of focus group on assessing water management in the Andarax. University of Almeria. Almería, May 29th , 2014.

During the ALTAGUAX project, a set of indicators for sustainability of water management assessment had been proposed. The indicators resulted from discussions in two workshops and were arranged in the three classical dimensions of sustainability.

This focus group was an excercise of assessment of water management in the Andarax basin. The session objectives were i) to assess opposed management strategies on one side; and ii) evaluate the information provided and methodology on the other. Fifteen invitations were sent to key stakeholders and 7 people attended including one representative from the gricultural sector, two from urban water supply, three from the academia and one from the New Water Culture Foundation. The representatives from the Mediterranean Andalusian River Basin District did not attend.

A baseline diagnosis of societal metabolism and sustainability indicators quantification was presented and discussed. Afterwards, the excercise of assessing management strategies was arranged in two groups, one for Alto Andarax and another for Bajo Andarax. The excercise consisted in valuating the change of the value of indicators on a qualitative basins, using a flag-multiscale template of Kovacic 2014. This template arranges indicators of the three dimenssions of sustainbility in different spatial and temporary scales. The first one are characterized by the levels on the left with an increasing spatial scale (n-1, n, n+1) and the latter by the differentiation between indicators of state and of performace. Each group had to evaluate two alternatives corresponding to opposed narratives identified in Chapter 4 under a number of explicit assumptions. However, the initial discussion about the baseline diagnosis raised a lot expectation and took more time than planned. In consequence, the assessment excercise could not be completed and only one alternative was appraised (Figures A3.1 and A3.2).

In what follows, I summarize what I consider the most interesting points of the discussion, including those of the final evaluation of the metabolism framework as a water accounting methodology. These reflections supported the discussion of analytical chapters in the Andarax and the final consclusions of this dissertation.

- The diagnose information on societal funds and water flows was considered useful and sufficient. Nevertheless, water funds data from the River Basin Management Plan 2009-2015 was not considered rigorous because the models used by the water administration are not properly calibrated.
- The lack of aquifer dynamic modeling is a clear drawback of the information provided, and of the hydrological information of the basin in general.
- Some attendees deemed the quantification of indicators as a form of objectification of the discussion, whereas others insisted on the idea of values underlying the indicators they proposed 4 years earlier.

- The Water Extraction Index is an essential indicator without standard calculation procedure that makes comparisons among studies impossible. It is necessary to incorporate an accurate assessment of environmental requirements in the index.
- The issue of appropriate scale for indicators calculation is central. Current scales used in the formal planning do not allow to link water uses with environmental impacts and a disaggregation into smaller levels would be advisable. The concepts of couple water-human systems and socio-ecological systems seem to fit in this requirement.
- The top-down approach of the WFD is questioned by some stakeholders as imposing environmental objectives that lack a thorough understanding of regional realities. They would prefer a combination of bottom-up and top-down approaches in water planning. On the other hand others advocated for a top-down coherent framework arguing that if contextual specificities are considered in water planning, the achievement of common environmental objectives will not be possible. This perception defends that ecological status assessment requires standardized protocols and the design process of the program of measures should be open to active public participation.
- The consideration of power relations was deemed essential in an assessment of sustainability. The lack of this analysis in the presented societal metabolism approach was considered a drawback of the method. The necessity of formal indicators to evaluate democratic quality, governance effectiveness and corruption was emphasized.
- The assessment method is considered useful for participatory discussions to achieve a common vision about where management strategies should be headed. Nevertheless, it is not detailed enough to go to smaller spatio-temporal scales of sustainability problems.

