ECOSYSTEM SERVICES IN PLANNING PRACTICE FOR URBAN AND TECHNOLOGICALLY ADVANCED LANDSCAPES

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Regional Planning
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2012

Urbana, Illinois

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ABSTRACT

Research on ecosystem services strives to build stronger linkages between ecological and economic systems in order to improve ecosystem management and human well-being. By clarifying how human populations benefit from ecosystems we may protect valuable ecosystem functions and improve human welfare more strategically. To advance the field of ecosystem services my dissertation asks three questions:

(1) How can historical research inform why ecosystem based management approaches have been integrated or ignored into watershed management?
(2) What is the relationship between technological innovation and the value of ecosystem services?
(3) Can the restoration of ecosystem structures and functions influencing stream temperature provide valuable ecosystem services for water treatment managers?

I focus on ecosystem services in the Llobregat watershed near Barcelona, Spain, where over 3 million residents rely on the Llobregat River for basic water needs. The withdrawal of drinking water from the Llobregat River has created clear linkages between local well-being and the river's aquatic ecosystem. Two water treatment facilities withdraw water from the Llobregat, and both have recently installed desalination technology. However the new treatment systems are expensive to operate. In this urban and technologically advanced context, I explore how ecosystem services may be managed to meet environmental and economic goals.

Chapter 1 reviews the literature on ecosystem services, describes the study area, and begins to outline my argument developed in the dissertation. The number of articles published on the topic of ecosystem services has exploded in the last decade, and in this chapter I describe how my research contributes to this discussion. One major argument pertains to the sequence in which the field usually studies the linkages between ecological and economic systems. Most research begins with the biophysical; and later draws on the social sciences to attach monetary values to ecosystem structures or

functions. Instead, I propose that we study the economic system first, including its decision-making and technological context, and then allow our ecological research to follow from that insight.

Chapter 2 consists of an environmental history that examines the individuals and institutions that have controlled the flow of water in the Llobregat River, and by extension, dictated water management practices. The study of ecosystem services is often presented as a new and innovative framework for addressing environmental problems. Through archival research and personal interviews, I examine how historic resource users have integrated or ignored this framework for decision making in the Llobregat watershed. I find that throughout the twentieth century, most river managers did not adopt an ecosystem services approach, but rather favored hardscaped and structural solutions. At the same time I find that proposals to manage ecosystem services related to flood control were proposed as far back as 1890, and these ideas were implemented in the 1930s. Notions of ecosystem services have more than a century of history in the watershed, and yet they have not played a central role in river and water management. Structural approaches have dominated decision making and continue to play a dominant role, as most recently demonstrated by the installation of desalination treatment plants. The recommendations from the Commission for the Study of Salinity of the Llobregat River (CESALL) in 1932 outlined structural solutions for addressing the Llobregat River's water pollution and supply problems, and these recommendations had a lasting impact for the remainder of the twentieth century. I argue that our current system of water treatment and distribution reflects a historical tradition that has favored technological fixes when addressing water management problems.

Chapter 3 examines the value of urban ecosystem services when sophisticated technology mediates our relationship with ecosystem processes. Most research on ecosystem services is being conducted in natural or pristine areas, while less attention has been directed at urban ecosystem services and their relationship with technological change. Understanding the relationship between technological change and the value of ecosystem services is relevant because it may broaden the circumstances in which ideas about ecosystem services may be implemented in practice. I argue that the expected tradeoff between natural and manufactured capital is false. Rather, the adoption of new technologies is complementary to ecosystem management. This point is illustrated with a case study that analyzes how the installation of sophisticated drinking water treatment technology increased the value of ecosystem services in Barcelona, Spain. The implication is that the supply of ecosystem services is not fixed; and technological change will reshape which ecosystem services are valuable but not obviate the need for them entirely.

Finally, in Chapter 4 I use a biophysical stream temperature model to assess how increases in riparian vegetation and stream discharge may reduce stream temperatures and treatment costs downstream. This chapter serves as an example of the type of research that I am proposing for the field. The type of ecological modeling I chose emerged from an analysis of the technological and decision-making context of ecosystem users. By modeling different ecological scenarios, I find that existing forests along the Llobregat River save water treatment managers €79,000 per year, while the restoration of additional riparian forests could generate economic savings in the range of €57,000- €156,000 per year. Stream restoration at higher elevations would yield greater benefits than restoration in the lower reaches. Moderate increases in stream discharge (25%) could generate savings of €40,000 per year. This research underscores that ideas about ecosystem services have the potential to be more widely adopted if research focuses on the demand for these services rather than the supply.

Acknowledgements

This dissertation would not have been possible without the support from my family, friends and colleagues. I thank my advisor, Daniel Schneider, for allowing me to pursue my own research path while also keeping me on track when I went astray. Nick Brozovic provided insightful commentary every step of the way and displayed extraordinary patience when I came with questions. Similarly, I benefited from several discussions with Edward Feser and Pedro Arrojo, both of whom made constructive and perceptive comments during the defense.

Lew Hopkins and Elizabeth L. Sweet made it possible for me to join the doctoral program at the Department of Urban and Regional Planning at the University of Illinois. The University awarded me a fellowship during my first year, and later offered me a Teaching Assistantship, a Dissertation Travel Grant, a Tinker pre-doctoral research grant, and a fellowship from the Human Dimensions of Environment Systems program. I also was fortunate to be granted a Research Assistantship under the direction of Professor Kathy Baylis.

Early on, when searching for a dissertation topic, I relied on guidance from experts in the field of urban planning and water management. I was fortunate to be granted interviews from Narcís Prat, Enric Tello, Germà Bel, Rafael Mujeriego, Oriol Nel.lo, David Saurí, Josep Anton Acebillo, Marc Monlleó, Ignasi Puig, and Jaume Freire.

When my attention turned toward the Llobregat River, those familiar with the waterway welcomed me without hesitation. These stewards shared with me their ideas and aspirations, all of which, in some way, have helped me develop a stronger research project. In particular I would like to thank Roger Lloret, whom I met while preparing for a backpacking trek down the river in July 2008. Roger taught me about water treatment, water chemistry, and the river's history. He also arranged important interviews with numerous co-workers and friends. I also thank Àngel Miralda for accompanying me during my hike down the river for two days, as well as Héctor Oliva and Sara Ortiz Escalante for also

joining me on the adventure. Ricard Sosa, Lluís Canals and Rafael Fernández from the Catalan Water Agency (ACA) gave me a fantastic tour of the Baells Dam, even though my visit was unannounced. Neus Santamaria introduced me to the magical history of the company towns along the Llobregat River. Josep Ribera, David Hernández, Eloi Escudé, Marc Vinyals and the committed community organizers at *Prou Sal!* brought me up to speed with the river pollution controversy in Sallent. Their work largely inspired me to write about the salinity conflict in the Llobregat River. In Martorell, Rafa Diez and Roger Arqué from *Martorell Viu* accompanied me along the Anoia stream and its confluence with the Llobregat. Joan Bordas and Pep Clavero kindly spent a morning teaching me about the plant life in the lower Llobregat River. Mia Morante, Pau Fortuño and Nuria Sánchez gave me a lesson in macro-invertebrates and biological indicators as we collected water quality samples along the Llobregat and its tributaries. And Josep Ferret generously granted me an interview, shared articles about the Llobregat River written by his grandfather in the 1930s, and gave me two books on the history of the river, its aquifer and floods.

Major funding to complete this research project was generously provided by Centre Tecnològic de l'Aigua (CETaqua) and the Catalan Water Agency (ACA), with assistance from the Catalan Institute for Water Research (ICRA). This grant would not have been possible without the unwavering support from Carlos Campos, Joana Tobella, and Montserrat Termes at CETaqua; and Antoni Munné and Gabriel Borràs at ACA. I am deeply grateful for the confidence they deposited in me to execute a project which, at the time, was merely an idea. Similarly, Ignacio Escudero and Josep Lluís Armenter at *Aigües de Barcelona* (AGBAR) allowed me to consult sensitive water treatment data.

At the AGBAR water treatment facility in Sant Joan Despí, I received valuable assistance from Àlex Vega, who helped me find my way within the water treatment facility. I also thank Marc Pons, Albert Teuler, Antoni Bernal, Christian Solís, Josep Planas and the entire team at the AGBAR-Sant Joan Despí laboratory.

At CETaqua I would like to thank Benoit Lefèvre, Jose Luis Cortina, Oriol Gibert, Susana González, Xavier Bernat, Catalina Balseiro, Rosa Maria Pieras, Isabel Escaler, and Carlos Montero.

At ATLL I thank Fernando Valero, Àngel Barceló and Ramon Arbós for their patience when explaining to me the complexities of the EDR desalination system. Under exceedingly difficult circumstances, they have shown to be model public servants.

Many at ACA have shared valuable data or insight with me. Most notably, I would like to thank Mònica Bardina, Lluís Godé, Jordi Rovira, Josep Maria Niñerola, Carles Cardona, Rosa Serrano, Carlos Barbero, Jordi Molist, Joan Verdú, Victoria Colomer, and Evelyn Garcia.

The research team at the Catalan Institute for Water Research (ICRA) generously gave me institutional support during my time in Catalonia. Sergi Sabater and Vicenç Acuña were early believers in the project. Throughout late 2009 and early 2010, when the institutional support was stuck in an impasse, they displayed extraordinary perseverance and reasserted their support for this project. Once I was invited to join ICRA, I benefited from discussions with Rafael Marcé, Marta Terrado, Roberto Merciai, Daniel von Schiller, Elisabet Tornés, Marta Ricart, Lídia Ponsatí, Xisca Timoner and Ramon Batalla. Carmen Gutierrez, Olga Corral, Emma Collelldevall, Anna Cornella, Jaume Alemany, Iván Sánchez and Damià Barceló also provided essential support at ICRA.

Emi Turull at the *Museu de les Aigües* generously gave me several books on the history of AGBAR and water management in Barcelona. I am grateful that this productive exchange with the Museum has continued with Sonia Hernández and Rosa Prat. I had illuminating conversations about the historical research with Santi Gorostiza and Albert Fàbrega Enfedaque, both of whom generously shared with me many of their findings. Esteve Torrens Pérez de los Cabos provided me with the detailed description of his grandmother, Antònia Burés Borràs, in addition to family photos.

Jordi Badia, Florenci Vallès and Sergi Falguera taught me about the geology of the Llobregat watershed. Albert Soler gave me a fantastic field visit of the Cardener River, the restoration work at Vilafruns, and an explanation of groundwater flows. Jaume Ribera also took me on an informative hike along the Cardener River in Súria, and Josep Illa did not hesitate to provide me with background information about the restoration of riparian forests. Antonio Palacios from the *Àrea Metropolitana de*

Barcelona provided valuable comments on work in progress. Annelies Brockman, Quim Pérez, Daniel Barbé, and Jaume Desclòs oriented me with regard to the social issues and political tug of wars over water management in Catalonia. Álvaro Martínez-Novillo González paid for my computer repair after an opening car door knocked me off my bicycle.

I would also like to thank those who inspired me to pursue my doctoral studies in the first place, especially Lincoln P. Brower, Isabel Ramírez, Carlos Galindo-Leal, Lee Pagni, William Toone, Roger Paredes, Judith Serna and Daniel Camós.

Lastly, I thank my entire family for their unconditional support.

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CHAPTER 1. INTRODUCTION

1.1 State of the Literature on Ecosystem Services

People and cities depend on the goods and services produced by our planet's ecosystems. This dependent relationship between human well-being and the biophysical world is encapsulated by the relatively new notion of ecosystem services. The food we eat, the air we breathe, and the water we drink all derive from ecosystem processes. However our dependence on these ecosystems has not prevented us from stressing them and reducing their capacity to meet our needs (MA 2005). To maintain our valuable ecosystem services intact, we must improve resource management and decision making. The ecosystem services framework promises to bring together the ecological and social sciences to meet this challenge.

Journals are publishing new ideas about ecosystem services at an extraordinary rate. Within the last six years, five leading publications have released special issues on ecosystem services: *Ecology and Society* (Volume 11, No 2, 2006); *Ecological Economics* (Volume 65, Issue 4, May 2008); the *Proceedings of the National Academy of Sciences* (Volume 105, No 28, July 2008); *Frontiers in Ecology and the Environment* (Volume 7, Issue 1, February 2009); *Ecological Economics* (Volume 69, Issue 6, April 2010); *Ecological Complexity* (Volume, 7 Issue 3, September 2010); and again *Ecological Economics* (Volume 69, Issue 10, September 2010). In 2012, a new journal will be released with the title *Ecosystem Services*. Furthermore, the National Research Council issued a comprehensive report on Ecosystem Services entitled *Valuing Ecosystem Services: Toward Better Environmental Decision Making* that has synthesized this emerging discussion (NRC 2005). And internationally, the United Nation's *Millennium Ecosystem Assessment* adopted the ecosystem services framework to assess the state of the globe's ecosystems (MA 2005).

The most well-known categorization of ecosystem services divides them into four groups: (1) *provisioning services*, which refers to ecosystems' ability to generate essential goods such as timber, fuel, food and fiber; (2) *regulating services* which refers to the regulation of climate or the water cycle; (3) *supporting services*, such as pollination, population control, soil formation, and other ecological properties upon which life depends; and finally (4) cultural services, which provide humans with recreational, spiritual and aesthetic values (MA 2005). This categorization of ecosystem services, while useful conceptually, has been difficult to operationalize. Problems arise when these four services are valued as separate entities because in practice, several services may overlap and therefore lead to double counting (Boyd and Banzhaf 2007). To address this problem, ecosystem services have been re-defined as "the components of nature, directly enjoyed, consumed, or used to yield human well-being" (Boyd and Banzhaf 2007). This definition makes a distinction between intermediate components and final services and also makes it easier to integrate natural capital into a system of national accounts. Building on this notion, Fisher (et al. 2009) further simplified the definition of ecosystem services as "the aspects of ecosystems utilized (actively or passively) to produce human well-being".

As these definitions suggest, the field of ecosystem services strives to build stronger linkages between ecological and economic systems with the purpose of improving ecosystem management and human well-being (Daily 1997, Arrow et al. 200, Farber et al. 2006). Research on ecosystem services is quintessentially interdisciplinary because it weaves together the physical, biological, and social sciences into a framework for analysis. The successful integration of these fields into a coherent, concrete and practical management approach has the potential to transform environmental policy at several scales. Proponents of ecosystem services have argued that this framework offers the most promising way forward for the field of conservation biology (Chan et al. 2006, Armsworth et al. 2007). Protecting our life support systems has also resonated with advocates for the global poor (Martínez-Alier 2002), because populations in less developed countries are more dependent on ecosystem services and more vulnerable to their loss (Sachs and Reid 2006). Major research institutions, conservation organizations, foundations and the private sector are investing in research on ecosystem services (Montenegro 2008, Stanton et al. 2010, Armsworth et al. 2011). These groups expect that a breakthrough in the field will open up new avenues for solving sustainability challenges.

The concept of ecosystem services was developed by conservation biologists (Ehrlich and Mooney 1983, Daily 1997) in collaboration with environmental economists (Costanza et al. 1997) to find new ways to protect biodiversity. The legacy from biodiversity conservation has left an imprint on the field, as researchers are far more likely to advocate for an ecosystem services approach in the biologically rich, yet economically poor countries in the developing world rather than in industrialized nations (Norgaard 2010). Research on ecosystem services took off in part because it held the potential to tie together ‘development’ and ‘conservation’ objectives.

At the same time, it has been acknowledged that ecosystem services are merely a new way of talking about an old idea. Economists have studied ecosystem services as positive and negative externalities, and it is well known that ecosystems generate valuable goods and services that are not accounted for in the market (Pigou 1920, Krutilla 1967, Costanza and Daly 1992). However advocates for research in ecosystem services suggest that the conceptual frameworks used in the past are insufficient to manage ecosystem services today (Daily and Matson 2008, Liu et al. 2010). Furthermore, the ecological processes that underpin ecosystem services remain poorly understood (Kremen and Ostfield 2005, Kremen 2005). For example, it is well know that mangroves provide habitat for shrimp production (Aburto-Oropeza et al. 2008), or that rivers purify waters (Grimm et al. 2005), and yet it remains exceedingly difficult to calculate the marginal values associated with restoring mangrove habitat or restoring river ecosystems because we have not successfully unified the language of ecology with the social sciences (de Groot et al. 2002, Fisher et al. 2008).

Conservation organizations were the first to use the idea of ecosystem services to advance their goals of habitat conservation (Pagiola, Bishop, and Landell-Mills 2002, Tallis et al. 2009). In particular, forest conservationists first began to exploit the funding opportunities that ecosystem services could bring to forest dwelling communities (Bishop and Landell-Mills 2002). In the late 1990s and early 2000s, the idea of payments for ecosystem services attracted attention from government officials and conservation donors working in the developing world. Costa Rica became the first nation to pay land owners for forest conservation based on the idea that their forests provided valuable services to the country at large (Pagiola 2008). Mexico and other countries soon followed suit with their own payment for environmental services program, often focusing on the protection of water supplies (Muñoz-Piña et al. 2008, Stanton et al. 2010). Payments for Ecosystem Services (PES) are defined as voluntary transactions where a well defined ecosystem service is bought by a buyer if the provider secures a provision of a service (Wunder 2005). Thus ecosystem services provided an economic rationale to invest in conservation, while at the same time it aligned development and conservation goals. Furthermore, the ecosystem services approach, one that bound together ecosystem beneficiaries with ecosystem service providers in a mutually beneficial financial transaction, promised to open up new opportunities for conservation. Paying for conservation radically differed from the existing conservation methods used to date, and quickly became seen as a viable alternative to the legal strategies, or development projects, that had been the standard conservation tools. Moreover, new arguments surfaced that direct economic payments would be economically more efficient than alternative conservation schemes (Ferraro and Kiss 2002, Ferraro and Simpson 2002), generating even more discussion about the need to quantify and understand ecosystem services.

While payments that pay for ecosystem services have been implemented in the developing world, more prosperous nations rarely rely on the idea of ecosystem services to manage their ecosystems. With the exception of conservation payments for agriculture (Dobbs and Pretty 2008), or the program on compensatory wetland mitigation (BenDor and Brozovic 2007, Palmer and Filoso 2009, BenDor and Doyle 2010), examples in the urban and developed world remained scant. The most prominent application was New York City's drinking water protection program in the Catskill watershed. Yet when policy makers tried to replicate New York's experience, it was found that water managers in most major cities of the United States had already installed the filtration technology that New York City successfully avoided. This outcome only reaffirmed the idea that ecosystem services came from predominantly untouched areas, such as the Catskill watershed, and managers would have fewer opportunities to adopt an ecosystem approach once a new technology was put in place.

Also in the late 2000s, it became increasingly evident that the excitement surrounding ecosystem services has not been accompanied by a parallel transformation in how ecosystems were managed. Even prominent scholars recognized that it was “time to deliver” (Daily et al. 2009). Critics raised questions about why more success stories have not been found (McCauley 2006). To encourage a speedier adoption of the ecosystem services framework in practice, proponents began to advocate for research that could help decision-makers implement these ideas with resource managers (Cowling et al., 2008; Daily and Matson, 2008; Daily et al., 2009; Muradian et al., 2010).

Throughout the dissertation, I argue that two major factors have limited the application of ideas about ecosystem services. First, researchers have ignored the opportunities to find and exploit ecosystem services in urban and technologically advanced landscapes (Chapter 3). Second, research has not dedicated sufficient attention to studying the demand for ecosystem services (Chapter 4). Instead, most research has focused mostly on the biophysical processes, while leaving the economic analysis and decision-making context as secondary. This dissertation addresses these limitations by studying the demand for ecosystem services in an urban and technologically sophisticated environment.

Of course, this is not the only gap in the literature. There are other obstacles that also must be addressed to move ideas about ecosystem services from theory to practice. According to the special report on ecosystem services released by the National Research Council, one fundamental challenge in the field of ecosystem services lies in linking ecosystem structure and function with economic values (NRC 2005). Ecosystem structure refers to “*the composition of the ecosystem and the physical and biological organization defining how these parts are organized*”, while ecosystem function “*describes a process that takes place in an ecosystem as a result of interactions of plants, animals and other organisms*” (NRC 2005). Both ecosystem function and structure are value free descriptors that provide ecosystem services when they generate human well-being. Whether or not ecosystem function and structure are ecosystem services often depends on seasonal fluctuations or where the ecosystem is located relative to human populations. For example, the capacity of wetlands to treat sewage, mitigate floods, or purify water, often depends on their proximity to human populations as well as seasonal fluctuations (Brauman et al. 2007).

The subtle, yet critical differences between ecosystem functions/structure; ecosystem service, and economic value have been the source of confusion. Their similarity may also have contributed to the simplifying assumption that these three processes are linearly related. For example, it has been assumed that growing mangrove habitat (ecosystem structure), will increase the populations of edible fish (ecosystem service) that can be harvested, sold and consumed (economic value). Assuming a linear relationship between ecosystem functions and value or between ecosystem condition and service can lead to misleading results. Note that the ecological production functions link ecosystem structure/function with ecosystem services, while ecosystem services are linked to economic values through economic valuation functions (Fig 1.1).

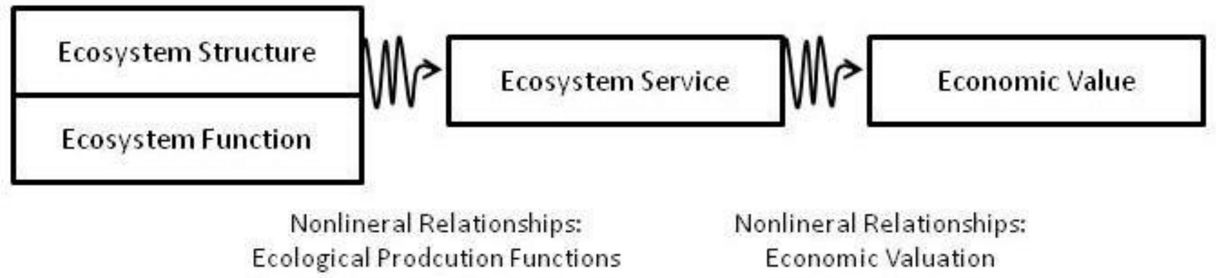

Figure 1.1 Ecosystem function and structure have nonlinear relationships with the ecosystem services they provide, and this relationship is described by ecological production functions. Similarly, the values of these ecosystem services also fluctuate, and this relationship is described by economic valuation functions.

Furthermore, spatial and temporal variability add two additional levels of complexity (Fig 1.2). The values of any ecosystem service can change depending on its location or season. The combination of these complexities has prevented us from acting on ideas about ecosystem services. In practical terms, this means that resource managers do not have the means to evaluate the impacts of their decisions on the ecosystem services in question.

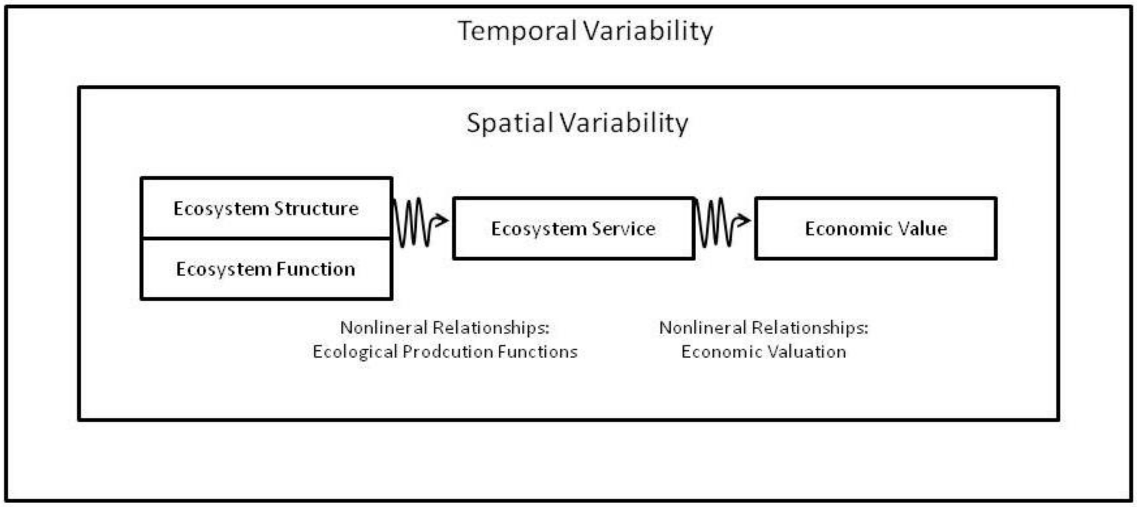

Figure 1.2 The chain linking ecosystem functions/structure, with ecosystem services and economic value increases in complexity when we consider spatial and temporal variability.

Similarly, Koch et al. (2009) studied how coastal habitats provided the ecosystem service of coastal protection. They demonstrated how valuation results varied significantly according to spatial and temporal fluctuations such as tidal changes, season, latitude, and spatial distribution. Also, Aburto-Oropeza et al. (2008) used a regression model to study the relationship between catch yields and the presence of mangrove habitat in the Gulf of California in a large data set between 2001 and 2005. They found that fish catch increased by the square root of the area of mangrove habitat. All three studies suggest that by incorporating nonlinear relationships between ecosystem functions and values we can offer more precise estimates as to the true utility of ecosystem services.

Social scientists have also turned their attention to non-linearities and thresholds. Repetto (2006) suggests that US environmental policy advanced primarily during short periods of rapid change. This has led political scientists to inquire into the conditions that may allow rapid policy change and implementation. Similar to their ecological counterparts, they see the value in understanding the location of thresholds and their triggers.

Before we can expect decision makers to act upon our understanding of complex ecological and economic systems, first we must identify and measure the flows of ecosystem services. This process of ecosystem service identification leads to a significant way in which this research distinguishes itself from existing studies on the subject. My point of departure is the demand for ecosystem services instead of the supply. Most studies on ecosystem services begin with a particular ecosystem of interest: the coastal mountains of Northern California (Chan et al. 2006), the montane forests on Hawaii's Kona islands (Goldstein 2007), the coastal habitat of Thailand (Barbier et al. 2008) or the mangrove forests of Baja California (Aburto-Oropeza et al. 2008). Having selected an ecosystem of inquiry, researchers proceed to describe the services generated by that ecosystem. In most cases, the local populations are passive or unaware recipients of the services provided by the ecosystem of interest, and new values are attributed to lands that previously were not valued in the market. The unspoken assumption behind these studies is that if the local populations were aware of the services, they would seek to protect them.

Instead of following the mainstream approach, in which one first characterizes the range of ecosystem services in the study area, I start by studying the economic and technological system that generates the demand for a particular set of ecosystem service. In other words, rather than beginning with the supply of existing services, I begin with the demand, or the user's objectives. I start with the context in which decisions are made and then identify ecosystem functions that can help resource users meet their management goals. This allows me to target my ecological research to the specific needs of ecosystem users. Identifying the demand for ecosystem services should also facilitate the adoption of these ideas in practice.

The inability to act on ideas about ecosystem services is a major criticism of the field. But the stuy of ecosystem services has been criticized for other reasons as well. To begin with, discussions about ecosystem services often latch on to romantic notions of "pristine areas" or "wilderness", which have been discredited by environmental historians (Cronon 1995), geographers (Castree 2005) and ecological scientists (Kareiva et al. 2007). And when programs pay landowners for services provided by ecosystems, the distributional outcomes are not exactly what one might anticipate, as marginalized communities may disproportionately be excluded from conservation benefits (Corbera et al. 2007). Furthermore, research on ecosystem services quantifies and commodifies our world (Kosoy and Corbera 2010). An obsession with the utilitarian contribution of ecosystems to human well-being, especially with quanitifcation and commodification, might lead us to ignore the larger complexities involved with functioning ecosystems (Norgaard 2010). Norgaard has thus criticized the notion of ecosystem services a "complexity blinder". This criticism fits into a larger critique of centralized decision-making, objective measurement and the hubris of rational planning and reductionism (Scott 1998).