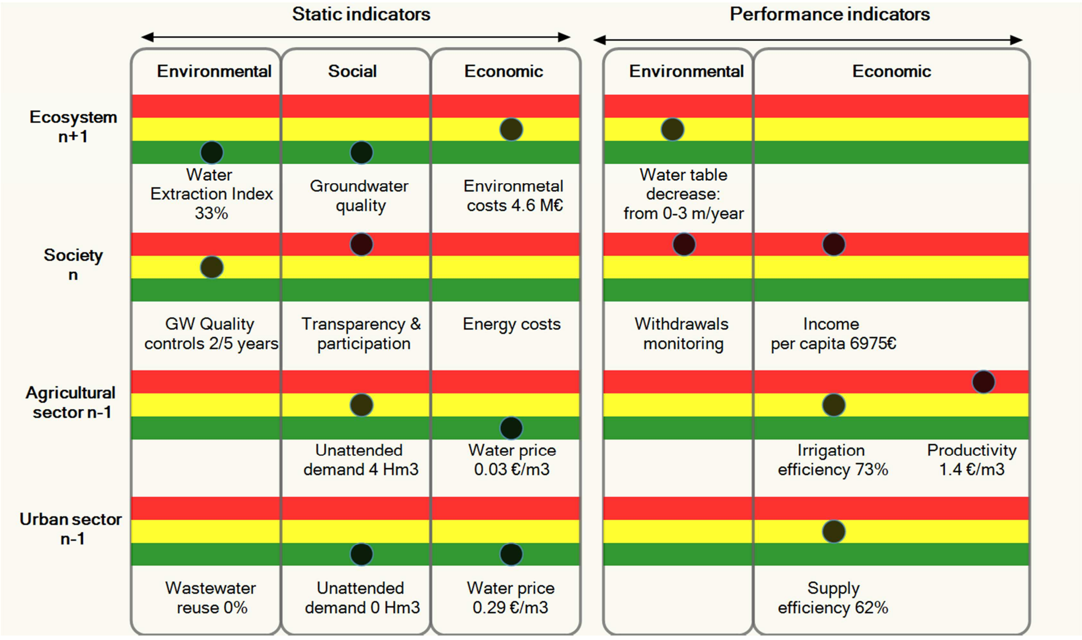

Figure A3.4 - Assessment of efficiency improvement in Alto Andarax

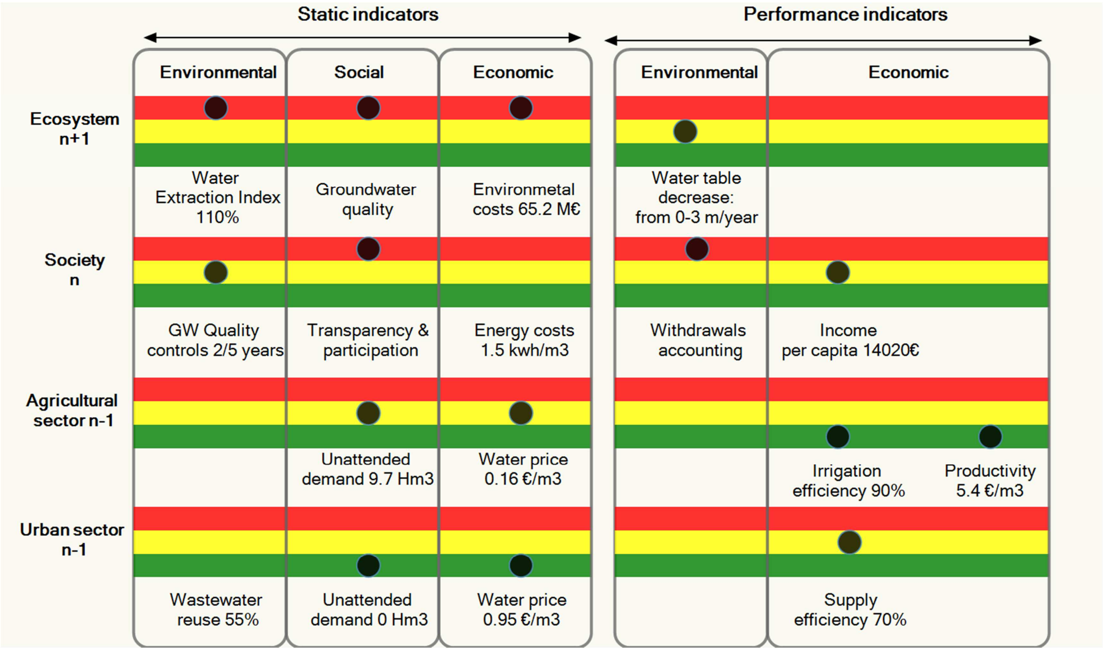

Figure A3.5 – Assessment of governance improvement in Bajo Andarax

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Appendix 4

Synthesis of the first SWAN Tucson basin stakeholders workshop. University of Arizona. Tucson, October 30th, 2013.

The primary goal of SWAN is to promote research links between the US and the EU through the development of a Transatlantic Dialogue on Water Governance. This goal is achieved through the collaboration on comparative analysis of water management issues in different case study locations in the EU and the USA. A Key component of SWAN is the development of research stays of European researchers at the iGlobes-UMI located in the University of Arizona.

During the spring semester of 2013 a group of international and US students who were conducting research stays at the University of Arizona either in association with SWAN or with University of Arizona SWAN-related faculty met weekly to develop a cooperative approach to trans-disciplinary research. The meetings were coordinated by UA Research faculty Aleix Serrat-Capdevila and Hoshin Gupta and were attended by University of Arizona SWAN-related faculty Francina Dominguez, Juan Valdés and UMI director Franck Poupeau. Their work had three specific outcomes:

- Institute the weekly meetings as the focus of the scientific cooperation building efforts.
- Agree to focus on the Tucson Active Management Area region as geographical area to realize the central case study and to develop a collaborative research on water management/ regulation.
- Set the groundwork for an academic paper on trans-disciplinary collaboration.

SWAN's scientific approach is built on ideas of the complexity and incommensurability associated with the management of social-ecological systems, as well as the need to deal with conflicts and politics unavoidably associated with environmental management. We recognize the uncertainty of model predictions in complex issues which implies the necessity of opening scientific outcomes to public validation. Therefore, any case-study based research must necessarily build on collaboration with stakeholders who are experts in the water management challenges of their region at different scales. The decision was therefore made to build a collaborative process with stakeholders intertwined with interdisciplinary research. This process was also intended to support the work of the students that will be conducting research stays at the University of Arizona in the framework of SWAN and minimize stakeholder fatigue.

Throughout the spring semester of 2013, in order to build this collaboration and start identifying key research questions for the Tucson Basin area, SWAN researchers met with Linda Stitzer (former Head of the Tucson AMA) and invited speakers at the April SWAN progress meeting, such as Ed Curley (Pima County), Ralph Mara (formerly in Tucson Water), Kathy Chavez (Pima County) and people from different academic institutions involved in stakeholder relevant projects. From these meetings initial research questions were identified and developed. Additionally, the decision was made to organize an initial workshop with local stakeholder experts in order to identify key areas of concern, validate research approaches, and start building a collaborative research process.

This first Stakeholder Workshop was organized on Wednesday, October 30th at the University of Arizona in the context of SWAN's Fourth Progress Meeting. Local experts, members of the UA academic community and SWAN researchers were invited to attend. The goal of the workshop was three-fold:

1. Indentify key management challenges in the Tucson basin region
2. Evaluate and prioritize the pre-defined research questions.
3. Identify knowledge gaps and propose new research questions.
4. Map a list of relevant Tucson basin region stakeholders.
5. Propose a roadmap for future collaboration.

The first SWAN Stakeholder workshop was designed for a group of 6-10 stakeholders. However, due to a variety of circumstances attendance to the workshop was limited. As it often happens with participatory research, there is a significant process of learn-as-you-go. The possibility of having an in-depth discussion with a small number of extremely knowledgeable and experienced stakeholders greatly facilitated the exchange of ideas and allowed for a rich and productive working session. As a result, it was decided that, to the extent possible, future interactions with local stakeholder-workshops will follow a similar pattern and be limited to working sessions with 2-3 stakeholders.

Identification of Key Management Challenges in the TAMA region

At the beginning of the workshop, participants were asked to write the single most important water management challenge in the Tucson basin from their perspective. The results are shown below grouped by type of participant:

Stakeholders

- Sustaining both human and natural systems with extremely variable water inputs (erratic rainfall, shifting human demands, etc.)
- Under pressure of population growth: balancing all water needs. In the context of the TAMA rules: private wells, environmental needs, outdoor/indoor reuse (use changes), reclaimed water (new resources).

SWAN/Academia

- Aquifer overdraft.
- Drawdown of the water table (caused by drying up the rivers and riparian zones). Water availability in the face of growing population and likely decreasing supply.
- How to deal with the stream-flow decrease of Colorado River basin plus its impacts on CAP transfer.
- Disconnection between land & urban development and water management (after the joint study).
- Growth (human demand and perceptions/acceptability of variable water service and quality).
- Challenges on the M+I water supply due to climatic and legal constraints on the CAP water
- Maintaining ecosystems services in an urban environment.

- Water quality – specific odor due to over bleaching? Water scarcity, riparian ecosystems.

Research Concerns

During this activity participants were presented with a list of research questions that had been identified during the SWAN weekly meetings. The activity was divided into three parts:

- Rate the relevance of the different questions by placing colored dots next to those they considered most significant.
- Propose new research questions based on the perceived knowledge gaps in the TAMA region. The results of this third activity are presented in section 4 below.
- Discussion about the relevance of the questions;

Evaluation and Prioritization of Research Questions

Participants were given a list of proposed research questions and 12 colored dots (red for stakeholders and blue for other participants). Questions had also been placed on the wall on large cards and grouped by categories. Participants were given 10 minutes to read the questions and assess their relevance by placing the dots on the most significant/relevant ones.