Others criticize the field of ecosystem services for placing undue emphasis on the economic arguments for conservation, and in this way, pushing aside the ethical or rights-based arguments to motivate environmental protection (MCauley 2006, Child 2007). After all, human self-interest and market forces are precisely what have caused ecosystems to be modified to begin with. These critics are wary that the economic arguments may be less appealing when the calculations point in the other direction. According to this view, what society needs is a stronger conservation ethic and less commodification, not more (McCauley 2006). Certainly, even the most ardent defenders of ecosystem services must recognize that the field of ecosystem services is anthropocentric, instrumental and somewhat reductionist. And yet the ethical motivations for conservation have never been sufficient to change human behavior in the past, and it is unlikely that this will change any time soon. At least this new integration with economics can provide additional motivation for improving ecosystem management (Reid et al. 2006, Costanza 2006).

Despite these criticisms, the field of ecosystem services is growing (Fisher et al. 2009). The most recent research analyzes tradeoffs between services (Kareiva et al. 2007; Raudsepp-Hearne, Peterson, and Bennett 2010; Chan, Hoshizaki and Klinkenberg 2011). And advances in geographic information systems (GIS) have given researchers the capacity to analyze multiple layers of physical and social data in new ways. This has led to the creation of specialized software - such as Integrated Valuation of Environmental Services and Tradeoffs (InVEST) - that tabulates the ecosystem services generated from specific land units (Nelson et al. 2009, Bai et al. 2011, Fisher et al. 2011). The problem with this approach is that researchers are more likely to focus on the biophysical conditions of the site without examining how specific users may interact with or benefit from ecosystems. This follows the mainstream research sequence in the field (Fig 1.1). Instead, research on ecosystem services would benefit from focusing on the social and economic questions first (Cowling et al. 2008). Re-orienting the sequence of how ecosystem services are studied, with a focus on the demand for ecosystem services first, is more likely to capture the attention of decision makers. Moreover, a comprehensive valuation is often not necessary, as long a research can show how policy makers can reach their objectives (Chapter 4, Powers et al. 2005, Sangenberg and Settele 2010).

In the chapters that follow I examine ecosystem services that influence water supplies. Throughout the dissertation, I examine how resource managers balance technological choices and ecosystem based solutions when managing their water resources.

1.2 Study Area

Water Supply and Treatment

Barcelona depends on the waters from the Llobregat River for municipal, agricultural and industrial uses. The Llobregat River provides the region with 45% of its drinking water supply (Mujeriego 2006). The other half comes from either groundwater sources or the Ter watershed to the north-east. In a normal year, the Ter-Llobregat system supplies the Barcelona Metropolitan Region with a total of 300 hm^3, two thirds for urban use, and one third for industrial use (Saurí 2003).

Barcelona had historically relied on groundwater to meet its drinking water needs. However starting in 1955, the private firm *Aguas de Barcelona* (AGBAR) financed the construction of the new treatment facility on the shores of the Llobregat River at the base of the watershed (Bolaños 2004). Yet even after the construction of the new facility, demand continued to rise, and in the 1960s, Barcelona expanded its territorial reach for freshwater by pumping in supplies from the Ter watershed.

The region of Catalonia in Spain relies largely on reservoirs to meet its water needs. Indeed, Spain is a global leader in the construction of dams, with one of the greatest number of dams per capita in the world (Arrojo and Naredo 1997, Bakker 2002, Arrojo 2003). In the 1950s, 1960s and 1970s, the Spanish government built several large dams throughout the Pyrenees Mountains. Today, three major dams regulate water flows in the Llobregat watershed: Sant Ponç (1956), Baells (1976), and Llosa del Cavall (1997). The Llobregat reservoir system has a capacity of 139 hm^3 while the neighboring Ter watershed has a storage capacity of 402 hm^3.

In 1980 a consortium of private firms built a second major water treatment facility on the Llobregat River in the town of Abrera, upstream of ABGAR's existing facility. Ownership of the treatment plant changed hands several times until the Catalan government finally took control from AGBAR (personal comment Antoni Bernal, January 2010). The public water agency *Aigües Ter Llobregat* (ATLL) now manages this facility. ATLL is a water wholesaler that treats water sources and sells potable water to municipal providers. ATLL is publically run however the Catalan Government has plans to outsource the management to a private firm (Expansión 2011). Both water treatment plants must report to the Catalan Water Agency, or *Agència Catalana de l'Aigua* (ACA).

Water managers at the ATLL and AGBAR treatment facilities have been dealing with contaminants in the Llobregat River for decades (Lloret 2004, Estevan and Prat 2006). In particular, mine tailings upstream release salts and bromides into the river. For years, relocating the mine tailings has been considered financially prohibitive (ACA 2006). To alleviate the pollution coming from the mines, in 1989, ACA financed the construction of a brine collector that significantly reduced the tailings' impact on water quality. However bromides in the water supply still react with disinfectants during the treatment process to form carcinogenic compounds called trihalomethanes (THMs) (Sorlini and Collivignarelli 2005). Drinking water standards require total THM content to be under 100 µg/L as of January 1, 2009 (Royal Decree 2003).

Between 2008 and 2009 both ATLL and AGBAR installed new desalination or membrane technologies to remove contaminants and safely comply with new drinking water quality standards. The public water treatment facility managed by ATLL installed an electrodialysis reversal (EDR) system, while further downstream, the private water company AGBAR installed reverse osmosis (RO) technology. The AGBAR treatment facility also extracts groundwater from an aquifer that is experiencing seawater intrusion, further compounding the salinity problem in its water supply.

Llobregat Watershed

The Llobregat River flows 170 kilometers from the Pyrenees Mountains to the Mediterranean Sea in the north eastern region of Catalonia, Spain (Fig 1.3). The watershed covers 4,948 km^2 making it Catalonia's largest watershed entirely within the jurisdiction of the autonomous community (Lloret 2004). The Llobregat is a fourth order stream whose primary tributaries include the Cardener, the Anoia, Rubí, and Merlès streams.

The upper segment of the watershed receives 1,000 mm of precipitation a year, while the mid section only 400 mm and the coast approximately 550 mm per year. In one year, approximately 660 cubic hectometers (hm^3) of water flows down the Llobregat (Mujeriego 2006), although this discharge is highly variable, and annual flows vary between 230 to 1,870 hm^3. The river also feeds into a groundwater aquifer below the Llobregat Delta, contributing approximately 57 hm^3 per year. The river's hydrological contribution to the aquifer is nearly three times the contribution received from precipitation (20 hm^3/year) (Mujeriego 2006).

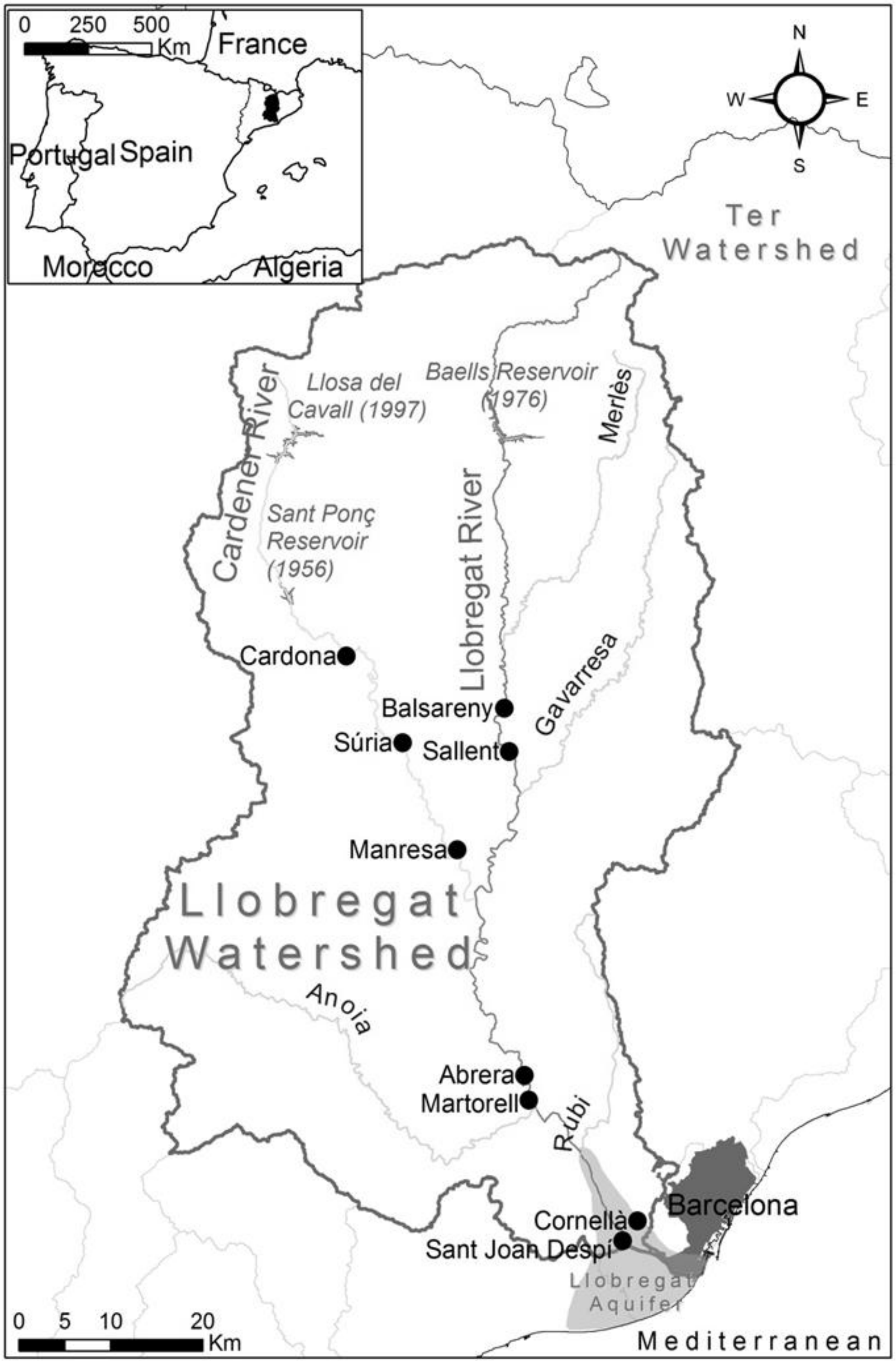

Figure 1.3 The Llobregat watershed in north eastern Spain.

In 2000 the European Union approved legislation designed to restore rivers and lakes across the continent. The Water Framework Directive (WFD) set targets and timetables for restoring water bodies to a "good ecological status" by 2015 (EU 2000). A major legislative innovation included the requirement to conduct an economic analysis prior to major policy decisions. Non-compliance with the WFD may result in monetary fines and reduce the member state's bargaining power within the European Union. Thus the WFD is seen as an integrative piece of legislation that responds to the expectations of watershed planners and has raised the hopes of environmental advocates.

While the WFD marks a major turning point for freshwater management in Europe, countries are allowed to exclude certain water bodies from meeting the "good ecological status" requirement if they can demonstrate that the costs disproportionately exceed the benefits of restoration (Hanley and Black 2006). As written, this provision pushes the economic analysis to center stage, and yet the environmental community is concerned that it will allow governments to shirk their restoration responsibility for restoring aquatic ecosystems (personal comment Daniel Barbé, October 2009). Still, the Catalan Water Agency has worked earnestly to meet the WFD timetable and targets. As of 2010, Catalonia was the only autonomous community in Spain to have fulfilled its obligations in the WFD before the European Union (personal comment Pedro Arrojo, May 2010).

However Spain's current budgetary crisis threatens to chip away at the progress made. Drastic budget cuts at the Catalan Water Agency are likely to postpone restoration projects for rivers, lakes, and estuaries. Currently the water agency is burdened with a debt of €1.3 billion that the Catalan Government has promised to restructure and reduce (Arbolí 2011, Zanón 2011). Up to 40% of the staff at the water agency may be cut by the end of 2012 (Garriga 2011). To further raise revenue, the Catalan government is exploring the possibility of leasing its public water treatment facilities - currently managed by the public agency ATLL - to a private firm (Garriga 2011). The prospect of transferring water treatment and distribution activities to the private sector has raised criticisms from civil society organizations, who assert that private operators will prioritize profit over service quality, capital investment and ecological restoration (Garriga 2011b). Critics also question why water rates did not increase in the period when the public enterprise was entering into debt. Instead, rate increases are likely to be pushed onto the public once the water concession is contracted with the private sector (L'Economic 2011). Negotiations are still underway between the water agency and prospective private operators. Throughout 2012 and beyond, the organization and structure of the water sector in Catalonia will continue to evolve.

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CHAPTER 2. ENVIRONMENTAL HISTORY OF THE LLOBREGAT WATERSHED

Abstract

This chapter examines the history of water use in the Llobregat watershed to explain why urban planners in Barcelona, Spain were compelled to install desalination water treatment technology along the Llobregat River instead of exploring other options, including the management of ecosystem services. In later chapters I explore how these technologies have created new opportunities for managing and valuint ecosystem functions and structures. But first I examine how we got here -- to a high tech system of water treatment and distribution. The answer can be found by reviewing the origins of a river pollution conflict that has vexed water managers for nearly a century. This historical analysis also explains why water managers have frequently preferred technological solutions over ecosystem management practices. While ecosystem restoration alone might not have resolved the salinity conflict that confronted water managers in the 1920s and 1930s, the outcome of that confrontation shows a clear preference for the construction of public works. The key stakeholders in this quarrel set aside their differences in other respects and came together to agree that the river pollution problem could be easily resolved with the construction of a brine collector and a dam in the mid section of the watershed. The consensus on this issue set the city of Barcelona down a trajectory of river and water management that favored structural solutions to address their water conundrums.

This chapter is divided into two parts. In the first segment I review the salinity conflict in the Llobregat and Cardener Rivers in the first half of the twentieth century. Previous research had identified the origin of the conflict in 1926, but only mentioned this date in passing without providing additional details. I have sought to take a closer look at the first decade of this conflict and study the planning process that followed once it became clear that Barcelona's water supply was in danger of becoming irreversibly polluted. I find that the deliberations of the CESALL Commission in 1931 and 1932 were the first exercise in watershed planning in the Llobregat basin and their recommendations have had a lasting influence on subsequent generations of water managers.

In the second segment I show how notions of ecosystem services were discussed as an alternative strategy for flood control in the late 19th century. Thanks to the writings of a forester, Rafael Puig Valls (1845-1920), we know that the restoration of forest ecosystems in the Pyrenees mountains became a serious management alternative for mitigating floods in the Llobregat watershed. This ecosystem approach serves as a precedent for contemporary discussions on ecosystem services in the Llobregat watershed.

Keywords: Cardener River, history ecosystem services, Llobregat River, salinity pollution, watershed planning

2.1 Introduction

Before humans withdrew water from the Llobregat River to irrigate their crops, propel their mills, or transport their waste, the river was a major source of problems; a threat and a nuisance; an obstacle and a barrier. First and foremost, the river's floods threatened to wash away life and property. The first recorded flood dates back to 1143, in an event that washed away the stone bridge at Martorell constructed by the Romans.[1] Soldiers, merchants and travelers had used the bridge as a critical river crossing along the *Via Augusta*; a transportation artery along the rim of the Mediterranean that connected Imperial Rome with the Mediterranean port of Tarraco in Hispania Citerior and the silver mines in Carthago Nova in Hispania Ulterior.[2] In the years that followed this first recorded flood, between 1143 and 1900, historians have counted 129 additional floods along the Llobregat.[3] All were large enough to wash away bridges, boats, people and property; and at minimum, generate sufficient wreckage so as to leave behind written record. We can safely assume that many more floods swept through the Llobregat without leaving historical trace.

The first concession to draw water from the Llobregat was signed by King Jaume I of Aragon and Catalonia in 1273 and granted to the monks of *Sant Cugat del Vallès* so that they could nurture their crops. In 1321, the King's son, Jaume II, granted another concession allowing river dwellers to harness the river's energy.[4] Former inhabitants along the Llobregat River have left us with clues about how they administered the rivers' waters, such as irrigation canals, or medieval bridges. Past water users have also left us with the nomenclature of familiar places that can easily be traced back to the river; the town of *Molins de Rei* was named after the first hydro-powered mill constructed with consent from the King, and

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[1] Codina, J. 1971. El delta del Llobregat i Barcelona. Gèneres i formes de vida dels segles XVI al XX. Hores de Catalunya. Esplugues de Llobregat: Edicions Ariel.

[2] Hughes, R. 1992. Barcelona. New York: Knopf.

[3] Codina, J. 1971. El delta del Llobregat i Barcelona. Gèneres i formes de vida dels segles XVI al XX. Hores de Catalunya. Esplugues de Llobregat: Edicions Ariel.

[4] Ibid.

Sant Andreu de la Barca was the site where one could cross the river in a boat.[5] However more subtly, and perhaps more importantly, past water users have left us with certain ideas about how rivers should be managed. These inherited ideas configure and constrain our relationship with the waters that rivers carry. We are all subjected to this historic influence. It is an influence that often goes unnoticed and unquestioned. These ideas shape how we speak about rivers, our assumptions about what should be done to them, our view of the river's natural conditions, and our expectations about future possibilities. In this chapter I argue that our current system of water treatment and distribution reflects a historic tradition that has favored technological solutions to water problems. We see this in the recommendations of the CESALL Commission in 1932, which outlined a structural approach for addressing the Llobregat River's water pollution problems.

At the same time, the historic review uncovers an alternative perspective as well. Not everyone advocated for engineered approaches to water management. This alternative was most clearly articulated by a forester, Rafael Puig Valls, who advocated for the management of forest ecosystems in order to mitigate flood damage. While Puig Valls made innovative proposals for his time, he was not the first to stress human reliance on ecosystems. The ancient Greek philosopher Plato has been credited with first appreciating human's dependency on ecosystems when he observed that the deforestation of the Attica caused fertile soils to erode and springs to disappear.[6] But it was not until the nineteenth century that George Perkins Marsh systematically compiled evidence showing that human societies depended on environmental support systems. Relying mostly on historical texts published in Europe, Marsh wrote *Man and Nature* in 1864, which was subsequently revised as *The Earth as Modified by Human Action* in 1874. Both texts synthesize the ecological knowledge of the time as it pertained to the progress (or decline) of civilizations and human well being. Working at the nexus between ecology and human history, Marsh

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[5] Codina, J. 1971. El delta del Llobregat i Barcelona. Gèneres i formes de vida dels segles XVI al XX. Hores de Catalunya. Esplugues de Llobregat: Edicions Ariel.

[6] Mooney, H., and Ehrlich, P. 1997. Ecosystem Services: A Fragmentary History. In G. C. Daily, Nature's Services: Societal dependence on natural ecosystems (pp. 11-19). Washington, D.C: Island Press.

wanted his description of ecological processes to "excite an interest in a topic of much economical importance."[7]

Marsh lamented that human societies appreciated ecosystem functions only after their services were lost. He wrote, "the destructive agency of man becomes more and more energetic and unsparing as he advances in civilization, until the impoverishment, with which his exhaustion of the natural resources of the soil is threatening him, at last awakens him to the necessity of preserving what is left, if not restoring what has wantonly been wasted."[8] Marsh provides examples of environmental mismanagement in Asia Minor, Northern Africa, Greece and Alpine Europe, whereby "action by man has brought the face of the earth to a desolation almost as complete as the moon."[9] After reviewing countless cases of decline across different cultures and continents, Marsh became convinced that unwise ecosystem management contributed to societal impoverishment. "The decay of these once flourishing countries is partly due, no doubt… to the direct violence of human force..[and] ignorant disregard of the laws of nature."[10] Marsh noted that ecosystems retained valuable soils and stabilized hydrologic flows. Later I will discuss Marsh's observations concerning hydrology in more detail, but for now, suffice to say that Marsh was probably the first to write about human dependence on functioning ecosystems with such detail.

However before embarking on the historic analysis, I begin with the present; where we find that Barcelona has built a system of water production that is technologically sophisticated and energy intensive. Taking a brief look at water distribution today gives us clues about the sorts of ideas that water managers have inherited from the past.

The high tech water treatment systems installed along the Llobregat River are the latest in a series of technological fixes to a river pollution problem that is decades old. The salinity contamination of the Llobregat from mining activity has even been called Catalonia's most severe environmental problem; and

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[7] Marsh, G. P. 1874. The Earth as Modified by Human Action. A New Edition of Man and Nature. London: Sampson Low, Marston Low, and Searle. Republished by Elibron Classics 2006. p 9

[8] Ibid. p 39

[9] Ibid. p 43

[10] Ibid. p 5

if the new desalination systems serve as evidence, the issue remains unresolved. The history of salt pollution in the Llobregat and Cardener Rivers helps us understand the connections between past conflicts, the solutions put forward, and contemporary water challenges. I trace this river pollution conflict from its origin in 1926, through the Spanish Civil War 1936-1939, and then rapidly bring it up to the present.

Then I move on to discuss the competing proposals to mitigate flood damage in the Llobregat watershed, with a focus on the Cabrianes dam project proposed in the 1890s. In this discussion on flood management we can see a clear alternative to the mainstream approach that relied on structural solutions. The writings of Rafael Puig Valls advocated for the management and restoration of ecosystem services for the benefit of downstream water users. Puig Valls sought to apply knowledge from the ecological sciences to construct a viable alternative to the structural approaches to flood control that dominated the era. Interestingly, the debate that Puig Valls began in the nineteenth century closely mirrors current ideological divisions in the watershed today. Many of Puig Valls' proposals for reforestation were eventually adopted during the Second Spanish Republic (1931-1936), but ultimately his ideas about ecosystem management failed to displace the hegemony of structural approaches to water management. And by taking a look at contemporary water treatment in Barcelona, we can appreciate just how technologically intense their system of water distribution has become.

2.2 Desalination of the Llobregat River

The Llobregat River is a freshwater system that has become brackish due to mining activity upstream. To remove the salts and dissolved solids from the river, water managers have turned to sophisticated desalination systems. In the late 2000s, the combined cost of installing both desalination systems surpassed €130 million.[11] Moreover the operation of these treatment technologies requires an enormous amount of energy. The electrodialysis reversal (EDR) system run by *Aigües Ter Llobregat* (ATLL) consumes approximately 13 Giga Watt hours (GWh) per year, at a cost of €1.2 million per year. Downstream, the ultrafiltration and reverse osmosis system operated by *Aguas de Barcelona* (AGBAR) consumes approximately 21 GWh per year, for an energy expense of €2 million per year.[12] In other words, the energy consumed to treat water from Llobregat River each year would be sufficient to meet the energy needs for the entire city of Barcelona; including gas for cars, electricity for air conditioners, lights and televisions etc... for two full days. The decision to install desalination technology on the banks of the Llobregat River was a strategic choice to trade energy for freshwater. It also committed the Barcelona metropolitan region to spend €3.8 million per year to desalinate water that, at its source in the Pyrenees, is of superb quality.

Not only is desalination expensive and energy consuming, but the membranes are complex to operate and vulnerable to fouling. Feed water entering the membranes must be groomed to meet exacting pre-treatment standards. Feeding the high-tech apparatus with unbalanced water could severely damage the capital investment and reduce long term efficiency. For example, aluminum compounds are used at the beginning of the treatment process to remove suspended solids and particles from the river water. However the aluminum added must be removed before entering the reverse osmosis membranes to prevent fouling. Water treatment engineers precipitate the aluminum by reducing the pH, but excessive pH reduction will cause the water to release carbon dioxide which is later added, at a cost, for more

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[11] Valero, F., and Arbós, R. 2010. Desalination of brackish river water using Electrodialysis Reversal (EDR) Control of the THMs formation in the Barcelona (NE Spain) area. Desalination 253:170-174.; Pedraz Yañez, G. 2007. Proyecto y obra de la Mejora del Tratamiento de Aguas por Osmosis Inversa en la ETAP de Sant Joan Despi. Documento 1. Memoria. Barcelona: Aguas de Barcelona.

[12] Calculations by author

balanced smell and taste.[13] Any misstep in the treatment process could drastically increase treatment costs or damage the expensive membranes.

What led Barcelona down this path of technological sophistication, energy intensity and high treatment costs? This historical review will analyze the circumstances that led water managers to favor this complex system for water treatment, over alternative options of ecosystem management.

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[13] Pedraz Yañez, G. 2007. Proyecto y obra de la Mejora del Tratamiento de Aguas por Osmosis Inversa en la ETAP de Sant Joan Despi. Documento 1. Memoria. Aguas de Barcelona: Barcelona.

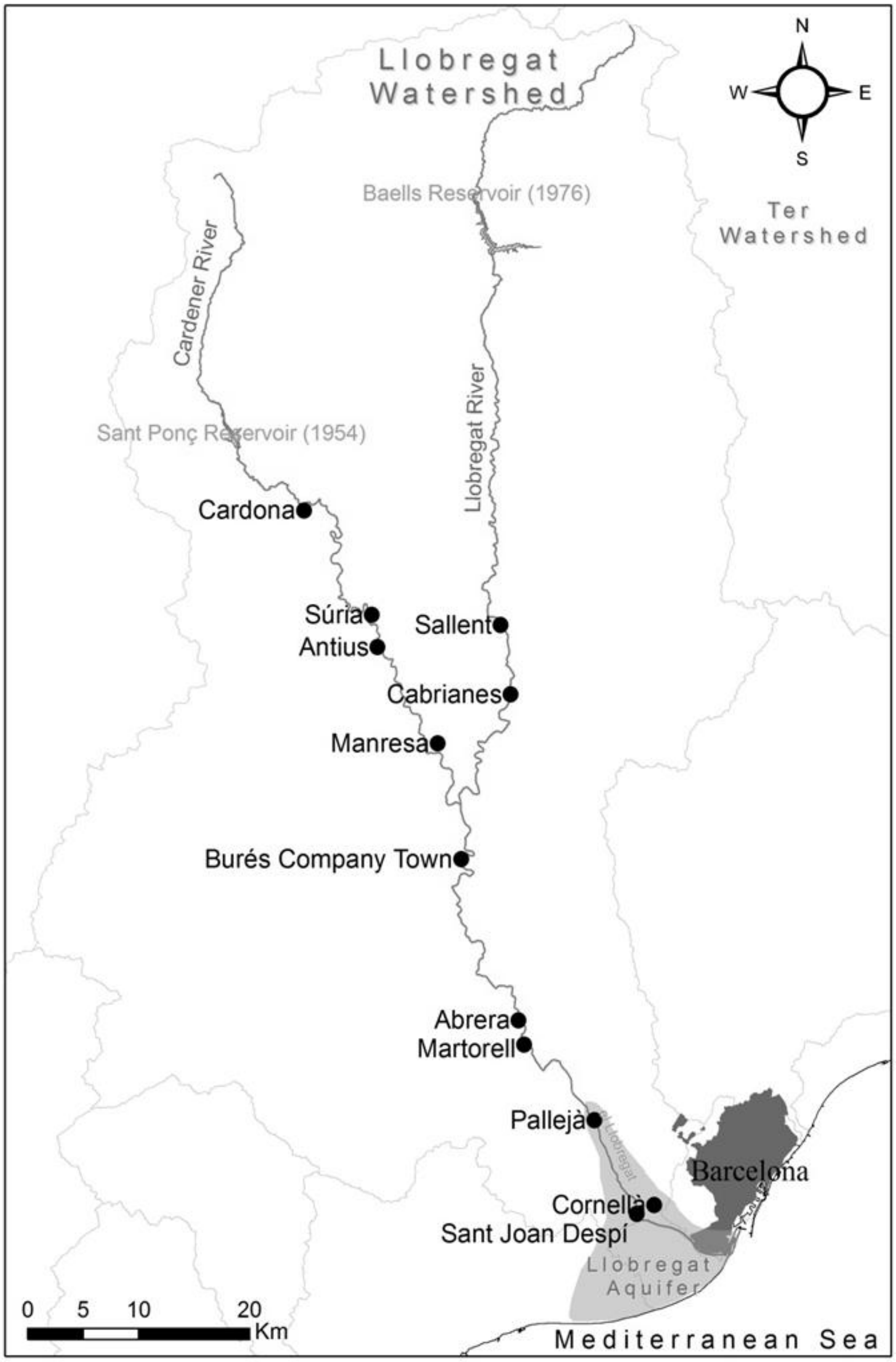

Figure 2.1 The Llobregat Watershed

2.3 Salinity Conflict

Minerals have been extracted from Llobregat watershed for centuries, especially in the mountains surrounding the medieval town of Cardona (Fig 2.1). The Romans who settled in Cardona extracted sodium chloride (NaCl), more commonly referred to as table salt, from an emerging salt dome that penetrated the earth's surface.[14] Geologists call these salty protrusions diapirs, and they are part of the area's natural geology. The salt deposits are the product of tectonic movements that pushed the Iberian Peninsula into mainland Europe.[15] The collision enclosed ocean waters in an enormous lake filled with salt water. Over time, the water evaporated, leaving behind layers of minerals including sodium chloride, potassium chloride, and magnesium chloride. Further tectonic movements buried the lake bed, and then pushed certain sections back up to the surface. With the exception of the salt diapir emerging in Cardona, the salts are usually hundreds of meters below ground. In Súria, where the salt minerals are closest to the surface, the salt is 150 meters below.[16] Mining for table salt peaked in the 18th century and then declined steadily. The extraction of salt was replaced by a more valuable mineral: potassium chloride (KCl). Local legend asserts that potassium chloride was discovered by accident when locals noticed that their livestock refused to eat the salts they would normally devour.[17] Laboratory analysis by the Frenchman René Marcay in Bordeaux confirmed the potassium find in 1912.[18]

News of the discovery generated considerable excitement. Potassium was a valuable fertilizer for agriculture, and useful as an explosive in war. Prior to the confirmation of potassium deposits in Súria, it was believed that only Germany, France and Poland had domestic sources.[19] Under pressure by regional

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[14] Fàbrega Enfedaque, A. 2009. Cum Grano Salis: La Sal i la Potassa a Súria 1185-1982. Ajuntament de Súria & Iberpotash.

[15] Arnau Reitg, R. 1981. La mineria del Bages: una visió retrospectiva. XXVI Assemblea Intercomarcal d'estudiosos a Manresa (pp. 53-58). Manresa: Centre d'Estudis del Bages.

[16] CESALL Report.1932. Arxiu Nacional de Catalunya (ANC) Fons 547. Agència Catalana de l'Aigua. Unitat 479.

[17] Fàbrega Enfedaque, A. 2009. Cum Grano Salis: La Sal i la Potassa a Súria 1185-1982. Ajuntament de Súria & Iberpotash.

[18] Ibid.

[19] Arnau Reitg, R. 1981. La mineria del Bages: una visió retrospectiva. XXVI Assemblea Intercomarcal d'estudiosos a Manresa (pp. 53-58). Manresa: Centre d'Estudis del Bages.

politicians in Manresa, the Spanish *Cortes* in Madrid quickly modified the mining legislation to expedite the extraction and commercialization of potassium.[20]

The Belgium chemical firm *Solvay* took the lead in developing the potassium mines in the Llobregat watershed. They began their operations in Súria - where the initial discovery came to light - located on the Cardener River between Manresa and Cardona (Fig 2.1). *Solvay* was a reputable chemical firm founded by the Belgian chemist Ernest Solvay (1838-1922), and in 1920 they set up their Spanish subsidiary *Minas de Potasa de Súria*. That year a managerial elite from Belgium descended onto the small town to run the operations. *Solvay* sent Norbert Fonthier, a disciplined ex-Army officer and World War I veteran to run the mining subsidiary.[21] Fonthier was a highly disciplined manager, who paid keen attention to detail, and dutifully relayed major decisions back to headquarters in Brussels.

As an initial sign of goodwill to their Spanish hosts, in 1920 *Solvay* donated funds to construct a public water system that would guarantee 150,000 liters of potable freshwater per day for the town's 3,200 residents.[22] In a display of appreciation for this generous gift, Súria renamed the street in front of City Hall, *Avenida Ernest Solvay*, making the name of the Belgian chemist ubiquitous on municipal letterhead. The town also engraved two plaques to commemorate the privately financed water system; one on the façade of City Hall and a second in the City Hall courtyard (Fig 2.2). What the residents of Súria could not fathom was that the same company that brought them clean water to their town of 3,200 would soon threaten the water supply of one million residents in Barcelona.[23] It is hard to believe that such a gift was coincidental, and suggests that the Belgian chemists and engineers already understood the relationship between their plans to extract potassium and water pollution. Perhaps because *Minas de*

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[20] See letters between the Mayor of Manresa, Sr. D. Maurici Fius Pala and the Director of Agriculture, Mines and Mountains in 1914. Arxiu Comarcal del Bages, Manresa.

[21] The first Director of Minas de Potasa de Súria was Louis Dupont, who was followed by Van Styovoort, and finally Norbert Fonthier who led the firm until the Spanish Civil War.

[22] Reguant, J. 1997. Súria: Història en imatges. 1894-1975. Angle Editorial. Manresa, Spain.

[23] Tello, E., and Ostos, J. 2011. Water consumption in Barcelona and its regional environmental imprint: a long-term history (1717-2008). *Regional Environmental Change* 1-15.

Potasa de Súria anticipated their company's huge demand for water, they first ensured that local needs were met, and resistance averted.

Figure 2.2 A plaque in Súria hangs on the façade of City Hall that that commemorates the renaming of the street Avenue Ernest Solvay. The plaque reads: *Avenue Mr. Ernest Solvay. Illustrious chemist and engineer, maker of good works for humanity and founder of the Society Solvay who donated potable water to Súria. 1838-1922* (Photograph by the author)

Small scale potassium mining in Súria had begun in 1918, but poor road conditions to and from the mines severely limited the volumes they could haul to market each day. To scale up production, *Minas de Potasa de Súria* built a rail line connecting their mine to the port of Barcelona where their minerals could then be shipped around the world. With help from the Spanish authorities, the rail line was finished in 1925, after which, large scale mining began. The new rail line allowed freight cars to haul potassium out from the mountains near Súria, and the rise in sales was meteoric. The mining company sold 2,989 tons of potassium chloride in 1925, a figure which more than doubled the next year to 8,386 tons, and doubled again to 16,084 tons in 1927. By 1928 operations were in full swing and *Minas de Potasa de Súria* employed 857 workers.[24] That same year, the Spanish Government decreed a law

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[24] Reguant, J. 1997. Súria: Història en imatges. 1894-1975. Angle Editorial. Manresa, Spain.

obliging the mining company to produce a minimum of 30,000 tons for the Spanish market. Exports were only permitted if internal demand was satisfied, and the export price had to be higher than domestic prices.[25]

Minas de Potasa de Súria had close ties with the Spanish government and monarchy. These relations were developed with the help of Don Amadeu Hurtado de Gálvez-Cañero, hired by the mining company to represent the firm in Madrid and to make the appropriate government contacts when needed. As an example of these close ties, in 1924 a mining executive from *Minas de Potasa de Súria* was knighted to the Order of Queen *Isabella la Catolica*. But the mining company's close relationship with the Spanish government weakened during Spain's transition to a democracy in 1931, after which, more transparent institutions were established to manage the river's waters.

Water Pollution Conflict

Doña Antònia Burés Borràs (1854-1928) was the first to complain about the salt being dumped in the Cardener River by *Minas de Potasa de Suria* (Fig 2.3). She was a woman with extraordinary wealth, power and personality, and yet her impressive pedigree was insufficient to halt the river contamination. Clashes over water rights were nothing new for the Burés family. Antònia Burés came from a powerful industrial class that had made their fortune from Catalonia's waterways, and were highly sensitive to modifications in the river's flow. For decades already, these industrial families had fought to control the river's current and the energy it helped them produce. Therefore the appearance of the mining company in the 1920's threatened to break the existing equilibrium among industrial water users. However in the legal complaint Burés filed against the mining company in 1926, she added another new dimension to this tussle – water quality. In addition to her claim against the illegal water withdrawal, she asserted that *Minas de Potasa de Súria* was "impurifying" the river's waters. The mineralized effluent from the mines

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[25] Gazeta de Madrid 1928. Núm 15. 15 enero 1928 p 436.

corroded the metallic turbines that propelled her hydro-powered textile factory in Antius.[26] Her claim against the mining company, one that combined charges about water withdrawals and water quality, makes it difficult to ascertain the relative weight she placed on water quality considerations. Other historians have suggested that her charge concerning water pollution was merely a way to pile on accusations against the mining company, when in practice, the real conflict was about protecting water rights.[27]

Certainly, losing water rights was an expensive proposition. Her business relied on generous flows from the Cardener River to produce valuable electricity. Antònia Burés owned a water concession for 5 cubic meters per second that she used to propel a hydro-electric turbine in Antius with a 7.2 meter vertical drop (Fig 2.4). A hydro-generator with these characteristics could produce 212 kW of electricity.[28] When flows were too low, as often was the case in summer months, the factory was forced to switch to steam engines. Of course, factory owners were reluctantly to turn on the steam engines, because of the cost of buying and burning coal.

Antònia Burés Borràs was born into a family of the emerging industrial bourgeoisie that had relied on hydropower for decades. Antònia's father, Esteve Burés Arderiu, had founded a large company town that produced fabric by capturing hydraulic energy from the Llobregat River (Fig 2.5). Hydropower was a relatively inexpensive energy source, although not without its inconveniences. River banks were rocky, isolated from towns, had poor road access and were vulnerable to periodic flooding. These desolate sites lacked even the most basic infrastructure. The distance between the planned industry and existing towns presented a considerable challenge for prospective entrepreneurs. The factory workers would need more than a place to work, but also a place to live, to house their families and to educate their children.

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[26] Personal Communication. Esteve Torrens Pérez de los Cabos. January 2011.

[27] Fàbrega Enfedaque, A. 2009. Cum Grano Salis: La Sal i la Potassa a Súria 1185-1982. Ajuntament de Súria & Iberpotash.

[28] The electricity generated is a function of head (vertical drop), discharge and gravity. Therefore the electrical power in Watts generated under these circumstances is: 7.2 m*5,000 liters/s * 9.8 m/s^2 = 353 kW. I assume 60% efficiency so only 212 kW of electricity is generated. For more information on the calculation of electrical generation with hydropower see http://www.reuk.co.uk/Calculation-of-Hydro-Power.htm

Industry leaders responded by embedding their textile mills within a company town complete with employee housing, a school, a general store, a church, and often a theater. In effect, the industrialists who set up shop along the Catalonia's rivers accepted their workers' personal and social needs as a cost of business. Their business model went beyond the creation of an efficient factory floor, and attempted to construct an efficient social structure for production. They created isolated societies in which everything revolved around the production of textiles. The patron's paternalistic provision for their workers and families earned the owners a degree of control over their labor force in addition to loyalties that lasted generations. In exchange, the workers received a secure income and above average working and living conditions for the era.

Antònia Burés married Llogarri Torrens Serra, whose family had also made a fortune producing textiles. Llogarri Torrens died in 1915 leaving her a widow. Over time, she became a well-known resident of Manresa and locals began referring to her extravagant home as *La Buresa*, a name that remains today. Antònia Burés left behind a paper trail that suggests that she was an active widow who managed the properties of her late husband. One of these properties included the Antius textile mill on the Cardener River; the site where the water pollution conflict along the Cardener and Llobregat rivers originally began.

By 1925, mining activity had begun in Súria in earnest. As mining activity increased, so did the volume of salty effluent being dumped into the Cardener River by the mining companies. While it is likely that several farmers felt the impact of the salty waters in their irrigation canals, few had the political clout to challenge the mining company. Antònia Burés became the first to break the silence. In a letter dated September 30th 1926, she filed a complaint with the Water Resources Authority against the mining company *Minas de Potasa de Súria S. A.* for "impurifying the waters of the Cardener".[29] In an era when woman were excluded from business and legal affairs, it was remarkable that Antònia Burés was the first

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[29] Letter from Delegat of Serveis Hidràulics del Prineu Oriental to Mayor of Barcelona. 7 October 1933. Obres Públiques. CV 50/237 1933. La contaminació de les aigües del riu Llobregat amb motiu de la explotació de les mines de potasa de Súria. Arxiu Municipal Contemporani de Barcelona.

with the courage to raise the issue. Although she died soon after her complaint was filed, her son, Esteban Torrens Burés, continued to organize the industrial water users and their oposition to the illegal dumping of saline waters into the Cardener River.

Antònia Burés inaugurated a water pollution conflict that would last for decades. The subsequent controversy would transform water management, infrastructure development and water treatment in the Barcelona metropolitan region for the next seventy five years and well into the twenty first century. As such, her letter to the Water Resources Authority marked the opening chapter in an enduring conflict over salinity values in the Cardener and Llobregat Rivers. More powerful figures would eventually join her cause, including the private water company *Sociedad General Aguas de Barcelona*, the Barcelona's Municipal Laboratory, the *La Vanguardia* newspaper, and the Mayor of Barcelona. Still, being first did not help her case. To the contrary, she would also be the first to fall in defeat against the powerful mining interests that repeatedly succeeded in evading responsibility for their effluents. But her claim did help justify the formation of a commission to study the salinity problem in the Cardener and Llobregat Rivers in 1928, another in 1929 and a third investigation in 1931. However by the time the last and most influential investigation began in 1931, the potash mines had already consolidated their power in Catalonia.

Figure 2.3 Antònia Burés Borràs (1854-1928). (Photograph courtesy of Esteban Torrens Pérez de los Cabos)

Figure 2.4 The Antius colony along the Cardener River owned and managed by the Torrens Burés family. (Photograph courtesy of Esteban Torrens Pérez de los Cabos)

Figure 2.5 The Llobregat River in its passage through Castellbell i el Vilar. The Burés factory and company town is on the left bank of the river, and was built by Esteve Burés Arderiu, father of Antonia Burés Borràs. (Photograph by the author)

Figure 2.6 The modernist home owned by Antonia Burés Borràs in Barcelona on Ausias March 46. Notice the inscription of initials A.B. above the doorway. (Photograph by the author)

Watershed Planning

In January 1927 the Governor of the Province of Barcelona reviewed the lawsuit submitted by Burés and ordered *Minas de Potasa de Súria* to halt the illegal water withdrawals until the company had obtained the appropriate water concessions. The mining company challenged the Governor's resolution and a legal battle ensued between the extractive industry and the owners of the textile factories. The plaintiffs were organized by the son of Antonia Burés, Esteban Torrens Burés, who rallied together an alliance of industry leaders to defend their pre-existing water rights. New diversions upstream, especially illegal ones from a growing industry, threatened their energy source and posed a significant challenge to their historic control over the Llobregat's main tributary.

With tensions rising between *Minas de Potasa de Súria* and the industrial leaders along the Cardener, the Spanish Ministry for Economic Development dispatched their lead engineer, Carlos Santa María, to review the claims and draft a summary report with recommendations. This would be the first of several investigations. On March 31st 1928, Santa María concluded that *Minas de Potasa de Súria* was indeed, illegally diverting water from the Cardener River, and that the mining process "appreciably increases the mineralization of the river". While he did not feel that this contamination was an immediate danger to public health, he did recommend for the formation of a committee comprised of specialists representing a wide range of backgrounds to study the "urgent issue".[30] He also suggested that *Minas de Potasa de Súria* install devices to monitor the quality and volumes of their effluent.

None of these recommendations materialized. Instead, on November 20th 1928, the Spanish Government requested that experts from the mining industry take charge of the issue. This group of mining engineers and geologists were organized in a governmental panel called the *Superior Board on the Extraction of Potassium Salts*.[31] The Spanish government asked them to determine the maximum admissible amount of salt that could be dumped into the river. At this point, there was no mention of how the mining effluents were impacting drinking water supplies. The conflict remained between the mining company and an elite group of industry leaders.

The *Superior Board on the Extraction of Potassium Salts* elected Agustín Marín y Bertran de Lis to lead the investigation into the salty effluents flowing out of Súria. He was asked to coordinate a team that would collect new data and make recommendations about how to "harmonize industrial processes". The *Superior Board on the Extraction of Potassium Salts* was comprised of mining specialists; and as a group, there were exceptionally well qualified to study the mine's impact on the Cardener and Llobregat Rivers. More than anyone, they had an intimate understanding of the methods used by the mines to extract potassium. They knew, for example, that *Minas de Potasa de Súria* depended on large volumes of

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[30] CESALL Report.1932. Arxiu Nacional de Catalunya (ANC) Fons 547. Agència Catalana de l'Aigua. Unitat 479.

[31] *Junta Superior de Explotación de Sales Potásicas*

water to dissolve the potassium chloride in the first phase of extraction. Once dissolved into a liquid porridge, the miners separated the valuable potassium from other worthless compounds through a decanting process. The problem was how to dispose of the remaining fluids, saturated in sodium chloride and magnesium chloride. The easiest option was to open the flood gates leading into the Cardener River. So when Agustín Marín was asked to study the salinity problem associated with the mining industry in Súria, there was no doubt in his mind that the activity was releasing large volumes of chloride into the Cardener River. The critical question was how much.

Agustín Marín set out to answer this question by taking water samples from the Cardener River above and below the mines. The samples taken in May 1929 showed that the mining company dumped approximately 26,940 tons of sodium chloride and 51,840 tons of magnesium chloride into the river each day (Table 2.1). Water quality samples were taken again in August 1929 with even more dramatic results -- the volume of magnesium chloride quadrupled downstream of *Minas de Potasa de Súria* and sodium chloride increased 50%. The *Superior Board on the Extraction of Potassium Salts* concluded that the mines dumped approximately 100 tons of chloride into the river per day, diluted in a daily effluent of 15,000 cubic meters.[32] However their internal discussions remained private, and the report they began to prepare for the Spanish Government probably would have stayed confidential had the problem not escalated.[33]

While the mining experts were still tabulating the chloride loads released into the Cardener River, the consequences of the chloride effluents began to be felt downstream. Sufficient chloride had travelled

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[32] CESALL Report 1932. Arxiu Nacional de Catalunya (ANC). Fons 547. Agència Catalana de l'Aigua. Unitat 479

[33] Marín co-lead the first investigation with Alonso Martínez. Mr. La Rosa and Mr. Santa María travelled to the Cardener to take water quality samples, and Marín and Martínez were responsible for presenting the results to the Board. Once the Board was informed that Sociedad General Aguas de Barcelona has begun legal proceedings against the mining company, the Board was approached by the representative of the mining company, Gálvez-Cañero for assistance, at the Board meeting on Christmas Eve 1930. The Board then asked Mr. Kindelán and Mr. La Rosa to visit the water company and the groundwater pumping stations in early 1931. Mr. Menéndez Puget was asked to visit the mining companies. Once the CESALL commission was created in March 1931, these working groups were dissolved and they passed on their information to Marín, who sat on the CESALL commission. (CESALL 1932)

down the Cardener River, into the main stem of the Llobregat, and then percolated into the aquifer beneath the Llobregat Delta, that chemists had begun to detect a rise in chloride concentrations in the groundwater wells starting in 1926. In Molins de Rei, located several miles upstream of Barcelona's wells, chemists noticed that chloride concentrations jumped 60% between 1928 and 1930; from 137 mg/L to 220.4 mg/L.[34]

Date	**Site**	**MgCl2 (mg/L)**	**MgCl2 (Kg/day)**	**MgCl2 released to river (Kg/day)**	**NaCl (mg/L)**	**NaCl (Kg/day)**	**NaCl released to river (Kg/day)**	**River Discharge (m3/hour)**
6 May 1929	Upstream	39	18,720		146	70,080		
	Downstream	147	70,560	51,840	204	96,920	26,940	20,000
10 August 1929	Upstream	123	27,457		213	47,544		
	Downstream	1,110	247,732	220,296	390	87,048	39,501	9,300
7 November 1929	Upstream	110	18,480		213	35,784		
	Downstream	279	46,872	28,372	1,200	201,600	165,640	7,000
13 December 1929	Upstream	100	24,000		198	47,520		
	Downstream	359	86,160	62,160	534	128,160	80,640	10,000
25 March 1930	Upstream	69	57,760		69	57,960		
	Downstream	129	108,360	50,400	164	137,760	79,800	35,000
Means excluding the highest two values				40,108			56,713	

Table 2.1. Results from the first water quality samples taken to assess the impact of mining effluents on the salinity of the Cardener River between May 1929 and March 1930 by the *Superior Board on the Extraction Potassium Salts*, upstream and downstream of mining activities in Súria. Reproduced from data in CESALL (1932).

Simultaneously, *Sociedad General Aguas de Barcelona* detected similar increases in chloride values in the freshwater aquifer at the pumping stations in Cornellà (Fig 2.1). The aquifer was monitored

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[34] Elsewhere in the CESALL report, additional data is presented from the wells in Molins de Rei: 83.33 mg/L Cl (August 1928), 124 mg/L Cl (July 1931), 187.7 mg/L (December 1931).

closely given that it provided much of Barcelona with its drinking water. As a reference point for what chloride concentrations were before mining activities, in 1915, three years prior to any mining of potassium, *Sociedad General Aguas de Barcelona* recorded a chloride concentration of 80 mg/L in the aquifer.[35] Ten years later, in 1925, precisely the year when industrial potassium mining began in Súria, the water company recorded a similar baseline value of 79 mg/L.[36]

But by late 1929, the rise in chloride values in the Llobregat aquifer became a grave concern. *Sociedad General Aguas de Barcelona* gathered the evidence and presented their case to the responsible water agencies in April 1930.[37] These findings seriously concerned everyone involved, since no technology was capable of removing the dissolved solids from the water supply. A rapid increase in chloride concentrations could permanently contaminate the water source, causing major disruption to the city of Barcelona, and financial ruin for the water company. *Sociedad General Aguas de Barcelona* quickly began to mobilize its resources and influence in order to protect the aquifer from further contamination.

The water company executive, José María Soler Nolla, became the outspoken point person on this issue for *Sociedad General Aguas de Barcelona*. When Soler Nolla contacted the responsible water agencies in 1930, he learned that the water company was not the first to initiate legal proceedings against *Minas de Potasa de Súria* for illegally dumping their waste into the river. The industrial leaders of the Cardener valley, led by the son of Antònia Burés, Esteban Torrens Burés, in collaboration with Luis Argemí, and the Baron of Montclar, had already filed a case. But the recommendations from the first investigation did not go far, and the second report was still being drafted by the mining experts behind closed doors in Madrid.

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[35] La Vanguardia 1935. March 23. La Salinidad de las Aguas del Llobregat. p 6.
[36] CESALL Report.1932. Arxiu Nacional de Catalunya (ANC) Fons 547. Agència Catalana de l'Aigua. Unitat 479.
[37] Archive Aigües de Barcelona. Box 5615. Folder 15. “Informe sobre la influencia que tienen las explotaciones mineras en la cuenca del río Llobregat en el aprovechamiento de aguas subálveas del mismo río para el abastecimiento de Barcelona y propuesta provisional”. 3 November 1931.

The threat of further contamination led the water company and their affiliated groundwater firm, *Empresa Concesionaria de Aguas Subterráneas del río Llobregat*, to file their first lawsuit requesting that the Spanish Government address the salt contamination flowing from the mining town of Súria.[38] The entry of *Sociedad General Aguas de Barcelona* into the controversy escalated the water conflict. What previously was an isolated dispute along the Cardener River became a regional confrontation of national significance.

Sociedad General Aguas de Barcelona filed their claim during a transitional period between the Primo de Rivera dictatorship, which ended in January 1930; and the democratic governments of the Second Spanish Republic, inaugurated in April 1931.[39] The transitional government took a more active role mediating between the mining company in Súria and the water company in Barcelona.

The Spanish Government wanted a resolution that would meet the needs of both parties. It was desirable for the mines to produce potassium fertilizers upstream, but downstream, the river needed to arrive clean enough so that it would not harm existing users, especially municipal water suppliers. The trouble was that the stakes were enormously high. Miscalculation could wipe out Barcelona's primary source of freshwater. Salinization of the aquifer would also drive the water company into financial ruin. This dismal outcome threatened to reverberate throughout the Spanish economy since Spanish banks had recently acquired the private water company from French investors. Therefore the question regarding how much salinity should be permitted to flow into the river was far too important to be left to the mining interests alone to decide. More stakeholders needed to be brought to the table, and the recommendations to emerge from the committee of experts needed to meet the interests of all involved.

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[38] Anonymous 1931. Informe sobre la influencia que tienen las explotaciones mineras en la cuenca del rio Llobregat en el aprovechamiento de aguas subalveas del mismo rio para el abastecimiento de Barcelona y Propuesta Provisional. AGBAR Archives. Box 5616. no. 15.

[39] Spain's Second Republic began following a landslide victory of pro-democratic political parties in Spain's Municipal Elections in April of 1931 and would last until the uprising led by General Francisco Franco in 1936.

To meet these diverse needs and interests, a third investigation began in March 1931. The *Commission for the Study of the Salinity of the Waters of the Llobregat* (CESALL)[40] was tasked to research the same questions as the investigations that came before them: quantify the extent of the salinity pollution caused by the mining activity in Súria and recommend solutions to resolve the problem. The composition of the CESALL commission struck a delicate balance among competing interests. Two members were from the Water Resource Agency of the Eastern Pyrenees; one from the Mining Department; another from the Public Health Department; the Director of the Municipal Laboratory of Barcelona, Pedro Gonzalez; and finally, Agustín Marín y Bertran de Lis, representing the *Superior Board for the Extraction of Potassium Salts* as the de-facto representative of the mining interests. Private parties were invited to the CESALL commission as non-voting members: José Soler Nolla representing *Sociedad General Aguas de Barcelona*; and Norbert Fonthier on behalf of *Minas de Potasa de Súria*. The Royal Order that created the CESALL commission also specified that the expenses associated with the commission would be financed by *Minas de Potasa de Súria*.

Starting in May 1931, the CESALL commission met every other week at the conference room of the Water Resource Agency of the Eastern Pyrenees on the Via Laietana no.10 in Barcelona. Once the CESALL commission was established, events moved quickly. By the second CESALL meeting on June 2nd 1931, the second potassium mining firm, *Unión Española de Explosivos* had begun extracting potash along the Cardener River in Cardona. This worked to the advantage of *Minas de Potasa de Súria* because it allowed them to point fingers at their neighbor for contributing to the salinization of the Cardener and Llobregat Rivers. The new arrivals also allowed *Minas de Potasa de Súria* to claim that they were being unfairly burdened with the expenses of the CESALL commission, when in practice, other mining companies were also contributing to the problem. Within the year, a third mining company, *Potasas Ibéricas*, would also set up operations on the right bank of the Llobregat River near Sallent, further adding to the mix of polluters.

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[40] *Comisión para el Estudio de la Salinidad de las Aguas del Llobregat* (CESALL)

Anticipating that the salinity problems would only get worse, the CESALL got to work immediately. They began with a fact finding mission to quantify the damages associated with the salty effluents. The CESALL commission sent out a public inquiry asking farmers, municipal governments, and industry leaders, to report the damages incurred by the river salinization.[41] Farmers reported that their crops had suffered, but that the specifics eluded quantification because too many variables obfuscated the precise causal relationships between river water quality and harvest yields. Furthermore, farmers expected that the salinization of their land would be gradual, rendering their fields barren over time. There was no doubt in farmers minds, however, that salinity values had increased. The Municipal Government of Olesa de Montserrat wrote on behalf of their residents in the summer of 1931, "That the water in the Llobregat is now saltier than it was a few years ago, is public knowledge, and that this fact is unfavorable to agriculture, is evident."[42]

Of all the institutions who responded to the CESALL Commission's request for information regarding the salinity of the Llobregat River, *Sociedad General Aguas de Barcelona* was the most interested party. Their business depended on protecting the aquifer whose waters they treated and pumped into the homes of the urban elite.[43] The chloride entering the aquifer was irreversibly changing the water's composition. Even small amounts could alter the taste to the palate. While the water professionals did not foresee any health problems associated with chloride in the drinking supply, there was a concern that the unpleasant taste would discourage new users from connecting to the urban network, and provide an excuse to use contaminated wells instead.[44]

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[41] Boletín Oficial de la Provincia de Barcelona (BOPB) 1931. Comisión para el Estudio de la Salinidad de las Aguas del Llobregat. 9 June 1931. No 137. Número disposición 7472.