Overarching questions
In the context of the Tucson basin, what are the emerging water management challenges and what would be most adequate methodological tools to handle them? What are the major uncertainties for water management and what are the plausible future scenarios?

Table A4.1 – Research questions validation

Questions	**Stakeholders**	**SWAN**
Institutional and policy analysis		
1) What is the impact of the GW credits on the present and future dynamics of the water use budget in the Tucson Basin?	4	12
2) How are decisions regarding water resources management made in Tucson basin? How are these decisions legitimized? Who sits at the decision-making table? Who chooses them? How are the players selected & who do they represent?	3	10
3) How are management boundaries defined in Tucson basin? What factors determine selection of these boundaries (physical, administrative, political, etc)? What implications do these boundaries have on actors involved, allocation priorities, power structures and resource distribution?	3	4
4) How are land use and water resources planning integrated? What are the challenges?	2	3
5) How can run-off decrease trends affect the provision of CAP water to Tucson basin according to the existing priority allocation system?	0	7
6) How has the politics of water management evolved in Arizona?	0	4

7) How have economic and social forces shaped water demand during the development of the city of Tucson?	0	2
Hydrology and climate modeling		
8) Are there real trends of runoff decrease in the Colorado River? What are the reasons for these decreasing trends (climate variability, land use changes, increasing groundwater abstractions, others …)?	2	8
9) How will water resources in the Tucson basin be affected by changes in precipitation patterns caused by climate and land use changes?	2	4
10) How is natural recharge of the Tucson basin aquifer likely to be affected by changes in precipitation?	2	0
11) How is the quality of groundwater affected by CAP recharge? What are possible explanatory variables (type of agriculture, urban development, industry, petrol stations...) for variations in groundwater quality?	0	4
Socio-ecological modeling		
12) How is water demand affected by changes in the social structure (demography, economy, land use, energy price)? Are scenarios under the IV TAMA Management Plan capable of meeting safe yield by 2025?	2	9
13) In the context of agricultural water use, how much of the water is imported (from out of state) and how much is exported (as food products)? How does the price of energy affect agricultural water use?	1	7
14) What kinds of terrestrial ecosystems exist in the Tucson basin and how much aquifer recharge do they generate? How does land use change affect aquifer recharge?	1	2
15) What are the main factors explaining urban water demand? What are the reasons for observed decreases in demand?	0	5

The most valued questions were those related to institutional and management settings, with an emphasis on the groundwater credit system. Other uncertainties like the shortages of water transfers in the CAP due to runoff decrease and the influence of changes in societal demand towards achieving safe yield were remarked in the other research areas.

Identification of Knowledge Gaps

After the initial prioritization exercise, participants were asked to spend 10 minutes thinking about key issues that had not been addressed in the initial proposed list of research questions and write them on a card. Below is a list of research questions proposed by participants grouped by category.

Hydrology and water availability

Stakeholders

- How will environmental water demands and ecosystems services be affected by changes in precipitation, climate and land use?

SWAN/Academia

- What are the space-time dynamics of water recharge/replenishment and removal from the TAMA system?
- How do these affect eco-biology of the system?
- How will groundwater withdrawals from shallow aquifer areas impact riparian habitats? Research on particular areas and sub-basins.

Socio-ecological modeling

Stakeholders

- What are the impacts of improved effluent water quality on natural systems?
- What emerging contaminants are found in CAP and effluents and which are their potential impacts?
- How to connect private well owners into water management? Decision making particularly in basin “edge” areas?
- How do environmental needs get factored into water resource decision making and management?

SWAN/Academia

- Future hydro-social impacts/dynamics of groundwater recharge credits and banking (especially future withdrawal)?

Institutional and policy analysis

Stakeholders

- How will changes in precipitation impact urban run-off? Potential impacts on growing green infrastructures investments?
- Where and how can green infrastructure compete with grey infrastructure in meeting needs of environment and people in the basin / larger regions? (for instance watershed restoration vs. new pipes and pumps)
- What format for regional water management are feasible in the Tucson basin, given the political state water law and private/public providers?
- What management choices can get us out of the trap of pitting human water demands against ecosystems water needs? Which are the win-win solutions?
- Which water use choices have the greatest potential to reduce trade-offs (conflicts) between human benefits (economic, growth etc) and natural systems functions.
- How does knowledge about natural systems values and vulnerabilities change water use choices at the level of individual users and policy makers?

SWAN/Academia

- Does rainwater harvesting create a “fixed demand” that has to be met using municipal water during drought (or even summer pre-monsoon)?

- Reflect on experience (successes and failures of water W/SP Public consultation). What is the appropriate outreach platform /techniques?

Other type of questions

Stakeholders

- What are resource needs and distribution scenarios for local food production?

SWAN/Academia

- How can this info/knowledge be used to better inform the public and affect the social and policy discourse?
- Could there be unintended consequences in adaptation efforts? (no regrets?)
- What are the gaps for water spatialised information? Since boundaries of water use change, you can't have spatial breakdown on urban demand, but only sectorial (like the water budget).
- Concerning the use of reclaimed water, is there an assessment of the effects on its use by the agricultural production in terms of food security and health?

Discussion

In the final part of the exercise participants were first asked to comment on the initial list of proposed research questions. They were then invited to present each of their new proposed questions, opening the floor to contributions and discussion with other participants. Below is a summary of the main issues that were raised during the discussion.

Water & Environment

- Environment and ecosystems water needs are not explicitly considered in the SWAN proposed list of research questions.
- Competition between increasing demand for the environment and from private well owners due to climate change, increases risks and vulnerability.
- Limited understanding of shallow groundwater dynamics is a significant limitation in the TAMA region. An updated well inventory, spatial information and groundwater modeling is required to better understand aquifer dynamics and the spatial distribution of effects from pumping and artificial recharge sites over shallow groundwater areas, and dependent ecosystems. This information could inform proposed spatial distribution of wells to minimize groundwater capture from environmentally valuable areas and thus maximize biodiversity conservation, in addition to achieving safe yield. .
- Over 70% of the Tucson basin region biodiversity concentrates in shallow groundwater areas. Mapping of key biodiversity hotspots linked to the levels of groundwater could help better target these areas for protection, concentrating pumping in regions where its impact is minimal to existing and potential riparian systems. Similar work such as the groundwater capture map in the San Pedro Basin and other initiatives in the Verde Basin were mentioned as precedent and illustrative examples.