[42] Letter from town of Olesa de Montserrat to CESALL in response to the public call for information on the salinity problems in the Llobregat watershed (BOPB. 9 June 1931). AGBAR Archives. Box 5615. No. 12.
Que el agua del Llobregat, de unos años a esta parte baja más salada que antes, es un hecho público, que esta particularidad no puede ser favorable a la agricultura, es evidente

[43] Martín Pasqual, J.M. 2007. Aigua i Societat a Barcelona entre les dues Exposicions (1888-1929). Doctoral Dissertation. Departament d'Història Contemporània i Moderna. Universitat Autònoma de Barcelona.

[44] "*Lo que ocurre es que el agua llegaría a ser salada y, por consiguiente, desagradable para la bebida, y entonces las gentes la rechazarían. Y como la inmensa mayoría de los barceloneses no puede permitirse el lujo de beber*

For years *Sociedad General Aguas de Barcelona* had relied on the filtration services of the aquifer which removed particles and suspended solids. The director of *Sociedad General Aguas de Barcelona* proudly claimed that "the waters captured at our wells in Cornellà, after a horizontal filtration of various kilometers and a vertical filtration of forty meters, has a biological purity that cannot be beat by any water source in the world." He added, "But unfortunately, not even this filtration nor chemical treatment is capable of separating the sodium chloride from the water."[45]

The private water company was also nervous about the destabilizing effects that this contamination episode could have on its consumers and the working class. The political risks were emphasized in the water company's concluding remarks to the president of the CESALL Commission:

> *"Forgive me, Don Enrique, for my insistence, but the issue concerns me more and more, especially during these times of quarrels and popular revolts, I do not know what would happen if one day, after serving Barcelona with salt water, we would force people to endure an enormous financial burden to replace the water that now flows to their faucets without any public expense."* [46]

During the summer of 1931 the salinity problems were aggravated by drought. In July and August 1931, the Cardener River started to dry up, and the salt concentrations spiked. That year the flow stations

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aguas minerales embotelladas, se recurriría al agua de los pozos. Y esto sí que constituiría un grave peligro para la salud, pues no controlados ni vigilados estos pozos, la mayoría de ellos contienen agua que no reúne las condiciones higiénicas necesarias para su consumo." Interview with Dr. Pedro González, Director of Barcelona Municipal Laboratory. La Vanguardia 1935. Voz de Alarma. 23 March 1935.

[45] La Vanguardia 1935. La Salinidad de las Aguas del Llobregat. 23 March 1935. p 6.

[46] Letter from Sociedad General de Aguas de Barcelona to CESALL. 17 August 1931. AGBAR Archives. Box 5615. No. 12.

"Perdone, Don Enrique, que le moleste tanto; pero el asunto me intranquiliza cada vez más porque en estos tiempos de querellas y explosiones populares, no sé lo que pasará si un día trás servir a Barcelona agua salda, obligamos a sus habitantes a soportar una carga financiera enorme para poder sustituir al cabo de unos años el agua que hoy, sin ningún gasto público, mana normalmente de sus grifos."

in Cardona and Martorell recorded average discharges that were half of normal.[47] In response to the rising chloride values, the Public Health Commission asked the Catalan Parliament to intervene immediately and require the mines to reduce their discharges into the river so that the Llobregat River would not surpass a chloride concentration of 250 mg/L.[48]

When the CESALL commission reconvened from summer break on September 1st 1931, the Director of the Municipal Laboratory, Pedro González insisted that the CESALL commission write the Provincial Governor of Barcelona requesting that regulations be established immediately, without waiting for the final conclusions of the CESALL investigation. The commission agreed, and within two weeks the Governor dictated an order that chloride concentrations could not surpass 250 mg/L on the Llobregat River at the confluence with the Cardener.[49] This provisional decree would buy time for the CESALL commission to study the issue in greater detail. The public health commission would monitor compliance and the laboratory expenses would be paid by the plaintiff parties if the measurements were below the limit, whereas expenses would be paid by the mining companies if a violation was found. The penalty imposed on the mining companies for the first violation would be the closure of mining operations for one day. A second violation would require closure for a week, and a third violation would be punished by indefinite closure.[50]

The CESALL Commission released its final report in the spring of 1932. The lengthy document was complete with tables, figures and elegant maps of the watershed. The commission concluded that four measures were necessary to bring the salinity problem under control. First, the commission proposed

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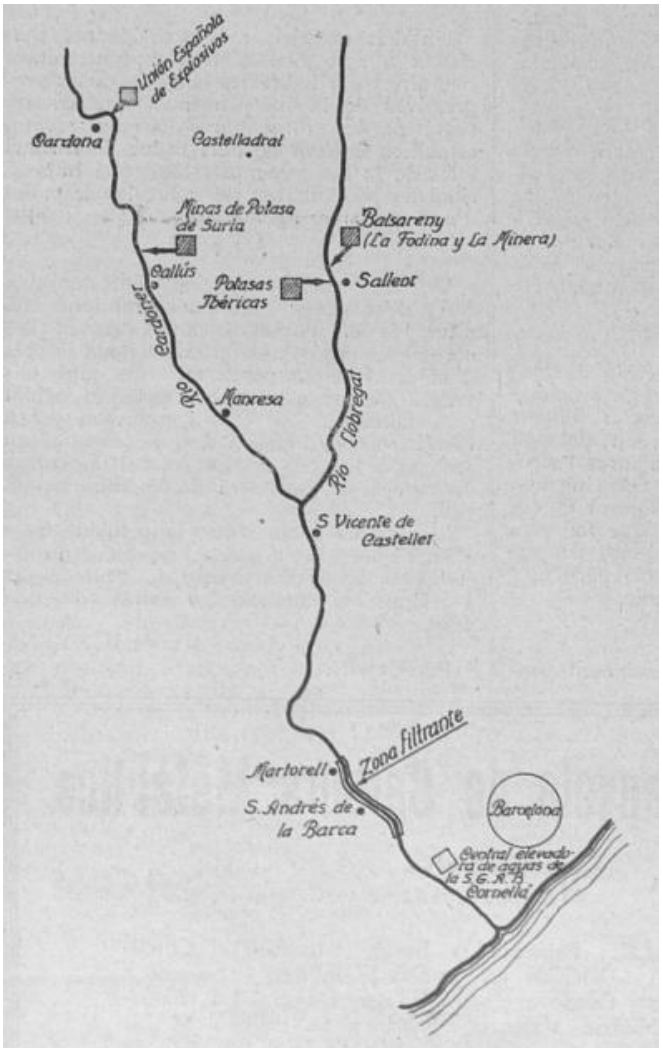
[47] Plan General de Obras 1936. Delegación de los Servicios Hidráulicos del Pirineo Oriental. Pla general d'obres per l'any 1936. Annex a l'informe. Arxiu Nacional de Catalunya. Fons 547. Agencia Catalana de l'Aigua. Unit 42.

[48] CESALL Report. 1932. Arxiu Nacional de Catalunya (ANC) Fons 547. Agència Catalana de l'Aigua. Unitat 479.

[49] The letter from Provincial Governor of Barcelona was published in Appendix 2 of the CESALL Report. It should be mentioned that the Chair of the CESALL Commission, and Director of the Water Resource Agency for the Eastern Pyrenees, Enrique González Granda y Silva abruptly resigned soon after this regulation was imposed on the mining companies in September 1931. He was substituted on the CESALL commission by a representative from the Mining District of Barcelona, Enrique Bayo Timmerhant, who chaired the remainder of investigation. A cynical interpretation might see a connection between the unexpected water quality regulation, the immediate resignation of the CESALL chair, and his replacement by someone from the Mining District of Barcelona, although no evidence has been found to verify any connection.

[50] CESALL Report.1932. Arxiu Nacional de Catalunya (ANC) Fons 547. Agència Catalana de l'Aigua. Unitat 479.

legislation that would limit chloride concentrations at 250 mg/L in the town of Pallejà. This figure was based on regulations inscribed in German law that oversaw the potash industry along the Rhine River. However this apparent victory for *Sociedad General Aguas de Barcelona*, was in reality, a good deal for the mining companies. Mining interests succeeded in ensuring that chloride concentrations were not regulated at the point of discharge, nor even at the confluence of the two major rivers, as originally established in the provisional Governor's decree from 1931. Instead, the Commission pushed the sampling site down river, nearly to the base of the watershed, where the dilution potential was greatest. The sampling site of Pallejà was justified because geologists estimated that the river recharged the aquifer at this point (Fig 2.7).



Gràfic de la situació de les mines de potassa i la central elevadora d'aigües

Figure 2.7 Map of the critical areas of the salinity conflict in the Llobregat watershed, published in the weekly periodical *El Mirador* on June 27th 1935 in an exposé article *The problem of the salinity of the waters of Barcelona*. The hatched squares show the location of the potassium mines along the Llobregat and Cardener Rivers in 1935: *Unión Española de Explosivos*, *Minas de Potasa de Súria, Potásas Ibéricas*, *La Fondina y la Minera*. The filtration zone where the Llobregat River feeds into the aquifer is marked between the towns of Martorell and San Adrés de la Barca as "Zona Filtrante". Finally, the transparent square shows the location of the groundwater pumping wells owned by *Sociedad General Aguas de Barcelona* in the town of Cornellà, south-west of Barcelona.

Second, the CESALL commission recommended that water quality be monitored periodically along the rivers. This was probably the most significant and tangible victory for those seeking to keep the aquifer salt free. Constant vigilance would be needed to enforce the new regulations. The monitoring methods proposed were advanced for the era and included modern automatic measurement devices.

Third, the Commission advocated for the construction of a brine collector that would transport the industrial effluent from the mines and pipe it to the Mediterranean. This proposal had the added advantage that the new canal might also transport municipal and industrial wastewater, and thereby protect Barcelona's drinking water from other contaminants.

Finally, the CESALL commission proposed the construction of dams along the Cardener and Llobregat Rivers. These structures could help regulate river flows and dilute salt concentrations during the dry season. Farmers could also benefit from the dams, and the CESALL commission was quick to point out the benefits for agriculture and flood control.

The conclusions of the CESALL report fit the long term interests of both the mining and water companies. Following the release of the CESALL report in April 1932, *Sociedad General Aguas de Barcelona* became a firm advocate for the construction of the brine collector and the dam. Especially with the dame proposal, the interests of the mining company overlapped with those of the water company. Storing water in the mountains would provide a generous source of drinking water for the metropolitan region, and releasing it during the dry season would dilute the contaminants and increase the volume of water entering the groundwater wells managed by *Sociedad General Aguas de Barcelona*.

The CESALL commission was a laudable exercise in river basin planning and should be credited with searching for constructive solutions to the conflict. The Spanish government sought to find compatible uses among competing water users. With scientific detachment and quantitative precision, the commission searched for practical ways to satisfy competing needs. What the CESALL did not foresee however, was the delays that would prevent the brine collector from being built for several decades. To the contrary, the CESALL commission was confident that the brine collector and dams would be built soon. But the projects stalled, and during the remainder of 1932, and through 1934, the salinity controversy largely disappeared from archival records and press reports. One major exception was the passage of the Salinity Law by the Catalan Generalitat published in August 1933. The law closely followed the CESALL recommendations, essentially codifying their regulatory recommendations into law.[51] The regulation stated that the chloride concentrations could not surpass 250 mg/L along the Llobregat River at Pallejà.

Following the release of the CESALL report, the commission was renamed the *Commission for the Inspection of the Salinity of the Waters of the Llobregat* (CISALL). As the new name implies, the CISALL focused on monitoring water quality. With funding from the mining companies, the CISALL established five sampling points, each below a mining operation on the Cardener or Llobregat Rivers: one in Malagarriga, below the mines in Cardona; another in Antius, below *Minas de Potasa de Súria*; a third in Torreroca, below the mines in Balsareny; a fourth at Soler Vicenç below *Potasas Ibéricas*; and the fifth at the critical point of Pallejà, the only site in which the data would have any legal implications.[52]

There is evidence that the Salinity Law and the regular inspections helped reduce the salinity concentrations entering the freshwater aquifer downstream. In 1934 the water company reported that the chloride concentrations fell from 202 mg/L to 169 mg/L, and they attributed this reduction to the Salinity Law of 1933.[53] However this success was short lived.

With the regulatory framework in place, attention shifted to the brine collector project which was supposed to provide the "definitive solution" to the water pollution problem. However the project lost momentum between the release of the CESALL report in 1932 and March 1935 when the issue finally resurfaced. The exact reason for this delay is unclear. Leftist political parties governed during most of this

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[51] Butlletí Oficial de la Generalitat de Catalunya. 1933. Llei de Salinitat. August 12, II, p. 229.

[52] It appears that the Malagarriga station was not built until after the Civil War (Personal Comment, Santi Gorostiza, October 2011)

[53] Meeting Minutees CISALL, 25 April 1936 "*La Sociedad que represento ve anulándose, poco a poco, los efectos beneficiosos que en la disminución de los cloruros contenidos en sus aguas se obtuvo con la inspección de los ríos Cardoner y Llobregat. Cuando empezó dicha inspección, nuestras aguas de Cornellá, contenían unos 202 miligramos por litro de ión cloro; durante el primer año y medio de inspección, disminuyeron hasta contener 169 miligramos por litro en Enero de 1935, pero desde dicha fecha, empezó un ininterrumpido aumento (con tendencia todavía al alza, según los últimos análisis), que ha hecho que la cloruración se cifrara como promedio en el mes de Marzo último, en 187 miligramos por litro*".

period, both in Catalonia and Madrid, and one might expect Lefist parties to be more willing to take on a polluting industry. Of course, this was a turbulent era, and many issues competed for the attention of civic leaders. In the early 1930s north-eastern Spain was at the center of political turmoil and unrest. The industrial areas of Catalonia were a hub of anarchist activity and occasional violent outbreaks.[54] In January of 1932, during a massive General Strike that spread throughout the Llobregat and Cardener valleys, anarchists revolted in the mining towns and took control of the municipal government in Súria. The anarchist flag flew over the city hall of Súria until the Spanish Civil Guards reclaimed control of the town and expelled the rebels to African colonies.[55] Following the revolt, the mining company saw the need for more police protection and donated funds to the Spanish Civil Guard so they could establish a permanent station near Manresa. Each mining enterprise in the region, *Minas de Potasa de Súria*, *Unión Española de Explosivos* and *Potasas Ibéricas* donated 12,500 Spanish pesetas to help build the police quarters.[56]

The political turbulence certainly contributed to the limited attention directed at the salinity problems in the Llobregat and Cardener Rivers, especially in 1934 when the issue nearly disappeared from public view.[57] However the water conflict resurfaced again in 1935, with considerable uproar, and more attention from the press in Barcelona. In March 1935, the Director of Barcelona's Municipal Laboratory, Dr. Pedro Gonzalez, released a report where he found that chloride values of Barcelona's

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[54] Brenan, G. 1943. The Spanish Labyrinth (12th Edition ed.). Cambridge: Cambridge University Press.

[55] Fàbrega Enfedaque, A. 2009. Cum Grano Salis: La Sal i la Potassa a Súria 1185-1982. Ajuntament de Súria & Iberpotash.

[56] Arxiu Comarcal del Bages, Manresa.

[57] I found surprisingly few documents that referred to the salinity conflict in 1934. In that year records show that the water company *Sociedad General Aguas de Barcelona* opposed a request from *Sociedad Potasas Ibéricas* to obtain water concessions from the Llobregat River. On 19 August 1934 the La Vanguardia newspaper published a photograph of Catalan President of the Generalitat, Lluis Companys, and the Catalan Comissioner of Public Health, Josep Dencàs, in an official visit to the mines operated by *Sociedad Potasas Ibéricas* in Sallent. As mentioned, there is evidence that effective water quality monitoring in 1934 helped reduce salinity values in the river and aquifer. However in a letter dated 8 March 1935 from the water company executive José Soler Nolla to the Governor of Catalonia, he asserts that "the water quality monitoring is only helping to document the rate at which chlorine is increasing in our rivers". He added that in January 1935 chlorine levels surpassed the permissible limit and reached 272 mg/L in Pallejà. The letter from José Soler Nolla can be found in Sallent Municipal Archives. Box 2525.

drinking water had risen to 176 mg/L, meaning that concentrations had more than doubled in the last ten years.[58] Dr. Gonzalez reiterated the recommendations from the CESALL report and was convinced that the brine collector was the only solution.

The renewed attention directed at the salinity problems of the Llobregat River coincided with the drought in the summer of 1935, in which reduced base flows increased mineral concentrations.[59] By 1935, records show that the mining companies were failing to comply with the Salinity Law of 1933. Chloride concentrations at Pallejà surpassed the limit of 250 mg/L and would often reach 300 mg/L.[60] The deteriorating conditions of the Llobregat River also began to mobilize river users. In April 1935 fishers, writers and artists gathered in Manresa to protest the salinization of the Llobregat River. Fishers from throughout Catalonia came to Manresa with their fishing poles in an event that the organizers called "Monster Meeting".[61] Leaders from the anarcho-syndicalist movement spoke at the event and called for the start of a "water revolution".[62]

Unfortunately, little is known about the grassroots activism that protested the salinization of the Cardener and Llobregat's waters.[63] But we do know that the conditions of the river had deteriorated severely. Downstream users lamented that the river had become a sewer for industry. A resident of El Prat del Llobregat lamented in 1935 that "poets can no longer sing of their clear waters."[64] Instead, the

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[58] La Vanguardia 1935. Dictamen del Director del Laboratorio Químico Microbiológico Municipal. 22 March 1935. p 9.

[59] Aldomà, I. 2007. La lluita per l'aigua a Catalunya. De l'us, abús a la gestió integral (1900-2007). Lleida: Pagès Editors.

[60] Letter from José Soller Nolla, Director of Sociedad General Aguas de Barcelona to the Mayor of Barcelona. 8 March 1935. Sallent Municipal Archive. Box 2525.

[61] "Miting Monstre" Poster at Sallent Municipal Archive. Box 2525.

[62] El Be Negre: Setmanari Satiric, 1935. La Revolució de l'Aigua a Manresa. Num 200. 24 April 1935 p 2.

[63] It appears that the President of the Federation of Fishers, Juan (Joan) Sebarroja was a strong defender of the Llobregat River, and may have been a key grassroots organizer among the fisher community. His name appeared on the poster that called for the protests in Manresa in April 1935. He also gave a lecture titled, "The impurification of the waters in Catalonia's Rivers: Affair Llobregat" in February 1935. (See La Vanguardia 21 February 1935 pag 13). In his lecture, he criticizes the "poisoning" of the river, and in particular, the "extraordinary rise in salinity". He expressed surprise that the authorities were not taking action to protect Barcelona's drinking water. To demonstrate the economic contribution of the Llobregat River, he estimated that annually, fishers extracted fish from the Llobregat worth 2 million Spanish Pesetas. In contrast, today, not a single edible fish is extracted.

[64] Pujol, J. 1935. Agrícoles: Insistint. Noticiero Pratenc. 25 May 1935. Pg. 2.

Llobregat had become “turbid… dirty, oily, milky, and even rotting during low flows.”[65] On the eve of the 1929 World Exhibition in Barcelona, one newspaper worried that visitors might wander down to the Llobregat River and find a “pestilent valley” that was an assault on the public health.[66]

The protesting fishers in Manresa had seen first-hand how river pollution was wiping away aquatic life. While many fish kills probably went unreported, one made headlines in October of 1933.[67] The floating dead fish covered the surface of the river, and the volume was so overwhelming that several company towns were forced to halt production to pull out the dead fish from the turbines. In all, an estimated 50 to 80 tons of dead fish floated down the river during the episode.[68] While the first news report published in Madrid initially attributed the fish kill to the potassium mines, another report published in Barcelona later attributed it to storm water runoff from calcium mines.[69]

In 1935 it was clear that the mining activity had not reached its full potential and that the salinity concentrations would continue to rise and threaten Barcelona’s primary source of fresh water.[70] In the spring of 1935 *Sociedad General Aguas de Barcelona* distributed water to one and a quarter million residents. The water company wrote the Catalan Minister of Health and reminded the Catalan Government of their “undeniable mission: to uphold the law approved by the Catalan Parliament on 11 August 1933 that prohibits that the salinity of the Llobregat river at Pallejà exceeds 250 mg/L.” If the problem were to remain unattended the outcome would be “disturbing” and “tragic”.[71]

The renewed pressure pushed the Spanish Government into action once again. In April 1935 the Spanish Minister of Public Works, Rafael Guerra del Río, called for a meeting in Madrid with top

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[65] Ibid.
[66] L’Avenç 1928, 12 February.
[67] Heraldo de Madrid. 24 October 1933. Las aguas del Llobregat contaminadas. Al verter en ellas residuos de las minas potásicas se ha producido un exceso de salinidad que determino la muerte enorme cantidad de peces. Pag 10.
[68] Ibid.
[69] La Vanguardia 1933. Por qué murieron los peces del Llobregat. El hidrato de cal. No hay peligro para los habitantes de Barcelona. 2 November 1933. Pag 7.
[70] La Vanguardia 1935. La Salinidad de las agaus del Llobregat. 20 March 1935 p. 5; La Vanguardia 1935. Dictamen del Director del Laboratorio Químico Microbiológico Municipal. 22 March 1935 p 9; La Vanguardia 1935. La salinidad de las aguas del Llobregat. 23 March 1935 p 6.
[71] AGBAR Archives. Box 5615 no. 36. Nota de la S.G.A.B. al Consejero Sanidad.

executives from the water and mining companies[72]. They were accompanied by the members of the CISALL Commission and the leadership of the Water Resource Agency of the Eastern Pyrenees. The meeting marked a turning point for the salinity conflict because all the stakeholders finally agreed to act upon the recommendations laid out by the CESALL Commission in 1932 including the building of the brine collector. The CISALL commissioners estimated that the project would cost between 10 and 12 million Spanish Pesetas. Meeting minutes show that the CISALL Commission proposed that the expenses be divided among the mining companies, the water company and the Ministry for Public Works.[73] José Soler Nolla from *Sociedad General Aguas de Barcelona* demonstrated his enthusiasm for the Minister's proposal by offering to finance the project with private capital in order to accelerate construction. By the end of the meeting, everyone agreed that the next step was to transform their ideas into budgets and blueprints. Those in attendance regained confidence that the brine collector would be built; it was just a matter of arranging the details.

The Public Minister for Public Works, Guerra del Río framed the brine collector project within the context of creating jobs for the working class. The Minister bragged in a press conference that he hurled an ultimatum at the mining companies. Either they collaborated in the construction of a disposal system for their industrial waste, or the Spanish Government would suspend the mining concessions and bring all mining activity to a halt.[74] This strong language was unprecedented and perhaps never repeated.

The timing of events suggests that key leaders within the Radical Party may be credited for putting the brine collector project back on the agenda. Debate surrounding the salinity conflict hit the press in Barcelona on a regular basis starting in March 1935, and remained a hot topic through the

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[72] Veu de Catalunya 1935. La Salinitat de les Aigues de Barcelona. 27 April 1935; Correo Catalan 1935. El Ministerio de Obras Publicas da una detallada referencia del mismo, ampliada en sus aspectos tecnico por el ingeniero D. Lorenzo Pardo. 27 April 1935. Num. 19229 p 31; Diario de Barcelona 1935. Delegación de los Servicios Hidraulicos del Pirineo Oriental. 28 April 1935. p 5; La Vanguardia 1935. Las Aguas del Llobregat. 5 May 1935 p 8;

[73] Fàbrega i Enfedaque, A. 2009. Cum Grano Salis. La Sal i la Potassa a Súria, 1185-1982. Iberpotash i Ajuntament de Súria, pg 428.

[74] Veu de Catalunya. 1935. La Salinitat de les Aigues de Barcelona. Manifestaciones del señor Guerra del Río. Saturday 27 April 1935.

summer. This coincided with the Lerroux Government in Madrid, but also with the appointment or election of Radical Party members in critical posts: Jaime Polo Otin at the Water Resources Agency of the Eastern Pyrenees, Rafael Guerra del Río in the Ministry of Public Works were both members of the Radical Party, as was the Mayor of Barcelona, Joan Pich i Pon. The political alignment in Barcelona, Catalonia and Madrid, may have contributed to the tangible steps toward the execution of the brine collector project in the spring of 1935.[75]

Another interpretation might trace the renewed attention to the letters written by *Sociedad General Aguas de Barcelona* on March 8th 1935 to the Governor of Catalonia, the Mayor of Barcelona, and later on March 26th 1935 to the Spanish Parliament. These letters were signed by a coalition of associations such as the Medical Academy of Barcelona, the Regional Federation of Fishers, and agricultural unions.[76] However the *Sociedad General de Aguas de Barcelona* had been pursuing this project for years, so it is unclear what pushed the government into action in the spring of 1935, if not something particular about those in power during that period.

After the Ministerial meeting in Madrid the salinity conflict continued to attract attention in the press, and the executives at *Minas de Potasa de Súria* followed these developments closely. Correspondence between the mine director, Norbert Fonthier and his supervisors in Brussels has left us with insiders' view of their deliberations. The mines monitored the Spanish press with special attention to controversy or political resistance to their operations. News of the mines in the popular press was immediately reported back to the headquarters in Belgium. In July of 1935 the Barcelona newspaper *La Publicitat* released two political cartoons mocking the poor conditions of the Llobregat River and the threat it posed to the city's water supply (Fig 2.8 and Fig 2.9). Fonthier despised improvisation, and

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[75] I searched correspondence from the office of the Mayor in Barcelona, Joan Pich i Pon, at the Municipal Archives of Barcelona (*Arxiu Municipal Contemporànea de Barcelona*) during 1935 but did not uncover anything related to the salinity conflict. This, despite the reports in *La Vanguardia* that the Mayor had met with the Director of the Municipal Laboratory Pedro Gonzalez in March 1935 to address the risk of salinization of Barcelona's water supply.

[76] La Vanguardia 1935. A los señores Diputados Catalanes jefes de minoria en el Parlamento Español. 7 April 1935. p 23.

sought to be one step ahead of his rivals. When the Ministry for Economic Development sent a government inspector without notice, Fonthier wrote to his supervisors baffled that such an inspection would come with no warning.

In February of 1936 *Sociedad General Aguas de Barcelona* complained to the Governor of Catalonia that the mining companies were continuing to dump their waste into the river and the concentrations were violating maximum levels established in the Salinity Law of 1933. The water company reported eight violations in December 1935 and six in January 1936. The mining companies paid the associated fines but were otherwise unaffected.[77] *Sociedad General Aguas de Barcelona* requested that the government revoke their authorization of mining activity until the brine collector and dam projects were completed. The water company submitted their letter to the Governor of Catalonia on February 15th, 1936, the day before national elections in Spain. These would be the last elections of the Second Spanish Republic. They handed a victory to the Popular Front, a coalition of Leftist parties. However the victory would be short lived, as the Spanish military began to plot a revolt.

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[77] AGBAR Archives. Box 5615. Escrito al Gobernador General de Cataluña Solicitando Pronta Construccion Canal Colector. 15 Febrero 1936.

Figure 2.8 The cartoon titled *The waters of the Llobregat* was published on the front page of the Barcelona newspaper *La Publicitat* on July 9th 1935. The artist mocked the deteriorating water quality in Barcelona by exclaiming: *A Barcelona resident in 1938 – Give me a soda, with potassium*.

Figure 2.9 A front page cartoon titled *The waters of the Llobregat* published in *La Publicitat* on July 12th 1935.
–What does the Institute say about the salinity of our waters?
–The Agrarian Institute is not dedicated to the humanities, and therefore we do not think anything, because we do not need to think.

Spanish Civil War and Aftermath

The military General Francisco Franco fired the first shot of the Spanish Civil War on July 17th, 1936. The immediate objective of the *coup d'état* was to remove the Leftist parties from government even though they had fairly won the election just months earlier. From the perspective of the Spanish Right, only a military insurrection could restore order and unity to a disintegrating Spanish society. According to this view, Spain was dangerously close to socialist revolution, and the democratic experiment had gone too far in redistributing land and permitting anti-clerical violence.[78] For the extreme Left, the violent clash initiated by the military heralded the beginning of the Socialist Revolution. The

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[78] Brenan, G. 1943. The Spanish Labyrinth (12th Edition ed.) Cambridge: Cambridge University Press.

moderate Republicans governing in Madrid were caught in the cross fire between radically divergent ideologies from the Left and Right. With the political space for moderates shrinking, the Republicans struggled to govern. And as Franco's military troops advanced from southern Spain, the Republicans' most immediate priority was to salvage the democratic institutions of the Second Spanish Republic.

When the news of the military uprising reached the workers in Barcelona, revolutionaries of every color sprung to arms. Anarcho-syndicalists, Marxists, Communists, Leninists, Trotskyists, and Stalin loyalists took fighting positions behind barricades in the streets of Barcelona. George Orwell described a celebratory mood in Barcelona as the war began in his book *Homage to Catalonia*. Soon the revolutionaries began to exert considerable influence within the Catalan Generalitat, and the city was decorated with canvas paintings of Marx, Lenin and Stalin that covered the façades of large buildings in central squares. Businesses were collectivized by the workers, and *Minas de Potasa de Súria* and *Sociedad General Aguas de Barcelona* were no exception. Norbert Fonthier was taken prisoner for several days, and when released, he escaped with his family on a boat to Marseille, France along with other blue-blooded Spaniards and foreigners.[79] *Sociedad General Aguas de Barcelona* was collectivized by the workers and renamed *Aigües de Barcelona Empresa Col·lectivitzada*.

Amid the revolution, the discussions about the brine collector continued. Comrade Carrerras, Comrade Subirana and Comrade Capell replaced Fonthier as representatives of the mines in Súria, and Comrades Tarafa, Batllori and Soucheiron replaced Soler Nolla at the water company. They gathered on June 19th 1937 with the Catalan Generalitat to reaffirm their commitment to the waste disposal project. The engineering plans for the collector had recently been completed on October 10th, 1936, a few months into the Spanish Civil War. The project included drawings of the collector, measurements and route demarcations which showed the path that the collector would travel between the mines and the

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[79] Fàbrega Enfedaque, A. 2009. Cum Grano Salis: La Sal i la Potassa a Súria 1185-1982. Ajuntament de Súria & Iberpotash.

Mediterranean.[80] Depending on the geologic or topographic conditions, the engineers envisioned that the collector would change its sectional profile. With the designs completed, the next step was to secure funding so that construction could begin.

The communication between the mining companies and government officials in 1936 and 1937 show few hints of war. By February 1937 the *Commission for the Inspection of the Salinity of the Waters of the Llobregat* (CISALL) had reached an agreement with each of the mining companies, old and new, regarding their contribution to the collector project. Even late in the war, correspondence showed the clear intent to build the collector soon.

The brine collector came very close to being built during the Spanish Republic. All that was needed was more time. But Franco's troops were faster. They marched towards Barcelona with the military support from other Fascist governments in Europe. The democratic powers of the West remained neutral in the conflict, and the defenders of the Spanish Republic were smothered.

The Franco Era

Barcelona fell to Franco's troops in late January 1939, and the executives of the water and mining companies returned to their posts while many members of the revolutionary government fled abroad, mostly to France and Mexico. The Franco regime was quick to nullify any reforms associated with the revolutionary governments that had briefly taken over during the war. The dictatorship issued a resolution directed at the potassium industry whereby it declared all exports by the workers collectives to have been illegal.[81] However the collectivized mines were unable to maintain potassium production at pre-war levels. Mining activity dropped precipitously between 1936 and 1939, and so did concentrations

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[80] I thank Santi Gorostiza for sharing images of this project with me that he obtained from the *Archivo General de la Administración* in Madrid.

[81] BOE 1939. 17 March 1939. Núm 77. Pág. 1561

of chloride in the Llobregat aquifer, from 183 mg/L to 110 mg/L.[82] This correlation provided further evidence linking the mining activity with water quality in the aquifer.[83] In the eyes of many, including José Soller Nolla, this was irrefutable proof that the rise in chloride concentrations observed in the aquifer was caused by mining activity.

The brine collector project underwent a series of redesigns during the early Franco period. The first project revision was published immediately, in 1939 – "The year of Victory" – as declared on the project's cover.[84] This design was approved by a Ministerial Order on August 28th, 1940, but the complexity of the enterprise caused additional revisions that delayed it further.[85] The project was reformulated in 1943, and then again in 1953. Opposition to the project may have also contributed to its delay. Agricultural interests at the base of the watershed were concerned that the brine collector would consume water and subtract from the total volume coming downstream.[86]

Throughout the 1940s, chloride effluents from the mines continued to build up in the aquifer. As mining activity accelerated, chloride concentrations in the aquifer started to climb and never looked back. In 1945 they reached 190 mg/L surpassing pre-Civil War levels, and in October of 1949 they were nearly 300 mg/L.[87] Communications from the water company to government officials showed increasing signs of frustration on the part of *Sociedad General Aguas de Barcelona*. After more than a decade of pleading,

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[82] AGBAR Laboratory Archive. Sociedad General Aguas de Barcelona. Escrito dirigido por esta Sociedad, en Diciembre de 1949 al Excmo Sr. Alcalde de la Ciudad Relativo al Servicio de Abastacimiento de Agua, Actual y Futuro y el Problema de la Salinidad de la Misma y Anejos al Escrito.

[83] Gorostiza, S. 2010. El conflicto salino en el suministro de agua a Barcelona (1925 – 1940). Encuentro Científico Salud y ciudades en España, 1880-1940. Condiciones ambientales, niveles de vida e intervenciones sanitarias. 8 y 9 de julio de 2010, Barcelona.

[84] Here I rely on documentation from the *Archivo General de la Administración* that was generously shared with me by Santiago Gorostiza.

[85] A letter from AGBAR on 1 December 1949 to the Mayor of Barcelona cites that this project was approved in an Ministerial Order on 27 July 1940, and that it was communicated on 5 August 1940. On 25 September 1940 the project was made public, and on 16 March 1941 the "Junta de Usuarios y Beneficiarios del Canal Colector" was created by the Ministerial Order of 14 April 1942.

[86] Gorostiza, S. 2010. El conflicto salino en el suministro de agua a Barcelona (1925 – 1940). Encuentro Científico Salud y ciudades en España, 1880-1940. Condiciones ambientales, niveles de vida e intervenciones sanitarias. 8 y 9 de julio de 2010, Barcelona.

[87] AGBAR Laboratory Archive. Sociedad General Aguas de Barcelona. Escrito dirigido por esta Sociedad, en Diciembre de 1949 al Excmo Sr. Alcalde de la Ciudad Relativo al Servicio de Abastacimiento de Agua, Actual y Futuro y el Problema de la Salinidad de la Misma y Anejos al Escrito.

the Chair of the Board of *Sociedad General Aguas de Barcelona* warned the Mayor of Barcelona, "if one day our company provides the city of Barcelona with salt water, it will not be our fault nor due to our negligence because we have done everything humanly possible to avoid this outcome since the beginning."[88]

Fortunately for the mining companies, the pressure to build the collector was relieved somewhat with the construction of the Sant Ponç dam, built between 1949 and 1956. The dam regulated discharges in the summer, and diluted salinity concentrations during months of low flow.

By 1950 *Sociedad General Aguas de Barcelona* supplied water for nearly 2 million residents.[89] Water shortages in the summer of 1949 had caused water restrictions, and raised concerns about long term water availability.[90] *Sociedad General Aguas de Barcelona* began to explore additional water sources and all options were on the table. In 1949 the water company asked the Mayor of Barcelona to approach the Spanish Government with a proposal that would bring additional water resources to the city from the neighboring Ter River.[91] While this proposal was being considered, *Sociedad General Aguas de Barcelona* needed to increase existing supplies in the short term in order to meet demand. Their solution was to build a new water treatment plant that would withdraw surface water directly from the Llobregat River at the base of the watershed in Sant Joan Despí. The new water treatment plant was inaugurated in 1955, and its opening marked a significant turning point for Barcelona's water supply. Until then, Barcelona had relied exclusively on groundwater. The last time Barcelona residents drank directly from surface water sources was during the Roman era, approximately 2000 years prior. The decision to collect

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[88] "*que si un día el agua de Barcelona llegase a beberse salada no sería ni por su culpa ni por negligencia de la Sociedad, que había hecho desde el nacimiento del problema cuanto humanamente cabía hacer para impedirlo*." AGBAR Laboratory Archive. Sociedad General Aguas de Barcelona. Escrito dirigido por esta Sociedad, en Diciembre de 1949 al Excmo Sr. Alcalde de la Ciudad Relativo al Servicio de Abastacimiento de Agua, Actual y Futuro y el Problema de la Salinidad de la Misma y Anejos al Escrito.

[89] AGBAR Laboratory Archive. Sociedad General Aguas de Barcelona. Escrito dirigido por esta Sociedad, en Diciembre de 1949 al Excmo Sr. Alcalde de la Ciudad Relativo al Servicio de Abastacimiento de Agua, Actual y Futuro y el Problema de la Salinidad de la Misma y Anejos al Escrito.

[90] Ibid.

[91] Ibid.

the murky stream flow at the base of the watershed may be surprising, especially when one considers that large cities usually seek out pure sources higher in the mountains. However selecting to locate the water treatment plant at the base of the watershed was an unequivocal vote of confidence in favor of the new water treatment technologies. Treatment engineers at *Sociedad General Aguas de Barcelona* were absolutely certain that they could clarify and disinfect the water themselves, "in the same way that is done in the other large cities of the world, Paris, London, Amsterdam, etc…"[92]

A few practical considerations also help explain this decision. The planned site in Sant Joan Despí was close to the groundwater pumping station in Cornellà, making it convenient for personnel working at the water company. Withdrawing surface water would also allow them to take advantage of dam releases upstream.[93] If the company only relied on groundwater sources, they would not be able to capture dam releases very effectively. However the primary explanation for the unusual downstream location of the water treatment facility probably had to do pre-existing water rights. By the 1950s most water concessions had already been distributed to industrial and agricultural users upstream, and these users aggressively defended their rights. This left the city of Barcelona to collect its drinking water from the base of the watershed, even though its quality was questionable. Thus the strategic decision to build the water treatment plant at the base of the watershed was a combination of technological hubris and simply showing up late.

The decision to build the water treatment plant at the base of the watershed set in motion additional measures to defend the water quality flowing down the Llobregat River, and this water quality protection strategy relied heavily on engineered approaches. In the 1960s two major tributaries, the Anoia

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[92] AGBAR Laboratory Archive. Sociedad General Aguas de Barcelona. Escrito dirigido por esta Sociedad, en Diciembre de 1949 al Excmo Sr. Alcalde de la Ciudad Relativo al Servicio de Abastacimiento de Agua, Actual y Futuro y el Problema de la Salinidad de la Misma y Anejos al Escrito.

[93] By this point the aquifer was noticing the impact of sea water intrusion. While the potassium mines had alleged sea water intrusion as a source of salinity in the aquifer in the 1930s, an exhaustive revision by the CESALL Commission discarded this possibility. A new source of surface water would allow the water company to reduce the amount of groundwater pumping. This reduction in groundwater materialized and let led the chlorine concentrations to drop slightly. See (Ferret 1985).

and Rubí, were diverted into pipes and channels that ran parallel to the Llobregat River until their contents were released back into the main stem of the Llobregat River a few meters below the treatment plant. This structural solution prevented both tributaries from releasing contaminats into the Llobregat River. It also allowed nearby industries to dump waste into the tributaries without contaminating Barcelona's drinking water supply. But this structural design had major limitations. The fabricated channels could not contain the large volumes of water that flowed during storm events, so every time it rained, polluted water inevitably overflowed into the Llobregat River and travelled towards the water treatment facility. A river monitoring team called the *River Police* was dispatched by the water company to visually monitor water quality on a regular basis. When they saw that the river carried an oil spill, foam, or some other unusual contaminant, the River Police would radio downstream to warn managers of the oncoming pollution and instruct them to shut down treatment. Storm events frequently caused water treatment to shut down, as did the presence of detergents or heavy metals such as nickel, zinc, chrome or copper from entering the facility. The halting of water treatment because of pollution problems was common throughout the 1960s and remains frequent today.[94]

Given these water quality problems, it is not surprising that city managers eventually turned away from the Llobregat to search for alternative and cleaner sources of freshwater. By 1964, the chloride concentrations in the Llobregat reached 2,411 mg/L in Pallejà, surpassing the maximum permissible levels established in the Salinity Law of 1933 by a factor of ten.[95] And in 1967 Barcelona began to draw water from neighboring Ter watershed to the East. The new supply diminished the Llobregat's relative contribution to the city's total water portfolio. This further helped reduce pressure on the Spanish Government and the mines to follow through on their commitment to build the brine collector.

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[94] Personal comment, Roger Lloret, August 2010.

[95] Lloret, R. 2004. La qualitat de l'aigua del riu Llobregat. Un factor limitant del passat, un element clau per al futur. In Prat, N and Tello, E. El Baix Llobregat: història i actualitat ambiental d'un riu. Centre d'estudis Comarcals del Baix Llobregat. p. 92-141.

In the 1970s, chemists discovered that the mining effluent also caused a public health problem. In addition to emitting salts, the mines also released bromine, which when combined with organic matter and chlorine, reacts to form a group of harmful disinfection byproducts called trihalomethanes. These carcinogenic compounds would eventually be regulated by the European Union and Spanish drinking water legislation, and their removal ultimately motivated the installation of the desalination systems.

Post Franco Democracy to Present

Stopping the salty effluent from flowing into the Cardener and Llobregat Rivers became a political priority of the Catalan government once they gained regional autonomy from Madrid in the early 1980s. In 1982 the Catalan Generalitat approved the brine collector project, and in September 1988 the collector project was finally completed, and began to divert salty effluent from the mines into a pipe that transported the waste directly to base of the watershed.[96] Water managers observed an immediate reduction in chlorine concentrations in the river.[97] And in a strange reversal of roles, the water company *Sociedad General Aguas de Barcelona* became responsible for maintaining the brine collector. Even though the water company manages the infrastructure, the collector still breaks frequently and releases salt concentrate into the river. As recently as January 14th 2009, chloride concentrations in the river reached 837 mg/L due to a break in the pipes, and water treatment managers in Sant Joan Despí were forced to halt water treatment because of high salinity values. The growth of the mine tailings, now huge mountains of salt, has also generated public discontent. Two mine tailings continue to grow in size. In the

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[96] The brine collector first dumped the brine back into the Llobregat River, but beyond the water treatment facility in Sant Joan Despí. Not until a few years later, did they complete the final segment that took the brine to the Mediterranean. The period in which highly concentrated brine ran through the final segment of the Llobregat, between the water treatment facility and the Mediterranean, may have also contributed to salt infiltration into the aquifer (Personal Comment, Roger Lloret, 2011).
Also see: http://www.lasequia.org/montsalat/Impactes/Salinitzacio.htm

[97] Estevan, A. and N. Prat. 2006. Alternativas para la gestión del agua en Cataluña: Una visión desde la perspectiva de la nueva cultura del agua. Fundación Nueva Cultura del Agua. Zaragoza and Bakeaz: Bilbao, Spain.

town of Sallent, residents have organized opposition to the continued growth of the salt mountains and the contamination problems they cause.[98]

At its core, the salinity conflict in the Llobregat watershed was a struggle to control the rivers' services. For the owners of industry, the Cardener and Llobregat rivers generated valuable electricity that allowed them to run their textile machines. For farmers the rivers' waters increased crop production. The water company relied on the Llobregat to replenish the aquifer and maintain a steady supply of drinking water for its customers. And finally, for the mining companies, the rivers provided a free disposal system that carried away their waste to the Mediterranean. These ecosystem services: food and water production, energy generation, and waste disposal, came into conflict, and each user maneuvered to protect the services that served their interests.

The salinity conflict in the Llobregat watershed is a critical piece of history that helps explain why Barcelona now relies on two desalination facilities to meet its drinking water needs. The solutions put forward to address this conflict demonstrated confidence in engineered methods to meet their water challenges, predominantly in the form of dams and pipes. This view dominated the management of water resources in Spain for much of the twentieth century. However we find an exception to this vision in the writings of Rafael Puig Valls and his proposal for addressing flooding problems with reforestation and ecosystem restoration. His proposal to manage ecosystems stood in opposition to the mainstream structural solutions, and may be considered as a precursor to contemporary advocates of ecosystem services.

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[98] See www.prousal.org

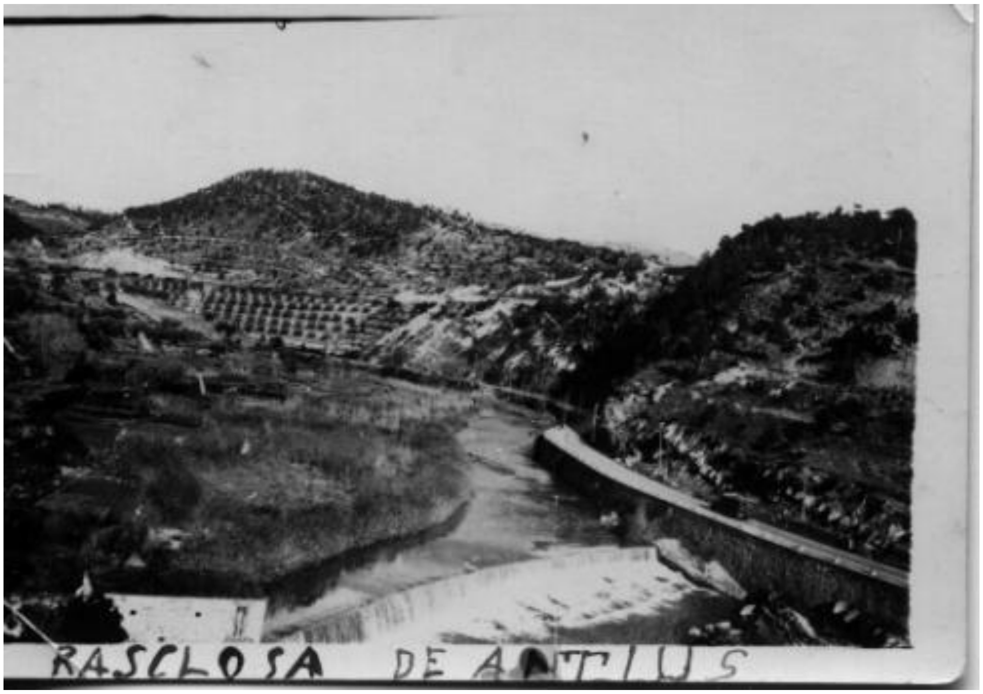

Figure 2.10 It is estimated that this photograph was taken between 1932-1936. It shows the small dam along the Cardener River that diverted water for the Antius factory owned by Antonia Burés Borràs and Esteve Torrens Burés. Antius is the first textile factory below the potash mines, located less than a mile upstream. The small structure in the lower left corner no longer exists. However it is possible, although not confirmed, that this structure housed the automatic water quality instruments established by the CISALL to monitor salinity values in the Cardener. (Photograph courtesy of Albert Fàbregas)

Figure 2.11 In the 1960s employees of *Sociedad General Aguas de Barcelona* regularly travelled upstream to check on the instruments that measured river water quality. The names of the sampling sites established by the CISALL commission remain the same, even if the exact locations have changed slightly. This picture taken in the 1960s shows a visit by AGBAR employees to the water quality measurement station located on the Antius canal next to the Cardener River. The original automatic station, possibly depicted in Fig 2.10, might have been washed away by a flood, and then moved to its current location midway along the canal. (Photograph courtesy of Roger Lloret)

Figure 2.12 The Antius water quality station in April 2011. The Catalan Water Agency still uses the instruments in this structure to collect water quality measurements. Today, the vegetation is so high that neither the canal nor the river can be seen from this point. Note the rapid growth of the pine tree next to the installation. (Photograph by the author)

2.4 Ecosystem Services for Flood Management

For centuries, residents living near the Llobregat River feared the destruction caused by the river's floods. Apprehension and anxiety would probably best describe their relationship with the Llobregat, a *flumen terrible et periculosum*.[99] This apprehension was diluted only by a firm desire to tame its waters and protect their property. The constant threat of flooding conditioned development around the river. Overflowing waters threatened to wash away the winter's food supply, essential bridges that connected goods to market, homes, barns or livestock. Residents in the town of *Sant Boi de Llobregat* pioneered flood control in 1597 by building a stone wall along the banks of the Llobregat River. However these walls did not last long, as the river flooded them out repeatedly. A few years later, in the early 1600s, the towns in the lower Llobregat joined forces to build a communal levee system. Alas, they built the levees too close to the river, suffocating its flood plain, and this system too failed to withstand the river's strength. In 1638 the collaborative venture started anew, and this time they conceded the river a 200 meter flood plain on each side in an effort that, records show, required considerable financial sacrifice on the part of each collaborating municipality. But these structures too failed to contain the Llobregat, and the floods continued.[100]

By the late 1800s, engineers began to look upstream for flood control measures. They surmised that if they could build a dam in the mid section of the watershed it would allow them to retain peak flows and prevent flood damage. The waters held behind the dam could be released gradually when the risk of flooding had past. A dam-oriented solution to the Llobregat's flooding problems would also permit the administration to store water for the dry season. Farmers were especially interested in water for irrigation during the summer months, and the owners of the hydro-powered textile mills sought reliable flows to maintain a steady energy supply.

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[99] "Terrible and dangerous river" Codina, J. 1971b. Inundacions al delta del Llobregat. Episodis de la història. Vol. 147-148. Barcelona: Rafael Dalmau.p 74.

[100] Codina, J. 1971. El delta del Llobregat i Barcelona. Gèneres i formes de vida dels segles XVI al XX. Hores de Catalunya. Esplugues de Llobregat: Edicions Ariel.

By 1890, an engineer named Salvador Peydró had drawn up the plans to construct a dam along the main stem of the Llobregat near Cabrianes. The project was designed to flood 400 hectares and retain 48 million cubic meters of water. The goal was to prevent flood damage by regulating flows, while at the same time increase irrigation supplies. Proponents of the dam also argued that it could provide the city of Barcelona with an additional source of drinking water. Peydró estimated that the dam would supply the lower Llobregat with a steady flow of 8 cubic meters per second year round. This would be a huge improvement, since between the months of June and September the discharge in the Llobregat often dipped below 4 cubic meters. When the project was submitted, it was Spain's largest hydraulic venture on record, with a total cost of 28 million Spanish Pesetas.[101]

The engineered approach to flood management found its opposition from a forester, Rafael Puig Valls, an avid field scientist and naturalist. Later in his career, in 1904, Puig Valls would become the first to advocate for the creation of protected areas in Catalonia: the mountains of Montserrat, the Montseny and the Collserola ridge that hovers over Barcelona.[102] But during the debate concerning the Cabrianes dam, Puig Valls merely spoke as a forester who understood the relationship between forest ecosystems and hydrologic flows. His criticism of the dam project emerged from his acute observations of the Llobregat River throughout the seasons. He saw that the Llobregat had been transformed by deforestation upstream and hypothesized that the flow regime observed in 1890 had already been modified by human activities. For instance, he felt that the severe channel incision in the Llobregat was the result of higher flows concentrated in shorter periods. Salvador Peydró and Rafael Puig Valls observed the same flooding events in the Llobregat watershed, and yet they drew remarkably different conclusions. Whereas Peydró characterized the torrential floods as part of a natural flow regime, Puig Valls concluded that the floods were the artifice of poor forest management in the Pyrenees Mountains. Puig Valls recognized that

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[101] Puig i Valls, R. 1890. El Llobregat: aguas y montes. Revista de Montes. Año XIV. Núm 325-327. Madrid. Real Academia de Ciencias y Artes de Barcelona.

[102] Boada, M. 1995. Rafael Puig i Valls (1845-1920) Precurso de l'educació ambiental i dels espais naturals protegits. Barcelona: Departament de Medi Ambient, Generalitat de Catalunya. Born in 1845, Puig Valls studied forestry. Following a trip to the United States, he returned to promote the celebration of Arbor Day.

Mediterranean streams naturally had erratic discharge, in fact, he emphasized this irregularity as a central feature of Mediterranean streams. But Puig Valls also stressed that recent flooding events had become more severe as a result of human modifications to the watershed and disruptions to the hydrological cycle.

In several essays published by the Royal Academy of Sciences and Arts of Barcelona, Puig Valls applied his ecological and hydrological expertise to criticize the Cabrianes dam project. For Puig Valls, the dam proposal was excessively ambitious, expensive and unnecessary. For the same financial investment, he argued, residents could achieve better results by investing in the restoration of forest ecosystems in the upper segment of the watershed, complimented with only smaller flood control structures. In contrast to the proposal offered by Salvador Peydró, Puig Valls argued that reforestation and ecological restoration could regulate the waters flow “without relying on the building of dams or on the specialized procedures of the domain of the construction industry.”[103] This positioned Puig Valls as the first in Spain to advocate for flood control measures that adopted an ecosystem approach.

When Puig Valls surveyed the upper Llobregat watershed, he lamented that severe deforestation and grazing were causing massive erosion and flooding. “The water precipitates onto the steep slopes of the upper Llobregat watershed, and when it falls on the denuded land and exposed rocks, the waters fall with a thunder, and rapidly searches for the channel toward the sea.”[104] This trend needed to be reversed. “We must research then, how to modify the effects of evaporation and retain these waters in its course in order to transform the rapid and violent flushes of water into constant flows, slow and calm, that is to say,

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[103] Puig i Valls, R. 1890. El Llobregat: aguas y montes. Revista de Montes. Año XIV. Núm 325-327. Madrid. Real Academia de Ciencias y Artes de Barcelona. pg 36

[104] Puig i Valls, R. 1890. El Llobregat: aguas y montes. Revista de Montes. Año XIV. Núm 325-327. Madrid. Real Academia de Ciencias y Artes de Barcelona. pg 379
Caen las aguas en las Fuertes pendientes de la Cuenca alta del Llobregat y al encontrar el suelo desarbolado, y la roca al descubierto, las aguas se precipitan con estrépito y corren veloces a buscar la vaguada principal hasta llegar al mar.

we must normalize the flow regime in our waterways, both in the main stem and its tributaries of the Llobregat which today has only a torrential flow."[105]

Puig Valls praised forests for regulating the Llobregat's waters. His essays went into great detail to describe the hydrologic cycle in a forest ecosystem. The forest slowed and retained water, cushioning the rain drop's fall on its leaves, travelling along its branches and trunks, slowed again by the forest understory, and then filtering into the soil and aquifer. He contrasted water's leisurely travel through the forest with the speed and strength that waters would develop in denuded areas, where regardless of how gentle the slope, the runoff would gush rapidly into the streams and swell them quickly. He compared the retention capacity of forests to a natural reservoir or sponge that gradually released water throughout the seasons. Forested areas "withhold large amounts of water that is retained by the roots of the vegetation, which, having acted like a sponge, do not let a single drop run along the surface, and do not create a single ditch."[106] He also pointed out that the forests shaded the earth, protecting the soil from the hot sun, and maintained humidity beneath the vegetation. Furthermore, forests helped maintain a steady flow in mountain springs since the slow percolation of water through the leaves, organic matter, and soil permitted a regular flow throughout the season.

Puig Valls was not the first to observe the relationship between forests and water flow, and in his writings we see considerable influences from George Perkins Marsh. Sixteen years prior to the publication of Puig Valls essay on the Llobregat, Marsh had written *The Earth as Modified by Human*

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[105] Puig i Valls, R. 1890. El Llobregat: aguas y montes. Revista de Montes. Año XIV. Núm 325-327. Madrid. Real Academia de Ciencias y Artes de Barcelona. pg 379
Hemos de investigar, pues, la manera de modificar los efectos de la evaporación, y retener las aguas en su curso para convertir los desagues rápidos y violentos en corrientes constantes, lentas y tranquilas, es decir, hemos de normalizar el régimen de las aguas en los cauces del río principal y de los afluentes del Llobregat que tienen hoy carácter torrencial.