Water & Food security, environmental justice

- Unequal access to shade and street runoff are key concerns in Tucson.

- Local food production. Inequalities in the access to water and food. Options for self-sufficient agriculture.
- Aesthetics versus ethics. Spatial classes segregation, functional relations of vegetation. Cultural gap between social classes, language.
- Higher dependency on ecosystem services of poor communities.
- Rainwater harvesting as local adaptation strategy. Rights? Conflict with prior appropriation rules? Additional demand to be managed? Options for upscaling?

Institutions & Management

- Most research questions proposed by SWAN are targeted to understanding the current situation while less attention is paid to potential future pathways, both in the immediate future and over the long term. Problems are already known by local stakeholders and expressed in different reports.
- What management choices can get us out of the trouble of confronting social and environmental demand? Where are the win-win choices? Where are they not? Which are the trade-offs?
- Potential pathways to face the fact that environment is not at the table in the Water Management Law. Inflexible institutions (rules to fix rules).
- Aquifer considered as a black box in the TAMA goals. Unacknowledged budget in relation to credits. GW replenishment district used to demonstrate 100 years availability but spatial disconnection between recharge and cuts. Cuts to the aquifers depending to the distance to the recharge area?
- Atomization of institutions, lack of coordination, pressure on discourses. 2008-2011 participatory process for Tuscon area infrastructure sustainability. Failures and successes? better cooperation between some administrations, the activist community is well informed.
- Motivation of institution to act? Institutions’ driver is to meet customer needs. Leverage points? Water resource availability as increasing pressure to make institutional changes - information requirements on CAP supply.

Stakeholder Mapping

Table A4.2 - Relevant stakeholders in the Tucson basin related to water management issues

Decision makers	Users and stakeholders affecting water system	Other stakeholders not affecting water system
Arizona Department of Water Resources	Agri-Business Council of Arizona	College of Agriculture and Life Sciences, University of Arizona
Bureau of Reclamation	Arizona Mining Reform Coalition	Department of Hydrology and Water Resources, University of Arizona
Central Arizona Project / CAGRD	Pascua Yaqui Tribe Land Department	The Nature Conservancy
City of Tucson	Tohono Tribe Water Resources Department	Save the Scenic Santa Ritas
Metro Water District	Business community	Hispanic Chamber of Commerce
Pima Association of Governments	Flowing wells irrigation district	Watershed Management Group
Pima County	Vail Water	Sonoran Institute
Tucson Active Management Area	Oro Valley (Philip Letto, John Kmiec)	Tucson Audubon Society
Tucson Water	City of Marana	Santa Cruz Pog (retirement community)
Southern Arizona Water Utilities Association	Herb	Friends of the Santa Cruz (Prescott VAnderbold)
	Fico-Green Valley	La Cienaga Creek Natural Preserve
	Chamber of Commerce (Ron Shorman)	

Appendix 5

Multi-criteria spatial analysis of sustainability in the Tucson AMA Water Accounting Areas.

In this appendix I develop a multi-criteria comparison of the three dimensions of sustainability for the different Water Accounting Areas (WAAs) with the aim of generating useful information that supports future sub-regional planning in the Tucson basin. The ADWR is on the process of disaggregating the water budget to the WAAs scale as proposed by the Safe Yield Task Force. A semi-distributed analysis of the water metabolism will then be possible. In the meantime, we downscale the overall sectorial budget for each Area to have an initial idea about how this is unfolding.

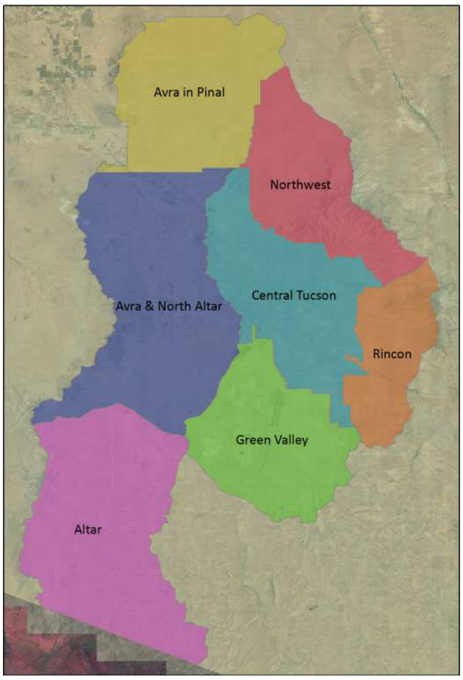

Figure A5.6 - Water Accounting Areas in the Tucson AMA

Methodology

The set of indicators chosen for each analytical dimension are explained in Table A5.1.

Table A5.1 – Definition of sustainability indicators for Water Accounting Areas in the Tucson basin

Dimension	Indicator	Description	Unit
Water metabolism	Water sources	Water supply sources in each WAA	-
	Water use	Total water use and shares of each sector	AF
	CAGRD area	Part of each WAA covered by the CAGRD membership	%
	Exempt wells	Number of exempt wells in each area according to the Wells Registry 55 database downloaded from the AWRD in December 2014	Nº
Social	Population 2010	Population in each WAA according to the American Census 2010 (5 years average)	People

	% Population growth 2000-10	Difference of population in each WAA from 2000 to 2010 census	%
	% Urban area growth & main density type 01-11	Difference of area classified as urban in the USGS land cover map of 2011 regarding 2001	%
	Housing units	Total number of housing units in each WAA	Nº
	Median age	Average of median each for each WAA	Nº
Economic	% Employment	Number of people with employment out of total active working population.	%
	% Economic sectors	Percentage of total employment in each economic sector	%
	Income per capita 2010	Average income per capita of all Census Designated Places in each WAA	$/yr
Environmental	GW level range 2009	Maximum and minimum monitored water table levels in 2009	Feet
	Aquifer area with declining table 00-09	Part of the aquifer in each WAA where water table decreased from 2000 to 2009	%
	Max GW decline	Maximum groundwater decline in each WAA from 2000 to 2009	Feet
	Nº & surface SGWA (acres)	Number of Shallow Groundwater Areas in each WAA and surface within them	Acres
	SGWA over declining GW levels	Parts of Shallow Groundwater Areas that overlap aquifer levels decline from 2000 to 2009	%
	Water bodies & wetlands area growth	Increment of land cover classified as water bodies and wetlands in the USGS land cover map of 2011 regarding 2001	%

The indicators have been calculated for each WAA through geo-processing in ArcGIS 10.1 from the different information sources shown in Table 5.2 in Chapter 5. Both raw and processed data have been gathered in an ArcGIS personal geodatabase that can be opened and modified with Microsoft Access.

Water metabolism

Available sources have been assigned per area in relation to the water budget per sector and groundwater management information (recharge and recovery sites). The numeric code in the table is: 0=not used; 1= used; 2=to be confirmed.

The different water use sectors have been spatially disaggregated from the TAMA water budget through the following processes: The municipal service area was dissolved from the original shapefile and intersected with the WAAs layer. Proportional to overlaps with each WAA, municipal and industrial demands were downscaled per Service Area in each WAA, while discounting the area covered by mining operations. Mining sector demand was downscaled per area in each WAA and agricultural demand per area of IGFRs with actual Irrigation (attribute in the shapefile). Indian Nations demand was assigned to Avra&North where Tohono D'Oham Nation is located.

Exempt wells from the Registry 55 were intersected with the WAAs layer. Finally, the CAGRD service and new development areas were intersected with WAAs to have an idea of the surface in which groundwater can be withdrawn by their members.

Socio-economic

Data from census 2000 and 2010 was downloaded for all Census Designated Places (CDPs) in Arizona from America Fact Finder[48] as well as shapefiles of CDPs from Tiger geodatabase for the two dates. Each CDP was assigned to a WAA using a topological criterion of polygon centroid. The most unclear one was Marana which is between Central Tucson and Avra&North Altar. Following the topological rule it was assigned to the later. Socio-economic variables were calculated as averages per WAA with Summary Statistics over the table of attributes of CDPs on 2000 and 2010.

Urban growth and density was obtained from the difference between the USGS Land Cover maps 2011 and 2001. Raster maps were converted to shapefiles and intersected with WAAs. The evolution of the surface area of wetlands and water bodies has been also calculated from these layers.

Environmental

Groundwater levels have been interpolated through Inverse Distance Weight geoprocess (IDW) of the point layer with levels measured in 2009. The range of levels obtained from resulting raster was processed with the Statistics to Table ArcGIS geo-process.

Groundwater level change was calculated interpolating of point layer attribute difference between years 2000-2009 and 2003-2013. Because for the second period there is a significant lower number of monitoring points, the analysis is based on the former while taking into account the later. The area of aquifer with declining water table levels was digitalized over the raster for the 2000-09 period.

The number and area of Shallow Groundwater Areas (SGWAs) within WAAs was obtained from the intersection of both layers. The percentage of SGWAs located over regions with declining GW levels was generated by intersecting the aquifer area with declining levels with the area of SGWA within each WAA.

Results

The results obtained are shown in Table A5.2, maximum values for each indicator are emphasized in bold.

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[48] http://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t#

Table A5.2- Sustainability indicators for the Water Accounting Areas

		Avra Valley Pinal	**Avra & North Altar**	**Altar**	**Northwest**	**Tucson central**	**Rincon**	**Green Valley**
	ACRONYM	**AVP**	**AVR**	**ALT**	**CAT**	**TUC**	**RIN**	**GRV**
Water sources	CAP direct	2	1	0	0	0	0	2
	CAP in lieu	1	1	0	0	0	0	1
	CAP recovered	2	1	0	2	1	2	2
	Groundwater	1	1	1	1	1	1	1
	Reclaimed	0	1	0	0	1	0	1
	Reclaimed recovered	0	1	0	2	1	0	2
Water use	Total (AF)	4,415	**122,970**	4,798	45,895	**214,621**	22,316	64,897
	% M&I_Service	0	44	0	80	89	88	38
	% Mining	0	2	0	0	0	0	57
	% Agricultural	100	40	100	20	11	12	5
	% Indian	0	14	0	0	0	0	0
	Exempts wells	617	**1,407**	662	819	**3,714**	907	1,206
	Area of CAGRD (%)	0.01	**0.5**	0.0	0.15	**0.94**	**0.45**	0.11
	Evapotranspiration							
Social	Population 2010	2,169	105,807	695	61,920	688,599	15,347	47,262
	Population growth (%)	**2168**	56	**695**	53	7	**518**	115
	Urban area growth & main density type (%)	11.7 High and medium	11.9 High	0.2 Low	**35.2 High**	13.8 High	**100 Medium and high**	**32.0 High**
	Housing units	786	43,069	492	31,332	308,469	5,798	28,190
	Median age	27	41	**58**	**53**	38	40	51
Economic	Employment rate (%)	NA	100	79	93	88	95	95
	% Agriculture & mining	NA	1.8	0.0	**1.9**	0.8	1.5	**3.0**
	% Manufacturing & trading	NA	**28**	0	25	24	**28**	**31**
	% Building & real state	NA	1.2	0	**8**	7	**8**	6
	% Services	NA	50	**100**	41	**57**	41	45
	% Government	NA	8	0	7	7	**19**	**11**
	Income per capita average 2010 ($/yr)	NA	19,523	23,507	34,086	26,168	35,094	29,778

Environmental	GW level range 2009 (feet)	53 - 452	**85 - 736**	4 - 460	19-687	11-655	23-608	9-453
	Aquifer area with declining table 00-09 (%)	4	21	61**	**95**	**72**	**71**	59
	Max GW decline (feet)	-4	-22	-**	**-71**	**-44**	**-45**	**-46**
	Nº & surface SGWA (acres)	0	1 - 368	5 – 3,853	7 – 1,029	**9 – 10,709**	**8 – 3,087** (83,013)*	3 – 1,491 (94,635)*
	SGWA over declining GW levels (%)	-	0	-**	47	**63**	25	**100**
	Water bodies & wetlands area growth (%)	2	79	**90**	6	9	11	**248**

* Whole SGWA system

** No representative data

Water metabolism

ALT and AVP are the only WAAs with water demand exclusively devoted to agriculture and a minor number of exempt wells. On the other hand TUC and AVR show the highest water demands and exempts wells. AVR stands out for containing all types of water uses and sources: the Tohono O'Odham Nation is located there, and the Area contains the greatest irrigation surface, an important urban area in Marana and two mines. It also contains the major CAP-USF as well as GSF and reclaimed water USFs. CAT, TUC and RIN demand is mostly urban depending on municipal providers, exempt wells or CAGRD. TUC has three reclaimed water USFs and uses direct reclaimed water, as well as imported recovered CAP water from AVR. GRV contains 3 recharge sites, one for CAP right south of Tucson city and 2 for effluent in the south disconnected from CAP. The greatest mines with groundwater withdrawal permits are located here as well as a significant number of exempt wells.

Regarding the area covered by the CAGRD (including service and new subdivisions), TUC is mostly covered in all its extension and AVR and RIN in half of it. CAT and GRV have a lower cover but the largest shares of new subdivisions (2% each).

Socio-economic

Population and urban areas have grown in all WAAs, and most of them are also densifying. ALT and AVP had their first Census Designated Places recognized in 2010 and thus their population was accounted in this census for the first time.