[106] Puig i Valls, R. 1890. El Llobregat: aguas y montes. Revista de Montes. Año XIV. Núm 325-327. Madrid. Real Academia de Ciencias y Artes de Barcelona. pg 380
La superficie arbolada presenta todos los caracters de un suelo abrigado, de evaporación lenta que retiene en su masa una gran cantidad de agua que absorben las raíces de las plantas, y que habiendo hecho oficio de esponja, no han dejado correr una sola gota de ella por la superficie, que no presenta como surco alguno

Actions while serving as an American diplomat in Rome.[107] As a diplomat and linguist who specialized in the Icelandic language, Marsh was an unlikely figure to write the first treatise on environmental protection. But his work caught the attention of scholars and intellectuals, and today he is credited with starting the conservationist movement in the United States. Puig Valls must have read the writings by Marsh and been influenced by his work.

When Marsh was writing in the late nineteenth century, pioneers in the United States were moving west, to the arid states of Colorado, Arizona and California. But while his contemporaries travelled west, Marsh went east, to the aging European continent, where he would read and write about the past. Stationed in Rome, surrounded by the eroded columns of an extinguished civilization, Marsh was intrigued by the causes of Rome's collapse. His linguistic dexterity allowed him to devour texts in Latin, Italian, French, German, and Spanish; all of which uncovered a series of environmental fiascos, which in some way contributed to the decline of their civilization.

Marsh recounted examples in which deforestation led to diminished stream flow or perishing springs. Puig Valls took this one step further by applying this knowledge to oppose a dam project and advocate for ecological restoration. The reforestation proposal became his alternative to the structural approaches offered by Peydró. From our historical distance, we can now appreciate that Puig Valls was advocating for the management of forests for ecosystem services. Furthermore, Puig Valls claimed that the management of the watershed would allow the Government to meet the same objectives at a lower cost. Puig Valls faith in ecosystems contrasted with his skepticism of engineered solutions. He warned that the rectification work of the Llobregat River in Molins de Rei would be "deficient, incomplete and useless" if they were not supported by improvements in the upper segment of the watershed.[108] Over

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[107] Marsh was exceedingly educated and well read. Born in Vermont in 1801, he studied at Dartmouth, and learned to speak many languages. In 1849, President Zachery Taylor sent him on a diplomatic mission to represent the United States before the Ottoman Empire. Later Marsh was sent to Greece, and in 1861 President Abraham Lincoln dispatched him to Rome as the American Ambassador in Italy.

[108] Puig i Valls, R. 1904. El Llobregat: sus cuencas alta media y baja y obras indispensables que hay que realizar en ellas para conseguir que las inundaciones sean cada vez menos temibles y las aguas normales más constantes con

time, Puig Valls became more explicit. In 1904 he wrote, "it is evident that if forests occupied large parts of the upper Llobregat watershed the effects from flooding would be reduced because of the forests' powerful influence as an agent that retains, filters, and captures the waters that fall on its slopes."[109]

Eventually, the Cabrianes dam project was discarded because of resistance from the flooded municipalities. The opposition from Puig Valls was probably a footnote in the final decision to table the project, however as we will see, his ideas remained influential in discussions on flood management in the Pyrenees Mountains.

Around the time of Puig Valls writings in 1890, land managers in the United States had also noticed that forest ecosystems helped retain hydrologic flows. One of the early advocates for hydro-reforestation works in California was William Mulholland, the Public Water Commissioner of Los Angeles at the turn of the century. Mulholland's leadership of the hydraulic projects that brought water to the city of Los Angeles has been immortalized by Marc Reisner's book *Cadillac Desert*, and the movie *Chinatown*. Therefore it may be surprising to learn that Mulholland initially opposed dams, and surface water transport systems in general, because of the water lost to evaporation. For Mulholland groundwater was more reliable and efficient. This led him to advocate for the reforestation of mountains in California to improve water retention and infiltration. And when the former Mayor of Los Angeles approached Mulholland with the idea of transporting water from the Owens Valley on the Eastern face of the Sierra

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aumentos de riqueza pública y particular. Memorias de la Real Academia de Ciencias y Artes de Barcelona, tecera época. Vol. IV, núm. 40. Barcelona. p 536.

[109] Puig i Valls, R. 1904. El Llobregat: sus cuencas alta, media y baja y obras indispensables que hay que realizar en ellas, para conseguir que las inundaciones sean cada vez menos temibles, y las aguas normales más constantes, con aumentos de riqueza pública y particular. Memorias de la Real Academia de Ciencias y Artes de Barcelona, tecera época. Vol. IV, núm. 40. Barcelona. p 427
Claro es y evidente que, si existieran grandes superficies arbolados en la Cuenca alta del Llobregat, los efectos de la inundación serían menores, porque las influencias poderosas de su acción, como agentes que retienen, filtran y detienen las aguas en su caída sobre las vertientes

Nevada's to Los Angeles, Mulholland originally thought the idea absurd.[110] Only later, the ex-Mayor of Los Angeles convinced Mulholland of the scheme, and he became the project's lead promoter.

The United States Senate also recognized the contribution of forests in stabilizing water flows. In the Organic Administration Act of 1897, the same Act that created the US Forest Service, it states that forests could be protected "for the purpose of creating favorable conditions of water flow."[111] Thus forests' contribution to water management was appreciated in Europe as well as the United States.

In 1907 a tremendous flood ripped through the Llobregat basin, washing away many industries in the Cardener and Llobregat valleys. This disaster re-energized concerns about flooding in the Llobregat valley. Motivated by this recent flood, the Spanish *Cortes* asked Senator Duran Ventosa to chair an investigation into the Llobregat's flooding problems. His recommendations published in 1914 picked up on ideas put forward by Puig Valls' to mitigate flooding through reforestation.[112]

Duran Ventosa emphasized that towns and villages depended on the Llobregat for their well-being. He spoke of "collaboration" with the river, and of developing activities that were appropriate with the river's needs. Like a sick patient, it was necessary to "dedicate the necessary attention to the Llobregat's problems", but not only during times of floods, but also under "regular conditions, when problems can be resolved with more sobriety and veritable efficacy."[113] The Senator's report came twenty four years after Puig Valls first proposed hydro-reforestation projects for the Llobregat basin and advocated for an aggressive reforestation program. But the Catalan Government was not able to act on these proposals until the return of the Spanish Republic in the 1930s.[114] Starting in 1933 the Catalan

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[110] Reisner, M. 1993. Cadillac Desert: The American West and its disappearing water. Penguin Books: New York. p 61

[111] Ibid. p 83

[112] Duran Ventosa, L. 1914. Memoria sobre alguns problemes que's presenten en el riu Llobregat. Barcelona: Diputació Provincial de Barcelona. Biblioteca de Catalunya.

[113] Ibid.

[114] In 1914 the Catalan government still had limited autonomy under the Spanish Crown.

Generalitat began to fund reforestation projects in the Pyrenees with the explicit goal of regulating water flows in the Llobregat Basin.[115]

The debate over flood management in the Llobregat watershed brings into sharp relief the competing approaches to river management. Puig Valls and Duran Ventosa interpreted the floods as symptomatic of poor ecosystem management whereas dam advocates asserted that the new structural designs would allow them to build a definitive solution to flooding problems. The competing camps also relied on different schools of knowledge to support their position; some favored knowledge about structures and cement, while others valued knowledge about forests and soils.

The writings of George Perkins Marsh, Rafael Puig Valls and Duran Ventosa show us that ideas about ecosystem services are hardly new. These ideas were even put into practice by the Spanish Republic in the 1930s. But ultimately, approaches that favored ecosystem management were pushed aside for engineering strategies that sought to dominate water resources through structural design.

It is difficult to pin-point exactly why notions of ecosystem services were pushed aside in favor of structural designs. Perhaps it was because projects relying on ecosystem management did not pull together a coalition of political and economic interests to support its execution. In contrast, structural solutions usually had strong backers who would benefit greatly from the contract and execution. Puig Valls even refers to these economic interests in his writings. And globally, dam builders have yielded considerable political influence.[116] I have not undertaken a detailed investigated into the political relationships between dam builders and political powers in the Llobregat watershed at the beginning of the twentieth century. But I did uncover at least one instance in where there was a connection. Joan Pich i Pon, the Mayor of Barcelona (1935), and later Civil Governor of Catalonia, built his financial fortune with the construction of dams in the Pyrenees and selling the electricity they produced. His company *Electricadad del Cadí* won several contracts, after which, he decided to enter politics. In 1929, prior to

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[115] (Boletin Oficial de la Provincia de Barcelona 1933)

[116] McCully, P. 2001. Silenced Rivers. The ecology and politics of large dams. Zed Books, New York.

becoming Mayor of Barcelona, Pich i Pon secured water rights to build a hydroelectric dam along the Cardener River.[117] His project never came to fruition, even though the dam was eventually built by someone else 30 years later. Therefore I suspect that there must have been more connections between the political and economic elites that would favor the building of large infrastructure projects. The mining companies took care to hire advisors in Madrid to stay informed with political and regulatory developments, and the same was probably true for proposals surrounding water management. Without the confluence of interests, it was much more difficult for projects to be developed.

Figure 2.13 Rafael Puig Valls (1845-1920). (Image from Boada 1995)

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[117] Gaceta de Madrid, 1929. Ministerio de Fomento. Dirección General de Obras Públicas. 24 Febrero. Num 55. p. 1479.

2.5 Conclusion

Nature tells us that we must look at the origin of our ills to find our cure.[118]

Rafael Puig Valls - 1904

Reviewing the struggle over salinity values in the Llobregat River has helped us identify the major figures and institutions in the watershed: the industrialists that harnessed the river's power; the private water company *Sociedad General Aguas de Barcelona*; the Water Resources Agency of the Eastern Pyrenees; Spanish Ministry of Public Works; the Regional Government of Catalonia; and the mining companies.

The conflict also illustrated how these stakeholders made decisions about their water resources. The degree of democratic participation in these decisions evolved in step with the political changes taking place in Spain. During the Primo de Rivera Dictatorship, power was centralized and the pollution problems of the Cardener and Llobregat Rivers were delegated to a small group of experts with close ties to the mining industry. A new formula did not appear until Spain transitioned to a Republican democracy. The CESALL Commission began to operate during a period of democratic governance, and they soon invited the competing parties to participate in the search for solutions.

It should be recognized that the CESALL Commission was a remarkable institution for its time, and they undertook the first watershed planning process in the Llobregat basin. This planning process revealed the competing visions for the river's future as rival water users sought to secure the river-related services that most benefited them.[119] But the commission members also sought to resolve these conflicts with the best science available. The commission meticulously collected water quality samples, they reviewed the new data, and consulted experts from Germany and abroad.

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[118] *Y que en el origen del mal cabe buscar remedio, lo dice la misma naturaleza.*

[119] Not all stakeholders were represented in the CESALL commission. Fishing interests were notably absent. But the CESALL commission at least began with a public request for information so the public could inform the deliberations.

It is difficult to argue the salinity conflict was not resolved because of an inappropriate institutional framework for watershed management. Instead I find that it was precisely the type of consensus that emerged from the CESALL commission that set Barcelona on a path of hydraulic dominance. Agreement was reached on various fronts, but first and foremost, the brine collector project emerged as the "definitive solution" to the salinity problems of the Llobregat River. The regulatory approach was only an emergency measure; designed to hold back chloride concentrations until the structural solutions were put in place. The Salinity Law of 1933 was loosely enforced as chloride concentrations regularly surpassed the maximum value of 250 mg/L starting in 1935. The lax enforcement suggests that the regulatory solution was never taken seriously. Instead of managing the pollutants at their source, governing officials in Barcelona and Madrid placed their bets on the brine collector, which together with the dams, would resolve the salinity problems in the Llobregat River.

The outcome of this planning process helps us understand how Barcelona was sent down a path of expensive and energy intensive water treatment. More often than not, major decisions in the watershed were guided by a faith in engineered solutions. This is evident in the decision to build the brine collector; raise the dams; withdraw water at the base of the watershed, and most recently, install desalination systems. All of these decisions share the conviction that technological mastery would solve Barcelona's water problems. These choices are in fact part of a continuum; evolving in step with technological changes, but yet repetitive because of a shared underlying logic.

The historian Donald Worster has described the irrigation society of the American West as "trapped by their own inventions", "encased in its past" and unable to "escape its own history."[120] Barcelona's hydraulic system is no different. Water managers have inherited dams, canals, pipes and membranes that pushes them further along a trajectory already chosen by their predecessors. They also have inherited certain notions about how the river should be managed. Over time, these beliefs go unquestioned, and they create new material realities.

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[120] Worster, D. 1985. Rivers of Empire. Cambridge University Press. London. p 329.

Visit the desalination system in Sant Joan Despí and you can touch the colorful pipes feeding the reverse osmosis membranes. At the drinking water plant in Abrera you can see the batteries that send electrical pulses through the water to pull out charged ions from the river's water. These desalination systems are the logical continuation of a belief system based on technical fixes and hydraulic dominance. The energy intensive systems form part of a long tradition of technological remedies that attempt to solve Barcelona's water treatment challenges with the latest gizmos.

Contemporary praise for reverse osmosis desalination as the "ultimate barrier" in water treatment is reminiscent of the reverence bestowed on the brine collector project as the "definitive solution". And this conviction that technology will resolve the problems of the Llobregat River has diverted attention away from the upstream sources of the predicament. Even when the brine collector was completed in 1988, fifty six years after it was proposed by the CESALL commission, water managers remained burdened by a cocktail of contaminants that arrive at the entry point of the two major drinking water facilities. Thus the technological improvements have arguably permitted the mines to continue their polluting activities without addressing the issue at the source.

The history of the salt pollution also informs a debate about the origins of the salts found in the Cardener and Llobregat Rivers. In 1932 not a single member of the CESALL commission denied that the potassium mines were dumping salty effluent into the river. If anything, the questions pertained to how much was being released and if those effluents could be causally linked with the rise in salinity in the aquifer down below. This history provides unambiguous evidence that the salinity in the Llobregat's waters is the product of human activities, and yet this conclusion would be redundantly obvious to water managers in the 1930s.

Without a clear historical account of a river's pollution problems, it is easy for competing narratives fill the void. Mining interests today insist that the chloride found in the Llobregat River comes from natural sources. And this narrative has gained traction among reputable institutions. In a document written by a regional planning agency in the 1980s, the Llobregat River is described "to have high concentrations of salts due to the dissolution of salt rocks that are mined in the watershed."[121] In other words, the high chloride values can be attributed to the protruding salt diapers in Cardona. The report goes on to explain that the Llobregat aquifer at the time (1980s) was extracting water with chloride concentrations of 600 mg/L, far above the 79 mg/L detected in 1925, or the legal limit in Palleja of 250 mg/L. Nevertheless, these chloride concentrations were deemed "acceptable."[122] It must be recognized that some portion of the chloride content in the rivers can be attributable to the natural geology. But it is equally undeniable that mining activity has caused the severe salinization of the Llobregat River and its aquifer.

Efforts to dominate rivers have overshadowed attempts to seek more symbiotic relationships with river ecosystems. Puig Valls appreciated how forest ecosystems could help retain water in the upper parts of the watershed through ecosystem processes that had no need for human intervention, only the restoration of ecosystem functions that had been lost. This makes contemporary advocates of ecosystem services heirs to the ideals proposed by Rafael Puig Valls and George Perkins Marsh. They sought to reawaken society to our dependence on ecosystem processes. Similarly, the field of ecosystem services invites us to reexamine our relationship with natural systems and broaden the management options available for addressing sustainability challenges.

So even if ideas about ecosystem services are not entirely new, they still diverge from mainstream approaches for water treatment and distribution. Few are proposing an ecosystem services approach to address the watershed problems found in the Llobregat today. And the idea that ecosystem processes can be of value to downstream users has often been met with skepticism by local users. Perhaps this is because ecosystem-based approaches to water management run contrary to the training provided in the

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[121] "*…río Llobregat, río que como se sabe lleva aguas con alto contenido de sales debido a la disolución de rocas salíferas de la Cuenca minera de la depresión central catalana.*" Corporación Metropolitana de Barcelona. 1986. Usos agrícolas de los márgenes y delta del Llobregat. Barcelona. p 21.

[122] Corporación Metropolitana de Barcelona. 1986. Usos agrícolas de los márgenes y delta del Llobregat. Barcelona. p 29.

water treatment field. Aspiring water treatment managers are taught to master mass-balance equations, or dominate techniques for coagulation, flocculation, filtration, disinfection or desalination. Understanding many ecosystem processes in freshwater rivers remains outside their field. In the field of water treatment, notions about ecosystem services might offer a useful and interdisciplinary perspective to address water treatment problems.

Finally, historical analysis offers us an opportunity for transformation. Historical examination is especially useful to interrogate mainstream notions that go unquestioned. Without a firm historical foundation, we may be tempted to believe that current dysfunctions are the natural state of affairs rather than an exception. We might also submit to the status quo, and accept that our rivers have always been managed this way. At worst, we might surrender to the poor state of our rivers instead of working for a cleaner future.

2.6 Acknowledgements

Many have helped me develop this historical research. Good friends and strangers have pointed me in the right direction and selflessly answered my questions. In particular, I would like to thank my advisor, Daniel Schneider for reading several drafts and providing suggestions for improvement; Santiago Gorostiza for sharing notes and documentation from the AGBAR Archives as well as providing valuable feedback on drafts; Roger Lloret for his vivid stories about key events in the watershed and for connecting me with other knowledgeable individuals, Esteve Torrens Pérez de los Cabos, grandson of Antònia Burés Borràs, for the detailed description of his grandmother and for family photos; Albert Fàbrega Enfedaque for selflessly sharing his insight and information about the history of mining in Súria; Antonio Sánchez, for his gift of the book *Cum Grano Salis* and for his willingness to answer my questions; Sara Ortiz Escalante, for help in translations; Jordi Mir for sharing his insight about Spanish trains of the era; Enric Tomàs Guix for providing tips on how to conduct historical research; the Municipal Archives of Sallent and Súria for allowing me to reproduce material; the Arxiu Comarcal in Vilafranca del Penedès; and the librarians at the Biblioteca de Catalunya and Arxiu Nacional de Catalunya for helping me find relevant primary sources.

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CHAPTER 3. URBAN ECOSYSTEM SERVICES AND TECHNOLOGICAL CHANGE

Abstract

Research on ecosystem services has focused mostly on natural areas or remote places, with less attention given to urban ecosystem services and their relationship with technological change. Perhaps this is because environmental planners, scientists and managers often view technology a substitute for services previously obtained from ecosystems. This substitution ostensibly reduces our reliance on nature's services since the superiority of the engineered system motivated the replacement in the first place. I argue that the expected tradeoff between natural and manufactured capital is false. Rather, the adoption of new technologies is complementary to ecosystem management. This point is illustrated with a case study in Barcelona, Spain where the installation of sophisticated water treatment technology increased the value of ecosystem services found there. This finding suggests that technological change is not a barrier for the implementation of ideas about ecosystem services. Instead, we can expect the value of ecosystem services to co-evolve with technological change. I propose that new technologies may shift which ecosystem functions and structures are valuable but are unlikely to obviate the need for them entirely. New technologies can generate new opportunities to harness value from ecosystems, and the engineered structures found in cities may generate more reliance on ecosystem processes, not less.

Keywords: Urban Ecosystem Services, Natural Capital, Technology, Substitution, Water Treatment, Desalination

3.1 Introduction

Research on ecosystem services has focused mostly on natural areas or remote places that harbor biological diversity (Naidoo and Ricketts, 2006; Armsworth et al., 2007; Fisher et al., 2011). Less attention has been given to ecosystem services in human-dominated landscapes (e.g. Goldstein, 2007; Eigenbrod et al., 2009; Bai et al., 2011). The focus on natural settings is driven by the assumption that ecosystem services are more likely to emerge from places untouched by human settlement. Urban environments, by contrast, are rarely associated with ecosystem services, but rather with engineered structures, artificial materials and technology.

The focus on natural areas makes sense if one remembers that the notion of ecosystem services was developed by conservation biologists (Ehrlich and Mooney, 1983; Daily, 1997) in collaboration with economists to find new arguments for ecosystem protection (Costanza et al., 1997). This origin has left an imprint on the field, as researchers are far more likely to examine ecosystem services in biologically rich countries, often in the developing world, rather than in industrialized nations (Norgaard, 2010). "Implementing the concept of ecosystem services is primarily being advocated for developing countries while in the developed countries, with few exceptions, it is much less frequently advocated, let alone implemented" (Norgaard (2010), 1222). Ideas about ecosystem services were well received in the developing world because they unified conservation and development goals (Sachs and Reid, 2006). It gave the land owners of biologically rich areas a new reason for stewardship. And the programs that paid for ecosystem services provided financial incentives for conservation (Wunder, 2008).

This chapter looks at ecosystem services in urban environments and examines the relationship between technological change and the value of ecosystem services. I question the implicit tradeoff between the two and find that technological change can increase the value of some ecosystem services. In the section 2, I motivate the study of ecosystem services in urban environments. Then, in section 3, I analyze the relationship between ecosystem services and technology and present my argument on how this relationship may be symbiotic and complementary. Next, in section 4, I provide a case study in which I examine how new water treatment technologies in Barcelona, Spain altered the mix and value of ecosystem services found there. The case traces the value of three ecosystem services: water quality protection, thermal regulation and nutrient cycling before and after technological change. Finally, in section 5, I extrapolate lessons from the case and discuss the broader implications for research on ecosystem services in urban environments.

3.2 Urban Ecosystem Services

Relatively few scholars have ventured into urban settings to identify the ecosystem services found within city limits. At the same time, ecologists have a long history of studying urban ecosystems (Sanders, 1984; McDonnell and Pickett, 1990; Forman, 1995). Undeterred by the smog, smoke and cement that dominate most metropolitan areas, urban ecologists have produced a reputable specialization within ecology that examines how species survive, behave and reproduce in urban environments. Abandoned lots, train tracks, city parks and parking lots provide unique conditions for ecologists to test theories about adaptation, selection or island biogeography. And the insight from urban ecology has generated practical guidelines for managing ecosystems in cities. This study of "ecology in cities" has established the foundation for our understanding of ecological processes in urban environments.

Perhaps somewhat surprisingly, urban ecologists have found that metropolitan areas support a wealth of species diversity, albeit largely non-native, that can surpass the diversity found in rural areas (Pickett et al., 2011). Biological diversity in urban environments is also strongly correlated with the social and economic conditions of its human inhabitants (Hope et al., 2003). This co-evolutionary relationship between ecological and social systems has raised doubts about studying urban ecology in isolation from the social context. If the ecological system being examined is, in practice, a reflection of the human conditions that surround it, then perhaps it makes more sense to study the human-environmental system as a singular entity. This line of research has been pursued by urban ecologists who study the "ecology of cities". In this approach, the human and biophysical environments are analyzed in unison, and the city is studied as a socio-ecological system that consumes energy, materials, and water. Research on the "ecology of cities" most clearly overlaps with the discussion taking place in the literature on ecosystem services. Notwithstanding, few authors who study the "ecology of cities" contextualize their research as one concerning "ecosystem services", even though the questions they ask are relevant to disentangle the complex relationship between ecosystems and human well-being.

Clearly, urban ecosystems provide multiple services for their human inhabitants. Urban ecologists have documented how urban street trees purify our air, dampen noise and moderate summer heat; while parks offer places to play, and wetlands process our waste (Forman, 1995; Bolund and Hunhammar, 1999). City street trees in Chicago capture 17 metric tons of C ha^{-1} y^{-1} while urban forests in Oakland, California capture 11 metric tons of C ha^{-1} y^{-1} (Pickett et al., 2001). Urban rivers cycle nutrients, and reduce the threat of flooding (Grimm, 2005; Lundy and Wade, 2011). Many times, the services provided by particular urban ecosystems are clear. But sometimes, certain areas are overlooked. A review of ecosystem services in England - a human-dominated landscape - showed that ecosystem services came from areas that were not targeted for payments for environmental services (Eigenbrod et al., 2009). Thus the sites that generate the most ecosystem services are not necessarily the ones prioritized for protection.

We also tend to associate urbanization with a decline in ecosystem services. For example, in a study in San Antonio, Texas, researchers examined the effects of urban sprawl on ecosystem service provision. They found that urbanization led to a 4% net decline in the value of ecosystem services because of the conversion of rangelands, forests and cropland to urban areas between 1976 and 1991 (Kreuter et al., 2001). The value of lost ecosystem services were estimated based on $/$ha^{-1}$ coefficients per biome type reported in Costanza et al. (1997). Urbanization has also been found to reduce the capacity of streams to process nutrients (Meyer et al. 2005, Grimm et al. 2005). The suite of services lost in urban rivers and streams are a central feature of the "urban stream syndrome" (Walsh et al., 2005).

Urbanization can change the demand for ecosystem services in addition to reducing their supply. Urban and suburban growth usually increases population densities, increasing the demand for services related to water purification, flood control, recreation, and food production, among others. A study in the Leipzig-Halle region of Germany found that between 1990 and 2007, urban growth increased the demand for ecosystem services, especially in rural and suburban areas (Kroll et al., 2012). Modeling the impact of future land use changes on the spatial distribution of ecosystem services remains challenging, because projected land use changes will alter both supply and demand simultaneously. In a study in the United Kingdom, projected land use changes led to decreases in carbon storage and agricultural services, in results that were otherwise somewhat inconclusive (Eigenbrod et al., 2011).

Ecosystem services can also be designed into urban environments. Urban planners have taken the lead in integrating ecological concepts and functions into city landscapes. Frederick Law Olmstead designed an “Emerald Necklace” of green areas along the Boston Fens and Riverway. This plan showed his appreciation for green spaces as useful amenities that can simultaneously provide multiple services for the public (Spirn, 1984). Later, Ian McHarg’s seminal piece *Design in Nature* encouraged planners to think about how to exploit the physical layout of a site to improve user functionality (McHarg, 1969).

More recently, landscape architects and urban planners are studying how ecological processes can be integrated into cities with urban designs that include solar panels, green roofs, or rain gardens. Green roofs improve storm water management, moderate building temperature, reduce the urban heat island effect, and provide habitat for wildlife (Oberndorfer et al., 2007). Lundy and Wade (2011) propose “designing-in” ecosystem services into urban water management through the restoration of urban rivers.

The new language of ecosystem services and “green infrastructure” is starting to be adopted by urban planners and city managers even if this new term merely describes practices that were well known in the past. Indeed, the management of “green infrastructure” for ecosystem services is emerging as a major new objective for city managers (Tzoulas et al., 2007). Similarly, a survey of city arborists finds that managing green areas for their ecosystem services has become a new priority, and that maximizing these services for local residents is beginning to take precedence over more traditional goals in urban forestry (Young, 2010).

City planners are enthusiastic about the potential to integrate green infrastructure and ecosystem services into their designs. However ecosystems are not always benevolent, but can be unpleasant, dangerous and produce unintended or negative consequences for human welfare. Urban ecosystem “disservices” might include allergens, invasive species that eliminate native organisms, the hosting of pathogens and pests, the obstruction of mobility, and an increase in greenhouse-gases (Pataki et al., 2011).

3.3 Ecosystem Services and Technology

The role of technology is largely absent from discussions on ecosystem services in human-dominated landscapes. If mentioned at all, engineered systems are perceived as alternatives that compete with “green infrastructure” and the services they offer. For advocates of an ecosystem approach, technology is suspect because innovation may lead decision makers to replace ecosystem functions with structural solutions.

Technology has always mediated our relationship with ecosystems and the services they provide. Tools and instruments of various kinds have allowed humans to extract the benefits generated by ecosystems for centuries. Irrigation techniques helped the ancient Egyptians harness water from the Nile in order to boost agricultural production sometime around 3000 B.C. (Worster, 1985). Similarly, mechanical farming has helped increase crop production (Boserup, 1976; Aldy et al., 1998; Raudsepp-Hearne et al., 2010).

Yet in the literature on ecosystem services, technological change is perceived as a substitute for nature’s services. Advocates for ecosystem services have certainly contributed to the juxtaposition between technology and ecosystems as substitutes. The well known example of water purification services for New York City (Daily and Ellison, 2002), or wastewater treatment with wetland ecosystems instead of municipal treatment (Bolund and Hunhammar, 1999) are the clearest illustration of this substitution. Choosing nature over hard infrastructure has been hailed as financially superior due to lower capital investments and lower maintenance costs (Chichilnisky and Heal, 1998).

When technology and ecosystems are compared side by side, environmentalists remind us that ecosystems are more complex and self sustaining (Ehrlich and Mooney, 1983; Costanza, 2003). It has been shown that technology is an inadequate replacement for ecosystems because engineered systems lack the multi-functionality and connectivity of natural systems (Moberg and Rönnbäck, 2003). Ecosystems provide many services simultaneously, while a technology is usually designed for only one (Raudsepp-Hearne et al., 2010). A wetland can treat wastewater and provide species habitat, or offer recreational opportunities and produce aesthetic value. In an urban context, wetlands, detention ponds and rain gardens may provide multiple ecological and cultural services (recreational and aesthetic values), while a manufactured stormwater system is designed for the singular service associated with evacuating urban runoff. Or when shrimp farmers convert mangroves to pools for aquaculture, they trade several ecosystem services for the singular service of food production (Barbier et al., 2008). These examples show us that the direction of the substitution matters greatly. The field of ecosystem services doubts technology's ability to substitute for ecosystems, and champions ecosystems over technology.

Perhaps the case that has most contributed to our mental juxtaposition of nature versus technology in the context of ecosystem services was New York City's decision to rely on watershed purification services instead of engineered filtration - a decision that saved the city an estimated $4.5 billion, plus $300 million in maintenance expenses (Chichilnisky and Heal, 1998). This celebrated example thrust the notion of ecosystem services into the spotlight for the research community and popular press (New York Times, 1994; Guterl, 2005). New York's management of ecosystem services generated the expectation that other municipal governments, or even private businesses, would be able to adopt similar ecosystem-based strategies with comparable financial outcomes. More than a decade later, however, these expectations have not been met; nor has the success from New York's experience been replicated in other cities (McCauley, 2006). The reason was that by the late 1990s, most municipal water suppliers in the United States had already installed the expensive filtration system that New York avoided (NRC, 2000). With the filtration technology already in place, ecosystem management was no longer deemed an option. This outcome fed the idea that relying on ecosystem services may be a viable in pristine contexts, such as the Castskill Mountains in upstate New York, but has a limited potential in technologically advanced landscapes, such as those municipalities that had already installed the water filtration systems. This conclusion also captures our intuitive sense that the management of ecosystem services is appropriate for pristine ecosystems, but once the engineered system is installed; there is no reason to return to "primitive" methods of ecosystem management. The superiority of the engineered system was the reason it was installed in the first place. According to this view, in technologically sophisticated environments, ecosystem services simply cannot compete.

Thus many assume that our reliance on ecosystem services is temporary until an engineered alternative is found; one that might be more efficient, cost-effective or both - at which point, resource users will switch to the designed systems instead. The necessity to switch to engineered systems has frequently been motivated by the modification or degradation of well-functioning ecosystems. For instance, engineers developed water treatment technologies in the 19th century because of increasing pollution in rivers and lakes (Melosi, 1999; Schneider, 2011). In these circumstances, the value of ecosystem services becomes more salient once they are lost.

However even in circumstances in which ecosystems are functioning adequately, technological innovation may develop the means to provide superior services. Consider the case in Gramercy, Louisiana, where a wetland processed wastewater from Zapp's Potato Chip Plant. The tertiary waste water treatment services provided by the wetland were initially valued at $215,220 ($34,700/acre). However when the volume of waste emitted from the plant exceeded the wetland's treatment capacity, the company worked with their congressional representative to secure a federal earmark for $150,000 USD to build a "major high-tech waste treatment facility" (Sagoff, 2011). In this case, the value of the ecosystem service was tied to the absence of a particular technology. Once the technological conditions changed, the wetland could not be valued in the same way, nor be attributed the value of $34,700 per acre. While the wetland certainly provided other services, those that generated the most value were substituted by the designed system.

Similarly, technological innovation can motivate a switch away from natural systems to designed systems. Take for example, the case of almond growers in California, who rely on pollination services from bees. Nearby, citrus growers keep the same bees away from their crops because cross pollination causes the citrus fruit to develop undesirable traits. If science were to develop new almonds varieties, genetically-modified to self-pollinate, this innovation might encourage both almond and citrus farmers to prefer "artificial" means of pollination. Thus the value of the pollination ecosystem services for both growers is situated within its current technological context. Sagoff (2011) expands, "The exchange value of an ecosystem service—like that of any good—is constantly negotiated in view of market conditions. Technology also changes. One of the largest nurseries in California, the Dave Wilson Nursery, has introduced an excellent "self-fertile," i.e., self pollinating, almond. If a new cultivar of almond that sets itself proves profitable, the citrus growers might pay the almond growers to adopt it, to eliminate the presence of pollination." (Sagoff, 2011)

The possibility that new technology will eventually substitute for ecosystem services has led authors to criticize the field for being naïve, or offering solutions that will be ineffective in the long run. In a highly cited piece from *Nature*, McCauley (2006, 28) makes the case that "conservation based on ecosystem services commits the folly of betting against human ingenuity. The entire history of technology and human 'progress' is one of producing artificial substitutes for what we once obtained from nature, or domesticating once-natural services… I would argue that conservation plans that underestimate the technological prowess of humans are bound to have short life spans." According to this view, ecosystems are unlikely to remain competitive with technological improvements because humanity will always be discovering better ways to meet our needs. These authors emphasize a tradeoff between services generated by ecosystems and those offered by technological substitutes (McCauley, 2006; Sagoff 2011).

Fossil fuel-based technologies in particular have allowed society to substitute for ecosystem services, with synthetic fertilizers replacing manure, water treatment systems replacing the capacity for self purification of rivers and lakes, or engineered structures replacing natural flood and erosion control processes (Moberg and Rönnbäck, 2003; Raudsepp-Hearne et al., 2010). Self proclaimed “technological optimists” assert that human progress can be decoupled from ecological conditions entirely, and that this substitution may continue as long as innovation outpaces environmental degradation (Goeller and Weinberg, 1976; Small and Jollands, 2006).

In this chapter I argued that the assumed tradeoff between ecosystem services and technology is false, since these approaches can be complementary. Indeed, technological change can raise the value of ecosystem services previously ignored, generate a demand for new services, or create new services entirely. Neoclassical economic theory originally made the simplifying assumption that natural capital could be substituted for other production inputs including manufactured capital (Gómez-Baggethun et al., 2010). As evidence of this simplifying assumption, ecological economists often cite the following quote by Robert Solow (Costanza and Daly, 1992; Clevland and Ruth, 1997; Gómez-Baggethun et al., 2010): “If it is very easy to substitute other factors for natural resources, then there is in principle no “problem”. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe” (Solow (1974), 11).

However this statement is taken out of context, since Solow himself argues that there are *degrees of substitution*, not perfect substitution. A central contribution from ecological economics has been to note the limits to substitution and the irreplacibility of many forms of natural capital (eg. Costanza and Daly, 1992; Clevland and Ruth, 1997; Stern, 1997; Gómez-Baggethun et al., 2010). Ecological economists have pointed out that manufactured capital will not be able to substitute for natural capital indefinately because our economic system is embedded within the limits of the natural world. It is unlikely, for example, that manufactured capital will be able to replace lost biodiversity.

Costanza and Daly (1992) were the first to posit that natural and manufactured were complementary, rather than substitutes: "For any given level of technical knowledge, human made capital and natural capital are, in general, complements, not substitutes" (Costanza and Daly, 1992). However this observation was made against the backdrop of the debate between technological optimists and skeptics. Therefore the substitution moved in one direction: trading natural capital for manufactured capital. My argument takes this proposition one step further. Even when sophisticated technology has already been installed, either to replace ecosystem functions, or isolate managers from the uncertainty associated with ecosystems, natural capital will remain complementary to technological change. That is,the complementarity will remain for the very ecosystems that are affected by the technological change. Furthermore, the mix of services used in the future will be different than today, with some services being created by the technological change.

Emphasizing that technology and human choice mediates the supply of ecosystem services amends our common conception of natural capital and the services they provide. Ecosystem services are not intrinsic functions of the natural environment, fixed, distant and removed from society. Rather the supply and value of ecosystem services are linked to human choices and technological change, and therefore in constant evolution. Yet the myth of a fixed supply of ecosystem services, steadily decreasing or deteriorating, has been enshrined as a central tenet in the field (eg Schröter et al., 2005; MA, 2005; Liu et at.. 2010). Discussions about a decreasing supply of ecosystem services overlook our fluid relationship with ecosystem services in the context of technological change. Too frequently we ignore the possibility that human choice will alter which functions are valuable. Recognizing that the supply of ecosystem services is not fixed opens the possibility of uncovering new ecosystem services in the future. Furthermore, the malleable value generated by ecosystems implies that the study of ecosystem services will remain relevant in technologically advance societies. My argument addresses both technological optimists and skeptics alike. For the technological optimists, the complementary feature of ecosystems reaffirms that the benefits of technological progress will ripple out to society in innovative and unexpected ways. While for the technological skeptics, I highlight the enduring relevance that ecosystems will have in a technologically advanced future.

In the case study that follows, I examine how a major technological improvement at two drinking water facilities changed the value of ecosystem services found upstream. I find that technology and ecosystem services remain complementary even after the membrane system was installed.

3.4 Case Study: Water Treatment Technologies in Barcelona, Spain

The city of Barcelona relies on surface water from the Llobregat River for nearly 50% of its drinking water supply (Mujeriego, 2006). Two treatment facilities withdraw water from the river. The Aigües Ter-Llobregat (ATLL) facility in Abrera, Spain is a public water treatment wholesaler that supplies municipal providers. Downstream, a second water treatment facility is owned and operated by the private water company Aigües de Barcelona (AGBAR) in Sant Joan Despí. Between 2008 and 2010 both treatment plants simultaneously improved their treatment process by adding new desalination membranes. ATLL purchased Electrodialysis Reversal (EDR) technology (Valero and Arbós, 2010) while AGBAR installed reverse osmosis membranes (Luque, 2008). This technological improvement was motivated by new water quality standards that reduced the permissible level of total trihalomethanes to below 100 μg/L in drinking water (Royal Decree, 2003). In order to comply with the new regulation, water treatment managers concluded that desalination technology was necessary.

The surface waters from the Llobregat River are mineralized, with an especially high concentration of salts and bromine (Fernandez-Turiel et al., 2003). These pollutants enter the river through surface or groundwater flows that come into contact with the large mountains of salt deposited by an extractive potash industry upstream (Fig 3.1) (Lloret, 2004; ATLL, 2008; Luque, 2008). The cause of the Llobregat's salinization was initially disputed by the mining companies, since the natural geology of the watershed contains the same minerals polluting the river. However a historical review (Chapter 2) as well as an analysis using isotope tracers has linked the mineralization of the Llobregat River with industrial processes from the potash mining industry (Otero and Soler, 2002).

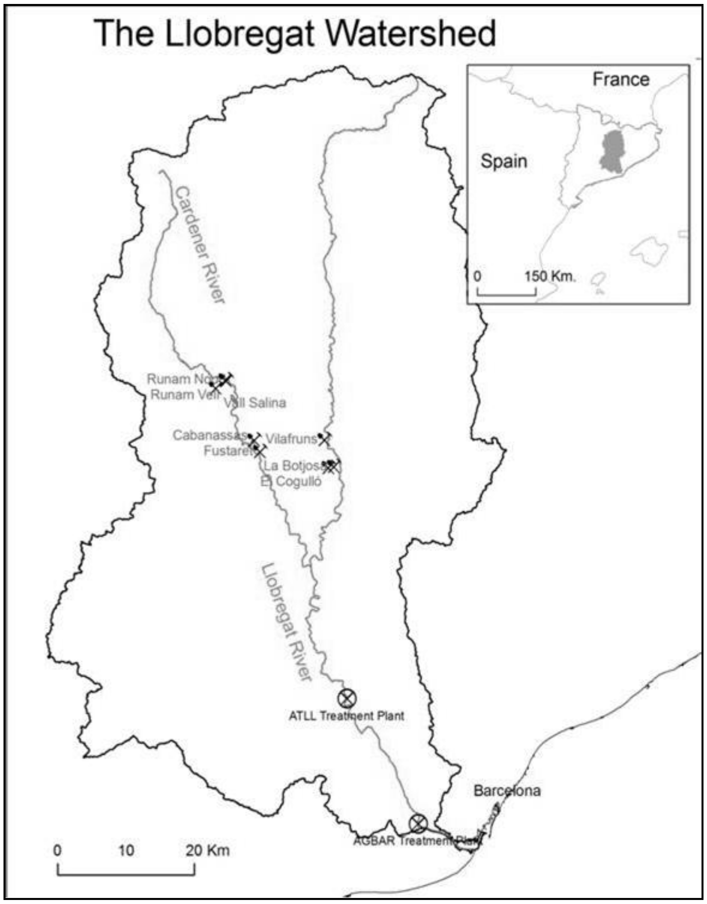

Figure 3.1 Mine tailings in the mid section of the watershed are a major source of salinity in the Llobregat River. The tailings are large mountains of salt exposed to the open air and in contact with the groundwater below. Trenches have been built around the perimeter of the salty mountains to collect the storm water, and channelize the runoff into a brine collector that transports the concentrate to the Mediterranean. However the mine tailings remain a major source of salinity through groundwater movements, and several springs surrounding the mine tailings have become saline. The names of the eight mine tailings are Runam Nou, Runam Vell, Vall Salina (in Cardona), Cabanassas, Fustaret (in Súria), Vilafruns, El Cogulló and La Botjosa (in Sallent).

3.4.1 Advanced Membrane Technologies for Water Treatment

In 2009 the ATLL treatment facility installed an Electrodialysis Reversal (EDR) desalination system to remove bromine, the critical precursor to trihalomethanes, and ensure compliance with the new water quality standards. Dissolved ionic bromines are problematic for water treatment managers because they contribute to the formation of trihalomethanes during the water treatment process (Nokes et al. 1999). Water with high concentrations of bromine and organic matter will form trihalomethanes when they are mixed with chlorine during treatment (Srinivas Madabhushi 1999, Sorlini and Collivignarelli 2005). The concentrations of trihalomethanes in drinking water supplies are regulated because they are carcinogenic (Nokes et al. 1999, Villanueva-Belmonte 2003), and higher water temperatures accelerate the formation of trihalomethanes (Toroz and Uyak 2005). Disinfection by-products such as trihalomethanes are usually removed by modifying the chlorine process or removing the chlorine sensitive compounds (Gopal et al. 2007). Together with an expansion in treatment capacity, the new system cost over €61 million (Valero and Arbós 2010). EDR technology separates dissolved ions such as Br^-, Cl^-, and Na^+ by applying electrical charges. The membranes reverse polarity between positive and negative charges every twenty minutes to clean the membranes and reduce fouling incidents (AWWA 1995). When the EDR system was installed it was the largest of its type in the world (personal communication, Valero 2009).

Simultaneously, the second water treatment plant managed by AGBAR installed an ultrafiltration and reverse osmosis system at their facility in Sant Joan Despí. Reverse osmosis has been hailed as the ultimate barrier within the field of water treatment (Greenlee et al. 2009). Its advanced non-porous material is capable of removing all dissolved solids including pharmaceutical compounds and pesticides (Elimelech and Phillip 2011). AGBAR's reverse osmosis system cost €75 million to purchase and install (Luque 2008). Reverse osmosis technology is rarely used to treat surface water because these sources provide lower quality feed water, which cause membranes to foul, and because of the expenses associated with brine disposal at inland sites (Greenlee et al. 2009). A literature review has failed to uncover any similar reverse osmosis systems treating surface water for municipal use. Only industrial users needing premium water quality have installed reverse osmosis for treating surface water along the Main River in Germany (Clever et al. 2000). On the other hand, reverse osmosis is frequently used to treat brackish groundwater (Greenlee et al. 2009). In comparison with older technologies, reverse osmosis marks a clear departure from the traditional municipal water treatment systems that dominated the 20th century.

While EDR and reverse osmosis technologies differ, both water treatment plants share several features. First, and most obviously, both systems adopt advanced desalination membrane systems that are expensive to install and operate. Second, the new membranes did not replace the older system, but were appended onto the pre-existing chain of treatment technologies (Fig 3.2 and Fig 3.3). Traditional water treatment methods clarify turbid waters with coagulants, flocculants, settlement tanks, and sand and activated carbon filters, and then disinfect the water with chlorine, chloramine, ultraviolet rays or ozone (Crittenden et al. 2005). These traditional methods now serve as pre-treatment steps. Both systems were also designed so that only a percentage of the treated water would be desalinated. Water managers control the mixing ratio by adding desalination modules. AGBAR seeks a constant mixing ratio of 50%, while ATLL varies their product mix based on seasonal considerations. Last, and most importantly for our study of ecosystem services, the new treatment technologies significantly altered the cost structure of the treatment process.

The new membrane systems incorporated two new water quality parameters into the treatment cost function: (1) salinity, as measured by conductivity (µS/cm), and (2) temperature (°C). Both of these water quality parameters became critical values once the new water treatment systems began to operate.

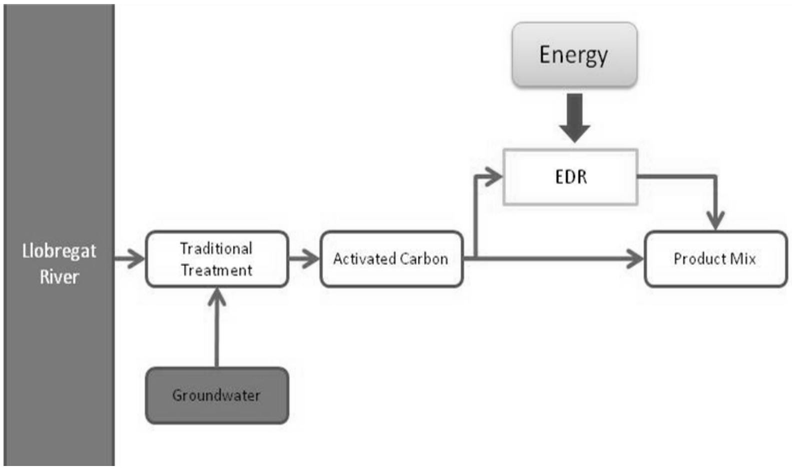

Figure 3.2 Treatment Process at the ATLL-Abrera facility.

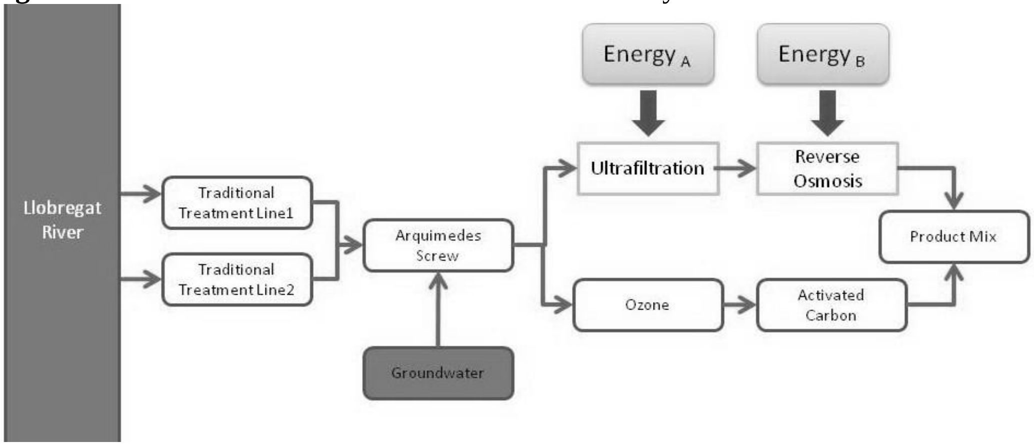

Figure 3.3 Treatment Process at the AGBAR-Sant Joan Despí facility.

By choosing to install new water treatment systems downstream, water managers revealed their preference for technological strategies over ecosystem approaches for improving source water quality. And with the new sophisticated treatment system, they attained the capacity to meet output water quality standards across a much wider range of input water qualities. Therefore, according to conventional wisdom, the sophisticated new technology further isolated managers from the influence of ecosystem processes. To assess the impact of technological change on the value of ecosystem services I analyzed three ecosystem services: water quality protection (affecting salinity); thermal regulation (affecting temperature); and nutrient cycling (affecting ammonium), before and after the adoption of new membrane treatment.

3.4.2 The Value of Ecosystem Services Following Technological Change

3.4.2.1 Salinity

The new water treatment technology was adopted to reduce the uncertainty surrounding freshwater provision, and yet this installation created new linkages with ecosystem functions. Prior to the installation of the desalination systems, treatment costs were impervious to fluctuations in salinity, largely because the traditional treatment methods were incapable of removing chloride ions from the feed water. Water managers did not modify their treatment process in response to fluctuating salinity values.[123] However following the installation of the new membranes, salinity became a significant driver of treatment costs.

Reverse Osmosis Technology at AGBAR-Sant Joan Despí

For reverse osmosis systems, the cost of removing salts is governed by the laws of osmotic pressure. I estimated reduced treatment costs associated with potential reductions in salinity in the Llobregat River with the Reverse Osmosis System Analysis (ROSA) software (version 7.2.7), created by Dow Chemical, the membrane manufacturer. ROSA allowed me to configure a desalination system with the specification of AGBAR's treatment plant in Sant Joan Despí (Appendix A). I ran ROSA with different concentrations of TDS and observed how much energy was needed to maintain the same system performance. As expected, higher concentrations of salt required more energy per cubic meter of water produced (Fig 3.4). The output relationship is nearly linear, but is best fit by an exponential functional form. When the feed water has higher salinity concentrations, marginal water quality improvements produce more energy savings than the same marginal improvements in cleaner water. The Llobregat

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[123] The exception was when salinity values passed maximum permissible concentrations, in which case, surface water treatment was stopped altogether. These high concentrations usually occurred when the brine collector that transports mining effluents from the mines to the Mediterranean would rupture and release highly concentrated salt water directly into the river.

River has an average conductivity of 1500 µS/cm. At this reference point, a reduction of 100 µS/cm would save AGBAR approximately €159,612 per year.

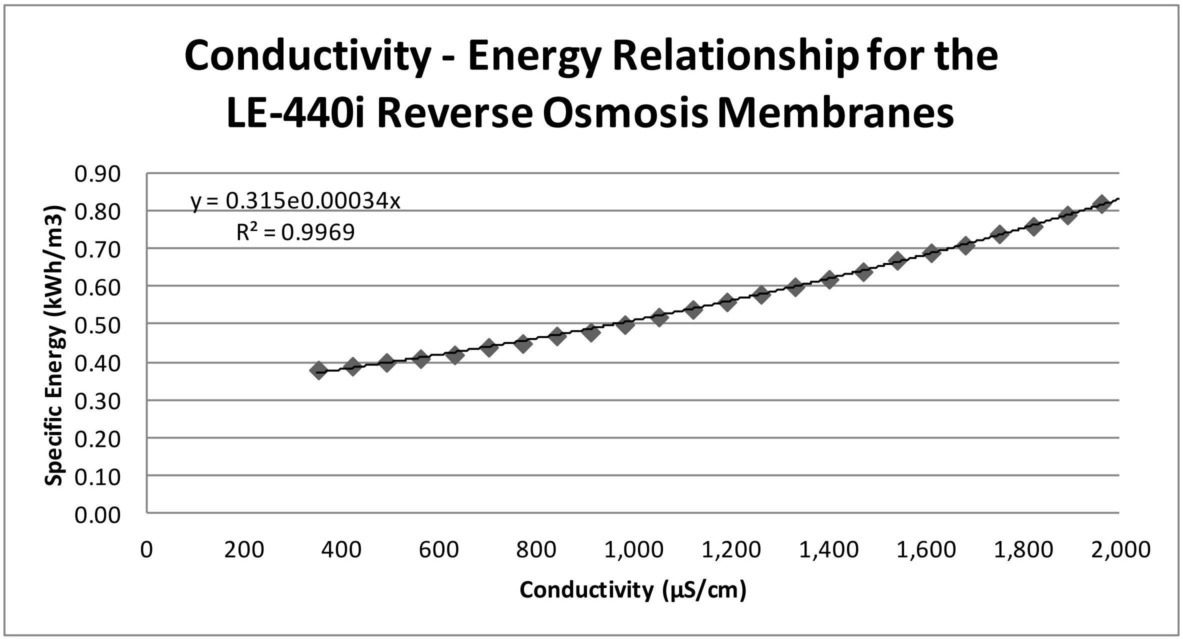

Figure 3.4. The relationship conductivity (µS/cm) and specific energy efficiency (kWh/m^3) for the LE-440i reverse osmosis membranes produced by Dow Chemical. $Y=0.315e^{0.00034x}$ $R^2=0.9969$

Electrodialysis Reversal Technology at ATLL-Abrera

The installation of new membrane technologies produced similar changes to treatment costs at the ATLL treatment plant. Lower salinity levels in the Llobregat River would allow ATLL to produce the same quality drinking water with less electrical current running through the EDR modules. To quantify the potential savings associated with salinity reductions I plotted observed conductivity values and energy use (kWh/m^3) at nine EDR modules operating in November 2010 and July 2010 (n=247). For every unit increase in conductivity (µS/cm) the treatment system consumed an additional 0.0002 kWh/m^3 (Fig 3.5). This implies that a reduction in conductivity of 100 µS/cm is associated with an increase in energy use of 0.02 kWh/m^3.

ATLL annually produces approximately 30 million cubic meters of drinking water with the EDR system. The energy expenses associated with this production is approximately €939,600 per year with a mean energy expenditure of 0.348 kWh/m^3 and an average energy cost of 0.09 €/kWh. Under these conditions, a reduction in conductivity by 100 µS/cm would generate savings of €54,000 per year for the ATLL treatment plant (Appendix B).

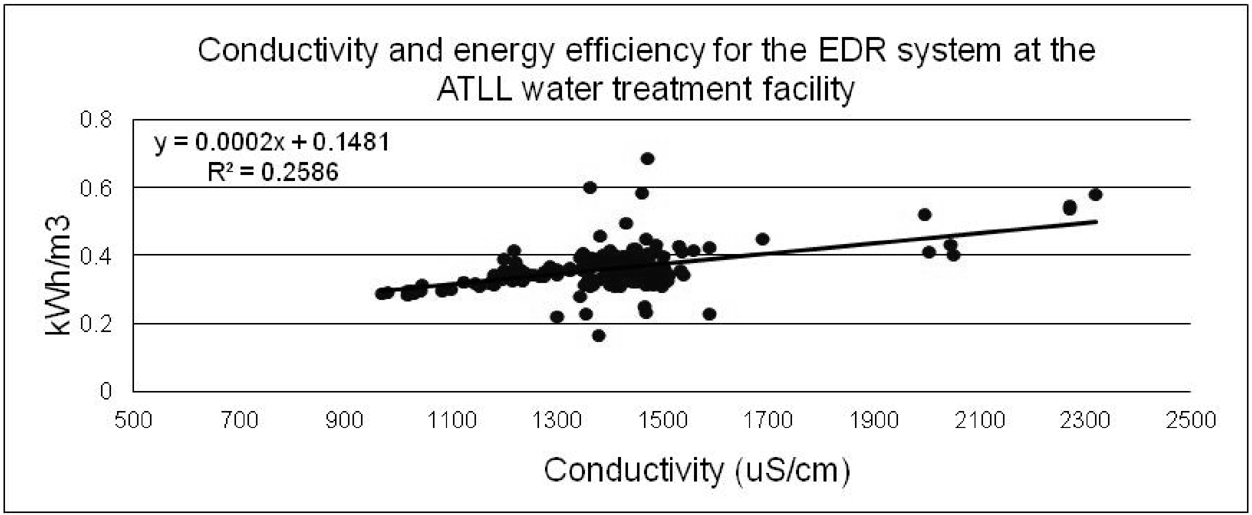

Figure 3.5 The observed relationship between energy consumed (kWh/m^3) and conductivity (µS/cm) in the feed water for the EDR water treatment system operated by ATLL. Y=0.0002x + 0.1481. R^2 = 0.2586

Water quality protection

The installation of the membrane technology has realigned economic incentives for both water treatment facilities. With the new desalination systems, water treatment managers now have an incentive to invest in ecosystem structures or functions that can protect the river from salt pollution. One approach for reducing salinity concentrations is to restore the mountains of mine tailings with halophytic vegetation. A restored ecosystem covering the salt mountains would help protect the water quality of the Llobregat River by reducing the volume of water coming into contact with the salt deposits and filtering into the groundwater. Restoring vegetation on these salt mountains would require specialized techniques, since most plant life is anathema to salty soils. However plant biologists have studied halophyte species which are tolerant to saltier soils and may be candidates for restoration (Adams et al. 1998, Bohnert and Cushman 2000). Despite inhospitable soil conditions, we can see evidence that the salt deposits can be restored with living vegetation. In the 1960s, environmental groups and the mining company collaborated to cover the abandoned Botjosa salt tailings with soil and seeds. The initial planting had difficulties, but over time vegetation has survived and the results of this project remain visible today (Fig 3.6). The Catalan Water Agency has also begun to cover one mine tailing at Vilafruns. The agency is covering the salt mountains with impervious plastics, soils and vegetation in order to reduce the flow of water filtering through the salt mountains and entering the Llobregat River through groundwater flows (ACA, 2009). The water agency will be monitoring the project to assess if the restoration is effective at reducing salinity concentrations in the Llobregat River.