ALT is a particular case of low density urban development with the eldest population in average and lowest employment rate. It is specialized on the services sector related to ecotourism. On the other hand, AVR, RIN and GRV show the highest employment rates, maintaining a significant rate of agriculture and mining employment and an important manufacturing sector.

The Santa Cruz sub-basin is the one that has experienced a greater development in the last ten years, mostly in RIN, CAT and GRV. RIN and CAT show very similar patterns: peak income per capita of all WAAs, a relatively lower importance of the services sector and the highest share of employment on real state and building activities. A remarkable difference is the relevance of the government sector in the RIN WAA with up to 19% of the employment. The GRV area also shows average income per capita higher than in the other Areas, highlighting the relevance of the mining sector.

TUC is the WAA that grew in the slowest pace in the last decade, essentially because it is already mostly urbanized. Expansion areas move up the hills in Tanque Verde, Catalina Foothills and Casas Adobes. These three CDPs raise the average income per capita since Catalina Foothills and Tanque Verde have the highgest of all CDPs (>45,000 $) while Tucson city has the lowest of all (20,300 $). They also have elder population and higher employment rates than Tucson.

Environmental impacts

Groundwater levels are increasing in most of the AVR and AVP area north of the recharge sites. Interestingly, AVR is still the area where the water table is the deepest of all, indicating that most groundwater overexploitation occurred here. This is likely related to the fact that most historical agricultural activity has taken place in this area. South of recharge sites in AVR, levels were still dropping in 2009. ALT data shows a mellow decline of 6.9 feet/year on average for its central part. Nevertheless, land cover maps show that an important increase in herbaceous wetlands has been experienced along the central riparian area from 2001 to 2011. This WAA counts with only 4 monitoring wells, and therefore interpolation results might not be very representative. More monitoring wells would be advisable. CAT, TUC and RIN are located over the wide Upper Santa Cruz aquifer plateau and show similar groundwater depths. They also have the highest portion of the aquifer with dropping levels concentrated around three hotspots: mines and new developments of Green Valley CDP in GRV, new developments of Rincon Valley CDP in RIN and Oro Valley and Casas Adobes CDPs in CAT.

Six of the seven WAAs have Shallow Groundwater Areas (SGWA), most of them located around the mountain ranges of Catalina and Rincon mountains (NEW, TUC and RIN). RIN and GRV have small parts of the largest SGWA-dependent systems that continue outside the TAMA. The interpolation of groundwater monitoring points shows that all WAAs of the Tucson aquifer have parts of the SGWA over declining groundwater levels, albeit these declines are low (~0-12 feet on average for the period 2000-2009) in the Tanque Verde-TUC area and moderate in Northwest CAT (~12-24 feet) and RIN (~24-37 feet). The updated data for 2003-2013 level changes shows the continuous recovery of Tucson central levels and a greater and more extended decline in the GRV hotspot up to 72 feet. An enormous increment of water bodies area in the GRV is observed due to the huge pools inside the mines.

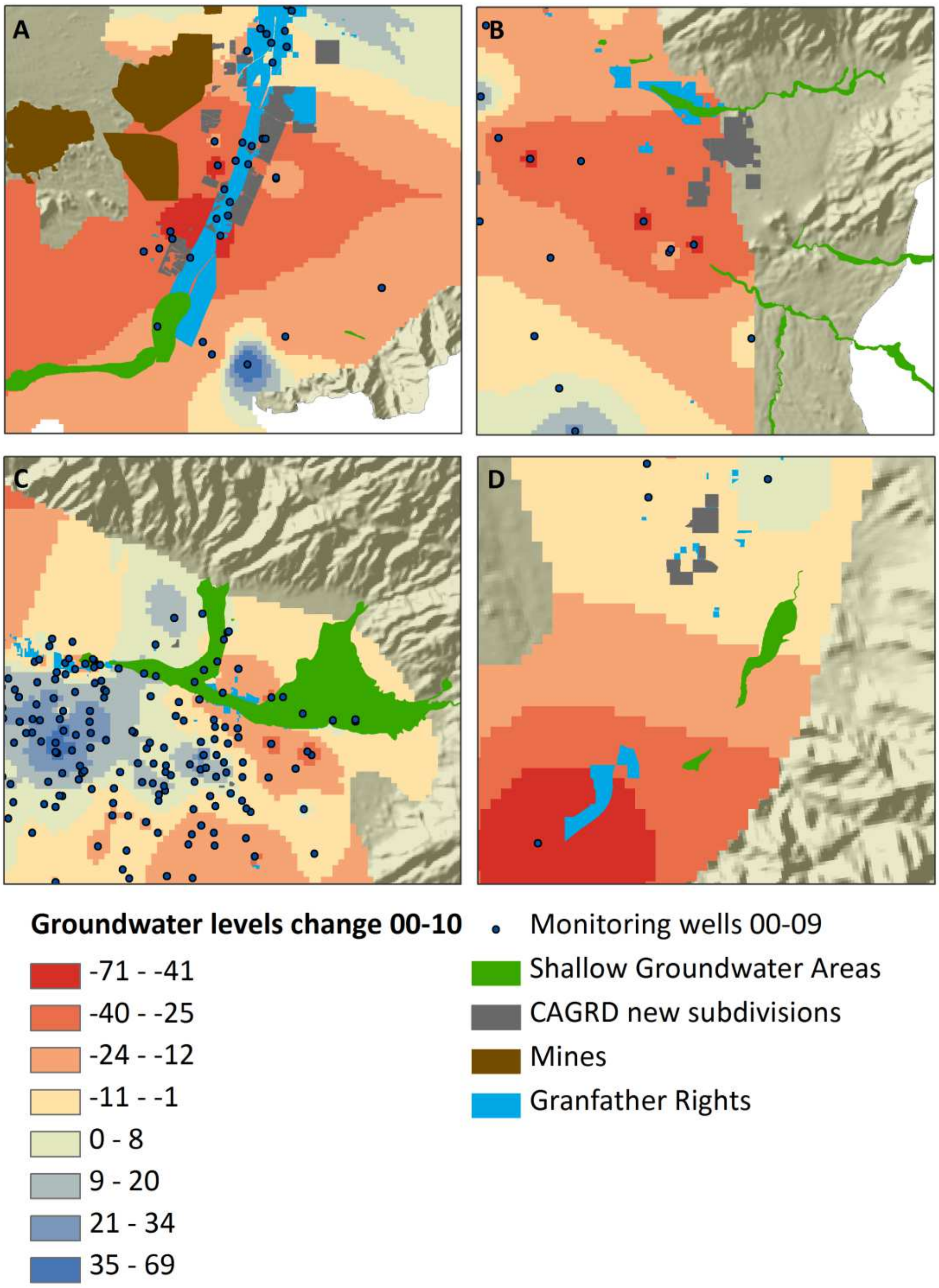

Figure A5.2 - Detailed maps of SGWA A – Santa Cruz – Sopori Wash in GRV; B – Cienaga and Rincon creeks in RIN; C – Tanque verde in TUC; D – Sutherland Wash in CAT

Appendix 6

Table A6.1 - Comparative of WFD and GMA

	Water Framework Directive	Groundwater Management Act
Year of approval	2000	1980
Planning horizon	Six year planning cycles (2015-2021-2027)	2025
Spatial scope	European Union Member States	State of Arizona
Sustainability objective	Achieve good status (chemical and ecological) for surface waters and chemical and quantitative for groundwater by 2015	Achieve specific groundwater management goals for each Active Management Area (Safe yield for Phoenix, Pinal and Tucson AMA, and maintain agricultural economy for Pinal AMA)
Governance regime	Centralized in River Basin Authorities in cooperation with sectoral policy administrations (agricultural, industrial, land use, etc.)	Decentralized in water providers and groundwater users
Planning mechanism	Management plans in 6 years cycles for each river basin lead by River Basin Authorities	Managements plans for each AMA in 10 year cycles lead by the ADWR
Management extent and delimitation criteria	River basins based on surface hydrological criteria. Environmental objectives are assigned for each surface and groundwater body	Active Management Areas in highly populated areas based on groundwater hydrological criteria

Appendix 7: Curriculum Vitae (10/2015)

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Twitter: @vcabellov @WaterP2P Research Gate Academia.Edu Linked-in

RESEARCH INTERESTS

Multi-scale connections between water governance, socioeconomic and ecohydrological processes; modeling of complex socio-ecological systems; land-water-energy-food nexus; inter and trans-disciplinary practices in sustainability research; citizen science; open data and ICT's for natural resources management.

ACADEMIC EDUCATION

Andalusia Center for the Environment. University of Granada. Spain

Msc. Environmental Hydrology. 2008

Thesis : Semi-distributed model of nutrients transport in the Guadalfeo river (South-East Spain). Published ISBN 978-84-692-4197-4

Department of Environmental Sciences. Halmstad University. Sweden

Msc. Applied Ecology. 2006

Thesis: Pathogens and nutrients removal in stabilization ponds in Kalyani, West-Bengal (India)

University of Malaga. Spain

Bsc. (5 year program). Environmental Sciences. 2007

ACADEMIC APPOINTMENTS

International EU research projects manager. BIOAZUL S. L. 2009-2010

University Teachers Education Program (FPU). Spanish Ministry of Education. 2010-2014

Sustainable Water Action-SWAN- EU FP7 INCOLAB research project. University of Seville. 2015

RESEARCH PROJECTS

Sustainable Water Action-SWAN- Building research links between EU and USA. INCOLAB VII EU Framework Program 2013-2016

Citrus-ProPlanet. Coordinated by Global 2000, funded by REWE. Participatory workshop coordinator. 2013-2016.

Participatory planning of water management alternatives in the Andarax river basin (ALTAGUAX). EU ALERT Program. 2009-2012.

Participatory Agenda 21 in Órgiva (Spain). Federación Andaluza de Ciencias Ambientales. 2011-2013

Trans-boundary Water Basin Management: Jordan River (TRANSBASIN). Marie-Curie VII EU Framework Program. 2011.

Biotechnological recycling of olive mill rinse water by micro-algae (ALGATEC). Research for SMEs VII EU Framework Program. 2009-2010.

PUBLICATIONS

Peer review journals

Cabello, V. Willaarts, B., Aguilar, M., and del Moral, L. River basins as social-ecological systems: Linking levels of societal and ecosystem metabolism of water in a semiarid watershed. *Ecology and Society* 20(3):20.

Pedregal B., Cabello V., Hernandez-Mora N., Limones N. and del Moral, L. 2015. Information and knowledge for water governance in the networked society. *Water Alternatives* 8(2):1-19.

Hernandez-Mora N., Cabello V., di Stefano, L. and del Moral, L. Networked water citizen organizations in Spain: Potential for transformation of existing power structures for water management. *Water Alternatives* 8(2): 99-124.

Cabello Villarejo, V., Madrid Lopez, C. 2014. Water use in arid rural systems and the integration of water and agricultural policies in Europe: the case of Andarax river basin. *Environment, Development and Sustainability* 16(4):957–975.

Ravera F., Gamboa G., Scheidel A., Dell'Angelo J., Serrano T., Mingorría S., Cabello V., Ariza P., Arizpe N. 2014. Pathways of rural change: An integrated assessment of the metabolic patterns of emerging ruralities. *Environment, Development and Sustainability* 16(4):1-10

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

Sova Patra Das T., Avila, C., Cabello V., Castillo F., Sarkar D. Lahiri S., Jana B. 2012. Cadmium tolerance and antibiotic resistance in Escherichia coli isolated from waste stabilization ponds*. Indian journal of experimental biology* 50(4):300-7.

Book chapters

Cabello V., Hernandez-Mora N., Serrat-Capdevila A., and del Moral L. 2016. Water use and sustainability in the Tucson basin: implications of a spatially neutral approach to groundwater management. In Gupta H., Gupta M.,Poupeau F., Serrat-Capdevila A., (Eds)*Water in the Desert. A transatlantic transdisciplinary dialogue.*

Working papers

Serrat-Capdevilla A., Cabello-Villarejo, V., Boyanova K., Poupeau F., Rodriguez, D., Salmoral, G., Segura, S., Yang, Z. 2014. *Analyzing new challenges for water management: a review of existing conceptual frameworks and outlines for a trans-disciplinary approach*. Deliverable of the Sustainable Water Action- SWAN- project. EU Incolab FP7.

Madrid, C. & Cabello, V., 2011. *Re-opening the black box in Societal Metabolism: the application of MuSIASEM to water*. ICTA Working Paper. http://www.recercat.cat//handle/2072/172087

RELEVANT INTERNATIONAL CONFERENCES

International Conference on Data, Information and Knowledge for Water Governance in the Networked Society. Seville. Jun 2014. Co-organizer. http://grupo.us.es/giest/es/node/906

IX Iberian Conference on Water Planning and Management. Lisbon. Dec 2013

Multiscale analysis of water metabolism to evaluate water planning scenarios. Communication

Transdisciplinary approach for sustainable action on water issues. Poster

IV EUGEO Congress: Europe, what's next? Changing geographies and geographies of change. Rome. Sep 2013. *The integration of water and agricultural policies: a societal metabolism approach.* Communication

EGU Leonardo Topical Conference Series on the hydrological cycle. Hydrology and Society: Connections between Hydrology and Population dynamics, Policy making and Power generation. Turin. Nov 2012. *Analyzing water metabolism in Socio-Ecological Systems: A Multi-Scale Integrated Approach*. Communication

ESEE 2011: Advancing ecological economics: theory and practice. Istanbul, Turkey. Jun 2011. *Multi Scale Integrated assessment of Socio-ecological metabolism of water*. Communication

RELEVANT SEMINARS

Water use and sustainability in the Tucson basin: implications of a spatially neutral approach to groundwater management. SWAN 4th Annual meeting. Sofia, Bulgaria. Apr 2015

#WaterP2P: An introduction to the citizen science and open knowledge movements. What about water? SWAN Central Seminar. University of Arizona, Tucson, USA. March 2015

Multi-scale analysis of Socio-Ecological systems metabolism: application to the Tucson basin. Kick-off meeting of the Observatory of Man and the Environment OHMI- project. University of Arizona, Tucson, USA. Nov 2015

Water Metabolism in Socio-Ecological Systems: A multi-scale integrated approach. The Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis. Indiana University, Bloomington, USA. May 2013

MuSIASEM for Water. Workshop on Water Metabolism. Universidad Pablo de Olavide, Seville, Spain. May 2012

TEACHING

University of Seville. Spain.

Arc-GIS: Vector data. Bsc. History and Geography. 2012/13 , 2013/14, 2014/15

Course on participatory methods for teaching. Institute of Education. Jan 2014

Course on participatory methods for research. Institute of Education. Feb 2014

VISITING STAYS

Funded by competitive grants

UNESCO-Institute for Water Education. Mar-May 2014

Department of Water Resources Planning

University of Arizona (USA). Mar-Jul 2013

iGLOBES – Interdisciplinary and Global Environmental Studies Center

REASM – Regional Economics and Spatial Modeling laboratory

Other stays

University of Arizona (USA). iGLOBES – Interdisciplinary and Global Environmental Studies Center. Nov 2014 – Mar 2015

University of Barcelona (Spain). Institute of Environmental Sciences and Technology. Sep 10 – Jun 11

University of Kalyani (India). International Center for Ecological Engineering. Mar-Jun 2006

FACILITATION OF PARTICIPATORY AND RESEARCH WORKSHOPS

Citrus-Proplanet project. *Water conservation at the farm scale.* Valencia (Spain). Mar 2014.

SWAN project

> *Let's tell the story of the Tucson basin case-study.* 5th progress meeting. Tucson (USA). Nov 2014
>
> *I participatory workshops on water research management links in the Tucson basin.* Tucson (USA). Oct 2013
>
> *New paradigms of water management and risks: data and information.* Seville (Spain). Jan 2013

ALTAGUAX project

> V workshop*. Decision Support System presentation and assessment.* Almeria (Spain) 2012
>
> IV workshop*. Collective allegations to the River Basin Management Plan*. Participant. Almeria (Spain) 2010

COMPLEMENTARY EDUCATION

IIFACe Institute for facilitation and change Spain

> *Introduction to groups' facilitation*. 2015
>
> *Basic course on groups' facilitation.* 2015-2016

Coursera

> *Introduction to R programming.* 2013
>
> *Data analysis with R.* 2014

University of Seville

> *Qualitative research methods.* 2012
>
> *Geographic Information Systems and Geodatabases I and II.* 2012 and 2013
>
> *Spatial databases: PosGis.* 2014

LIPHE4 Scientific Society. 7th Summer School: *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM): An innovative approach to energy analysis.* Barcelona (Spain). 2012

XV International Erasmus Program Seminar on Geography of Water. *Sustainable Water Policies for Europe*. Munich (Germany). 2012

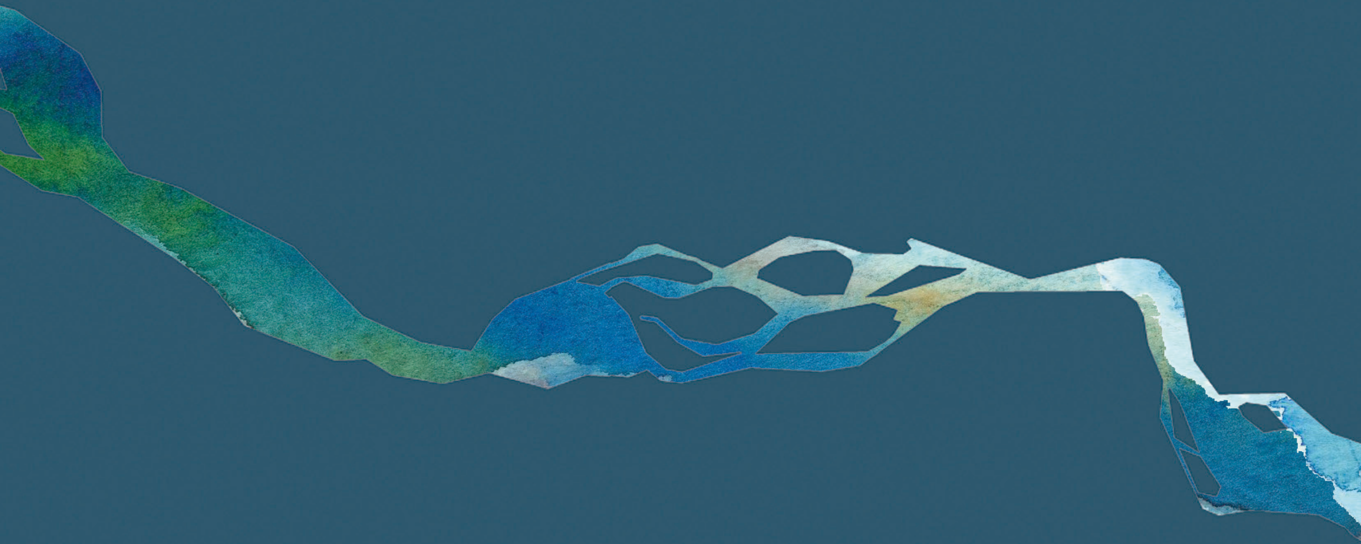
SCARCE-CONSOLIDER Project. *Economics for water ecosystem services management*. Seville (Spain). 2011

UNIA International University of Andalusia

> *Image code: data visualization with Processing*. 2011
>
> *Digital tools for participatory mapping*. 2011
>
> *Complex Thought and Sciences for Complexity.* 2011

LANGUAGES

Spanish: Native speaker English: Proficient user Portuguese: Basic user



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