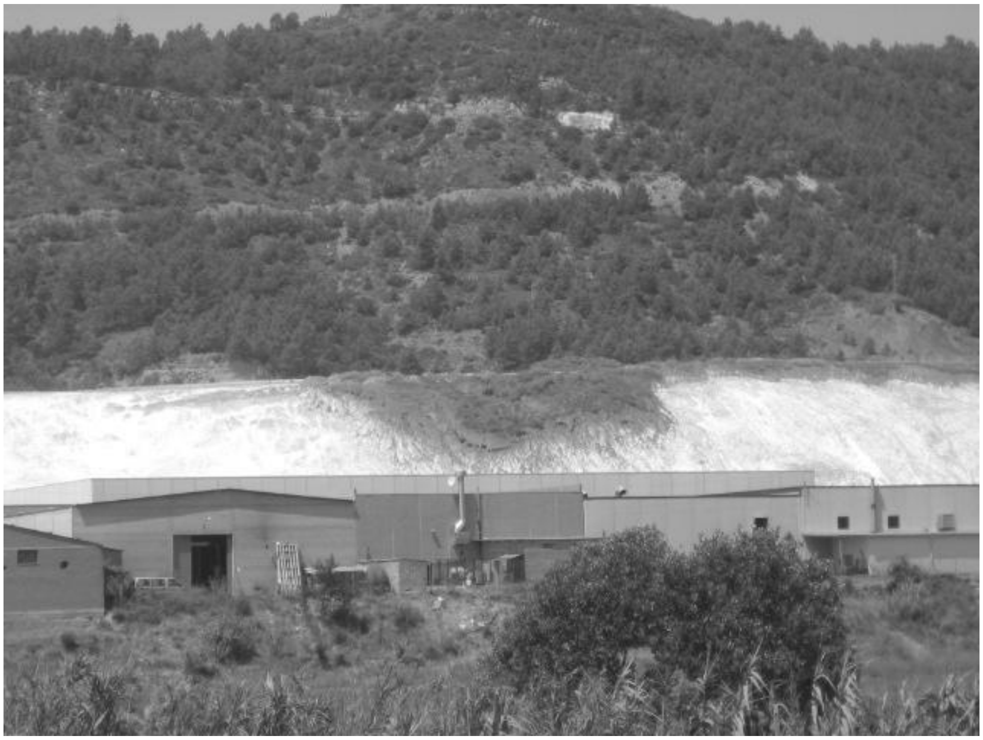

Figure 3.6 A segment of the Botjosa mine tailing in Sallent with restored vegetation growing on top. (Photo by Author. July 2008)

Based on the salinity-energy relationships presented above, we can estimate the benefits that such restoration projects could produce for the water treatment managers downstream. For example, given current conductivity of 1500 µS/cm, a reduction in mean daily conductivity values in the Llobregat River by 100 µS/cm would generate ecosystem services worth €213,612 per year. A reduction of conductivity by 500 µS/cm would generate services worth €868,546 per year (Table 3.1).

Table 3.1 Treatment costs savings associated with reductions in conductivity (µS/cm) at both treatment plants with their respective desalination technologies. Conductivity reductions depart from a baseline value of 1,500 µS/cm.

Mean daily reductions in feed water conductivity (µS/cm)	Reduced Treatment Cost AGBAR	Reduced Treatment Cost ATLL	Total Savings per year
100	€ 159,612	€ 54,000	€ 213,612
200	€ 272,321	€ 108,000	€ 387,321
300	€ 399,030	€ 162,000	€ 561,030
400	€ 518,740	€ 216,000	€ 734,740
500	€ 598,546	€ 270,000	€ 868,546

3.4.2.2 Temperature

Stream temperature is another water quality parameter inserted into the cost function following the change in water treatment technology. Because trihalomethanes form more rapidly during warmer months, stream temperature is particularly important for the ATLL facility. Water managers have adopted a treatment protocol in which additional EDR modules are turned on as stream temperatures rise in the spring and summer (ATLL, 2008). Every additional EDR module costs approximately €1,000 per day to operate (personal comment Valero, 2010).

Stream temperature also controls critical ecosystem processes such as the metabolic rates of aquatic species (Acuña and Tockner, 2009). Warm temperatures also reduce the solubility of oxygen, and low concentrations of dissolved oxygen make waters less hospitable to fish and invertebrates (Graczyk and Sonzogni, 1991). Thermal heating is symptomatic of urbanized watersheds and disturbed river systems (Webb et al., 2008). Stream temperatures can be moderated with the restoration of riparian forest or increases in stream discharge (Bartholow, 1991).

Thermal Regulation

ATLL's water treatment protocols for the EDR system relies on stream temperature to guide operation decisions. This choice created a link between the ecological condition of the Llobregat River and operating costs at the treatment plant. In this case, the sensitivity of the EDR system to high temperatures increased the value of thermal regulation services offered by riparian forests since the temperature reductions provided by riparian habitat would allow managers to use less intensive treatment. The restoration of additional riparian vegetation could further reduce the days in which EDR modules operate (Chapter 4). Depending on the extent of the forest restoration, the restoration of riparian vegetation could provide ecosystem services in the range of €57,000-€156,000 per year (Chapter 4). This specific value generated by the riparian forests would not exist in the absence of the EDR treatment. Increasing stream discharge and restoring floodplains could have a similar cooling effect on stream temperatures, and reduce treatment expenses for the ATLL facility. In a scenario that would increase discharge by only 25%, the treatment plant benefitted from ecosystem services valued at €40,000 per year. Similar to the circumstances found with salinity, the adoption of the EDR technology created a new incentive for ATLL managers to explore ecosystem management practices that would restore ecological functions and reduce thermal heating in the Llobregat River.

3.4.2.3 Ammonium

The marginal value of nutrient cycling services may also increase following the installation of new treatment technologies. The AGBAR-Sant Joan Despí water treatment facility is frequently forced to halt treatment when the Llobregat River fails to meet minimum water quality standards (Lloret, 2004). Ammonium concentrations are especially problematic because they often exceed the maximum permissible values for treatable water. Between 2000 and 2010, high ammonium concentrations forced

AGBAR to stop on 285 occasions (Fig 3.7). Stoppage events generate a penalty cost because they oblige the treatment company to purchase water at a higher cost elsewhere.

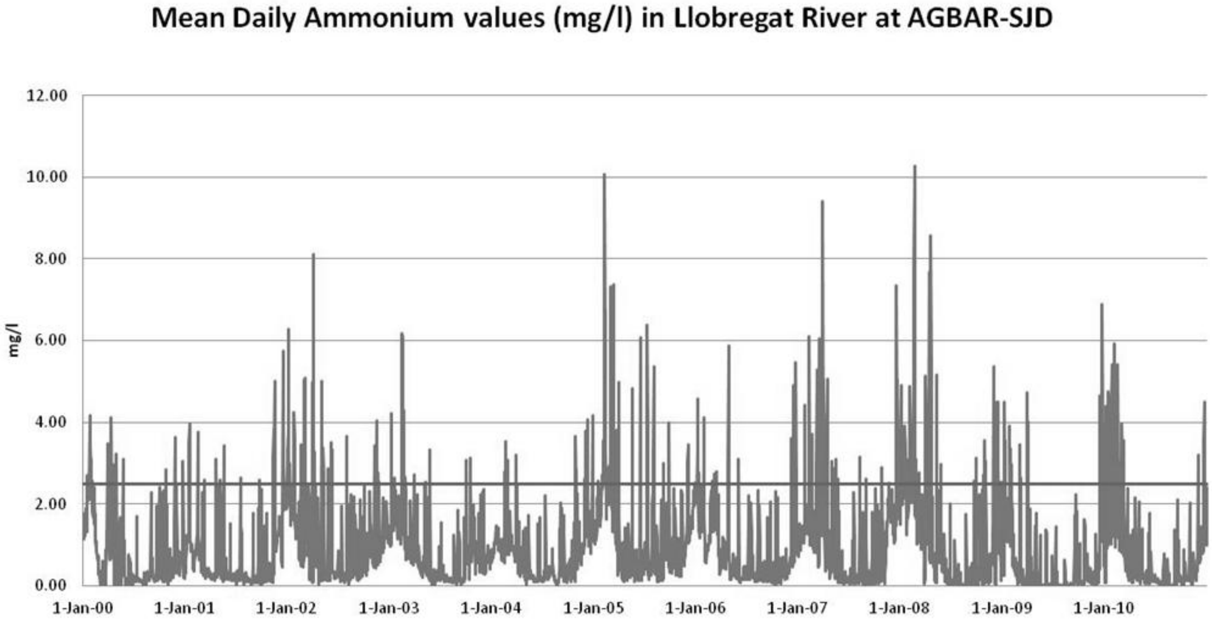

Figure 3.7 Ammonium concentrations at the AGBAR-SJD water treatment facility from 1-January-2000 to 31-December-2010. The line at 2.5 mg/L marks the treatment stoppage threshold. Total exceedance days in 11 years: 286 (7.1%). (Data AGBAR-SJD)

Ammonium is released into the Llobregat River and its tributaries primarily by wastewater treatment plants. The concentrations rise during wet weather events because of combined sewer overflows that release untreated wastewater into the river. Ammonium concentrations are also high during winter months when the colder temperatures slow down the bacterial nitrification of ammonia (Mugeriego, 2006).

With the new membrane treatment technology, AGBAR has the ability to treat water with higher ammonium concentrations. Thus, treatment managers have been studying the possibility of increasing the stoppage threshold for ammonium. Currently the stoppage threshold is at 2.5 mg/L, but with the new membrane system, it is feasible to continue water treatment at higher concentrations and thereby avoid stoppage events. It thus appears that the new technology could substitute for ecosystem services that reduce ammonium concentrations in the watershed.

Nutrient Cycling

Ecosystem processes play a critical role in determining the concentration of ammonium in the Llobregat River. Nitrification occurs in the river's soils or other surfaces where biofilms accumulate (Butturini et al., 2000), and streams that are impaired have lower nitrification rates than rivers in good ecological condition (Martí et al., 2004). Restoration measures such as recovering meanders, widening flood plains, hyporheic restoration, or revegetation can increase instream nitrification rates (Admiraal and Botermans, 1989; Butturini et al., 2000; Kaushal et al., 2008). In the case of the Llobregat, river restoration measures would be particularly valuable because higher nitrification rates could also reduce the number of days in which water treatment is stopped and penalty costs are assumed.

Under these new circumstances, the value of investing in nitrification services may increase or decrease, depending on where the new threshold is located (Fig 3.8). Unexpectedly, once a new technology has allowed water treatment managers to raise the stoppage threshold to a higher level, the same investment in ecosystem services might be worth more with the technology than without. Take for example, an ecosystem service that reduces ammonium concentrations by an average of 4% (Fig 3.8). This same service has a higher marginal value if the new technology allowed the stoppage threshold to be revised at around 2.8 mg/L than it would at lower threshold levels. In this case, improved nutrient cycling would produce greater marginal benefits than that same investment would have produced under previous conditions, before the new technology (Brozovic et al. in prep). This makes intuitive sense if one can imagine the new (higher) stoppage treatment threshold being located just below a cluster of peak ammonium values.

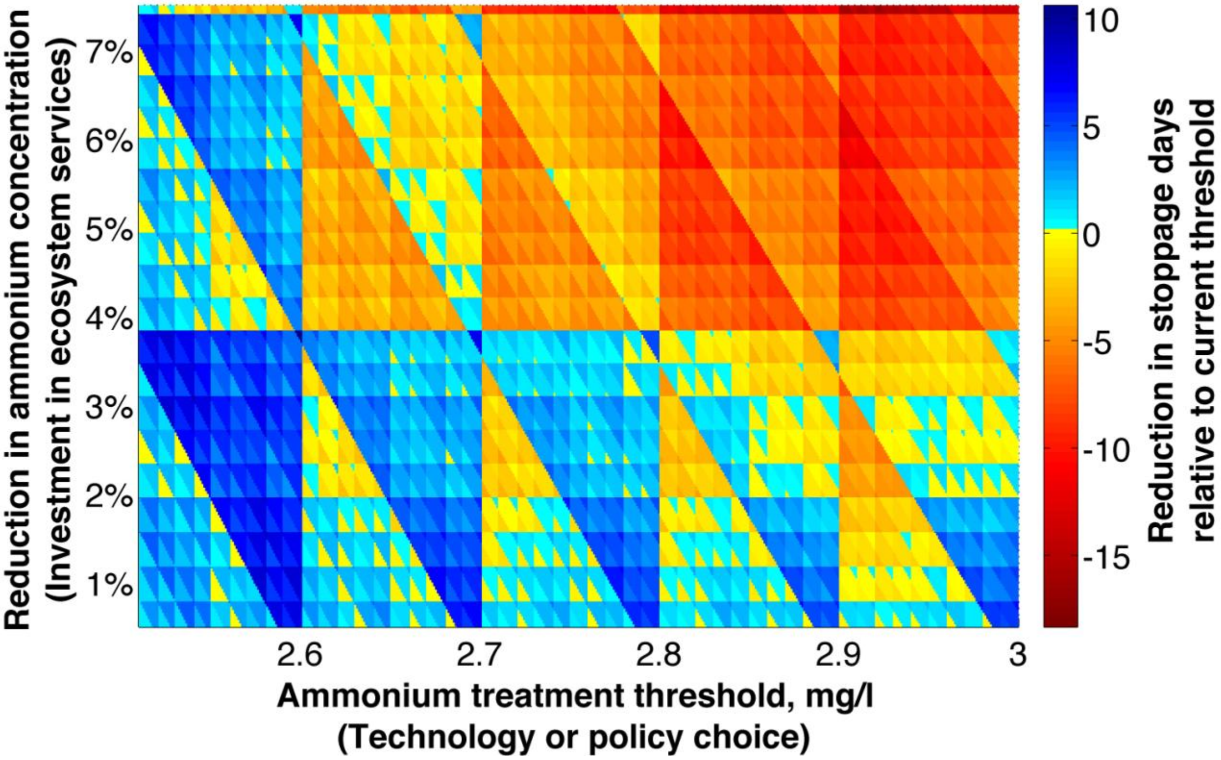

Figure 3.8 The value of ecosystem services related to the nitrification of ammonium (z-axis) given different stoppage threshold levels (x-axis) and different percent reductions in ammonium concentrations (y-axis). Figure from (Brozovic et al. in prep)

3.5 Discussion

Urban environments provide new opportunities to discover and manage ecosystem services. The engineered structures found in cities may generate more reliance on ecosystem processes, not less. In the case of water treatment in Barcelona, the new membrane technology did not eliminate the demand for ecosystem services associated with water purification. To the contrary, several ecosystem services that regulated water quality became more valuable. Water treatment managers installed the new membrane systems to allow for more continuous treatment across a wider range of input water qualities – in essence, protecting themselves from ecosystem variability and uncertainty. And yet unexpectedly, the new technology created additional reasons to invest in ecosystem management.

Considerable attention has been given to how technology can liberate society from the constraints of the natural world. In water treatment, filtration systems reduced the value of watershed services associated with soil and sediment retention, and chlorination reduced the value of natural processes that eliminated infectious bacteria. These technological advancements have created unquestionable benefits for society. However less attention has been directed at how ecosystem management may complement the new technologies once they already have been adopted.

Of course, technological change will not always increase the value of ecosystem services. Recall the case from Gramercy, Louisiana, where the wetlands lost much of their value following the installation of a wastewater treatment facility, or in California, where farmers might switch to genetically modified varieties that eliminate the need for pollination services. As our technology changes, so too will the values we assign to different ecosystem processes. In a more technologically advanced future, the bundle of ecosystem services we use will transform as different technologies favor different sets of ecosystem functions. Ecosystem values are not static. Rather they are a function of human preferences and our interaction with technology (Pritchard et al., 2000).

This case also invites a more controversial claim: that technological change can create new ecosystem services. In Barcelona I observed how new services were generated from existing ecosystem structures and functions because of technological choice. Certainly, the ecosystem structures and functions that protected water quality and reduced stream temperatures existed prior to the membrane technology, but without the membrane technology, society did not benefit in the same way, nor were the values of ecosystem services as connected to explicitly defined beneficiaries. While these ecosystem structures and functions produced other valuable services (nutrient cycling, flood mitigation, recreation, etc...) the specific services produced did not exist prior to the membrane treatment. In this case I focus on use values, but there is no reason why this argument cannot be generalized to ecosystem services that generate non-use values. For example, underwater exploration technologies may allow us to view and appreciate submerged life forms previously unknown or unseen, increasing their value to society. Even in the context of non-use values, technology may increase the value of ecosystems and their services.

Barcelona's experience in water treatment suggests that ideas about ecosystem services remain relevant in technologically advanced settings. Globally, over 1 billion people remain without clean drinking water and approximately 2.3 billion live in water scarce regions (Service, 2006). If countries in the developing world leap-frog to advanced water treatment systems to purify their contaminated sources, the management of ecosystem services must be considered simultaneously as a viable option to improve river ecology and reduce water treatment costs. Even in technologically sophisticated environments, an ecosystem services approach can uncover new management options that may bring both environmental and economic benefits.

This chapter has sought to underscore the potential of ecosystem management in urban and technologically advanced contexts. The new system allowed water managers to improve drinking water quality and increased water security. It is difficult to imagine ecosystems providing equivalent improvements in quantity, quality and certainty in such a short period of time. However the water quality improvements from the new technological systems also came with a considerable financial and environmental cost. Addressing water demands with energy-intensive systems is unlikely to be a sustainable solution in the long run (Mehan, 2009). Instead, water managers would do well to explore ecosystem alternatives regardless of their technological circumstances. The mere presence of modern treatment systems should not blind us to opportunities to manage ecosystem services.

This chapter has shown that the installation of new technologies is not a barrier for the application of ideas about ecosystem services. While technology change may obviate the need for some ecosystem services, new technology will also generate a demand for new services or previously unvalued services. The values ascribed to ecosystems will depend on the context and the technology that surrounds it. Future technologies will rearrange the importance that managers will place on different environmental parameters and services. The rise of new technologies will not reduce our reliance on ecosystem services, but rather ecosystems will benefit us in new and different ways. Regardless of the technological environment the future may hold, investing in knowledge about ecosystem services will remain a wise development strategy.

3.6 Acknowledgements

This research has received funding from the Centre Tecnològic de l'Aigua (CETaqua) and the Agència Catalana de l'Aigua (ACA). I thank AGBAR and ATLL for providing water treatment data and Benoit Lefèvre for assistance with the ROSA model.

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CHAPTER 4. MANAGING ECOSYSTEM SERVICES TO MEET STREAM TEMPERATURE OBJECTIVES IN THE LLOBREGAT RIVER, SPAIN

Abstract

Ecosystem services have the potential to be incorporated into decision making more often if research were to focus on the demand for these services rather than the supply. This demand-oriented approach could catalyze changes in ecosystem management by directing more attention to the needs of resource users. A demand-oriented approach also implies inverting the sequence in which the linkages between environmental and economic systems are studied. Instead of tagging economic values to well known biological processes, a demand approach first examines the economic, decision making and technological context of the end-user. This chapter provides an example of how this research approach for ecosystems services could unfold. In the Llobregat River in northeastern Spain, higher stream temperatures require water treatment managers to switch on costly water treatment equipment during warm months. This creates an opportunity to align the economic interests of downstream water users with the environmental goals of river managers. A restored riparian forest or an increase in stream flow could reduce the need for this expensive equipment by reducing stream temperatures below critical thresholds. I used the Stream Network Temperature Model (SNTEMP) to test the impact of increasing shading and discharge on stream temperature at the intake of the drinking water treatment plant. The value of the stream temperature ecosystem services provided by existing forests is €79,000 per year, while the restoration of riparian forests could generate economic savings for water treatment managers in the range of €57,000-€156,000 per year, depending on the extent of the forest restoration. Stream restoration at higher elevations would yield greater benefits than restoration in the lower reaches. Moderate increases in stream discharge (25%) could generate savings of €40,000 per year.

Keywords: Ecosystem services, stream temperature, SNTEMP, riparian restoration, drinking water treatment

4.1 Introduction

The extensive research on ecosystem services has not generated a commensurate transformation in how ecosystems are managed in practice. If ideas about ecosystem services are to make a unique contribution to environmental management, the discussion must move from theoretical frameworks to practical applications (Cowling et al. 2008, Daily and Matson 2008, Daily et al. 2009, Muradian et al 2010). I argue that ideas about ecosystem services would be more widely adopted if researchers were to focus on the demand for ecosystem services rather than their supply. This demand-oriented approach implies inverting the sequence in which linkages between ecological and economic systems are frequently studied. The approach would begin with the end users, their policy objectives, or decision making and technological context. This starting point is more likely to uncover opportunities for the management of ecosystem services and the implementation of these ideas by resource managers.

At its core, the field of ecosystem services studies the linkages between economic and ecological systems (MA 2005, NRC 2005). However this inquiry often begins with the ecological or biophysical (Kremen and Ostfeld 2005, Chan et al. 2006, Naidoo et al. 2008). Researchers will frequently define the ecological site of interest – a protected area, a forest ecosystem, a watershed, or a river corridor – and then identify the range of services obtained from these areas, such as flood protection, recreational values or spiritual values. Questions concerning economic valuation are left to the end, so by the time economists commence the valuation exercise, the ecosystem scale and end-users have either been pre-determined or are only vaguely identified as “society”. This sequence can lead to poorly targeted research, sub-optimal management or controversial valuation estimates (Sangenberg and Settele 2010). In this chapter I contend that ideas about ecosystem services would be more widely adopted if we studied the management objectives that ecosystem services could help us achieve. However to do so, we must understand the context in which decisions are made and how ecosystems may generate value. This decision making context may then guide our inquiry, and help us identify services provided by ecosystem structures and functions. This demand-oriented approach directs our attention to the needs of resource users first, and then seeks to show that the interests of resource users and managers may be aligned.

This chapter provides an example of how this research approach for ecosystem services could unfold. Water users at the Aigües Ter-Llobregat (ATLL) water treatment facility in Abrera, Spain, treat surface water from the Llobregat River to supply the Barcelona metropolitan region. Treatment managers rely on stream temperature to guide major operation decisions. As stream temperatures rise in the spring and summer, water managers progressively turn on electrodialysis reversal (EDR) treatment modules (Valero and Arbós 2010). EDR modules must be added because warmer water accelerates the formation of harmful disinfection by-products during the treatment process (Villanueva-Belmonte 2003, Sorlini and Collivignarelli 2005, ATLL 2008). The additional EDR modules ensure that the output water quality will comply with drinking water legislation during warmer months (ATLL 2008, Valero and Arbós 2010). As a result of these treatment protocols, a reduction in stream temperatures would reduce the number of days in which the expensive EDR modules would be needed.

Direct solar radiation and air temperature are the primary determinants of stream temperature, although the river also captures heat generated from friction with the stream bed, and long wave radiation emitted by surrounding topography and vegetation. Streams are generally coolest at their headwaters and then temperatures rise as water moves downstream, rapidly at first, and then more slowly at lower elevations. Urbanization, deforestation and water withdrawals also contribute to thermal heating in streams (Webb et al. 2008). In contrast, hypolimnetic water releases from dams usually cool streams. River managers can alter stream temperature by restoring riparian forests that block direct thermal radiation, by increasing stream discharge, or by restoring stream meanders and surface-subsurface interactions.

Thermal heating in rivers and streams can disrupt important ecological processes (Webb et al. 2008). Warmer waters may limit fish reproduction, accelerate ecological metabolism, and increase the vulnerability of aquatic life to disease (Acuña and Tockner 2009). Temperature also plays an important role in determining the availability of dissolved oxygen for freshwater organisms. Low levels of dissolved oxygen during summer months are associated with major fish kills (Graczyk and Sonzogni 1991).

Modeling of stream temperature has been widely used to predict the potential effects of management options (Bartholow 1991, Chen et al. 1998, Bartholow 2000 and 2000b; Watanabe et al. 2005). Aquatic ecologists originally developed stream temperature models to study habitat suitability for fish, particularly in the Pacific Northwest of the United States where Federal and State agencies have regulated maximum stream temperatures to protect endangered salmon (Caissie 2006, Webb et al. 2008). Most stream temperature studies use deterministic models that calculate the total heat fluxes in the river system. Others have used models based on regression techniques in which air temperature is the primary input parameter; or stochastic modeling methods that separate annual temperature cycles from short-term components (Caissie 2006). Temperature models that rely on calculations of the stream's heat budget allow model users to evaluate the effects of altered conditions affecting solar radiation.

Riparian forests moderate water temperatures by protecting the river from direct sunlight (Bartholow 1989, Larson and Larson 1996, Bescheta 1997). Yet the precise impact of stream shading on stream temperature varies with baseline conditions, vegetation height, latitude, and stream discharge. These contextual differences make it difficult to compare shading's impact on stream temperature even when values are translated into temperature reductions per kilometer.

Nevertheless, a few examples are illustrative. In the Cache la Poudre River, Colorado it has been estimated that the doubling of shading from 13% to 23% would reduce maximum temperatures in the summer by approximately 1.25°C over a 32 km reach (0.04°C/km) (Bartholow 1991). In contrast Seedang et al (2008) estimated that shading decreased maximum temperatures by less than 1°C (0.01°C/km) in a 92 km reach in the upper main stem of the Willamette River, Oregon. The authors hypothesize that the voluminous discharge and wide stream width prevented shading from altering stream temperature.

Increasing stream discharge is another management option that may mitigate thermal heating. Again in the Cache la Poudre River, Colorado, it was estimated that increasing discharge by 3 m^3/s (300%) would allow the reach to comply with temperature requirements year round (Bartholow 1991). In contrast, Seedang et al (2008) found increasing discharge in the upper main stem of the Willamette River had limited impact on temperatures.

In this study I used a deterministic stream temperature model to explore how ecosystem services associated with river shading and discharge might reduce stream temperatures at the intake of a drinking water facility in Abrera, Spain. This allowed me to avoid measuring all ecosystem services provided by the Llobregat River, such as nutrient cycling, water provision, or flood protection etc…, and instead target those services for which there is a known demand from specific water users.

4.2 Study Area

The Llobregat River flows 170 km in a southward direction from its headwaters in the Pyrenees Mountains to the Mediterranean Sea (Fig. 4.1). The upper segments of the Llobregat watershed receive 1000 mm of precipitation per year while the mid section of the watershed is considerably drier with only 400 mm per year (Mujeriego 2006). The Llobregat River has an annual discharge of 660 hm^3 although its flow regime is highly variable. The Llobregat has one major tributary, the Cardener River, which is slightly smaller in size when the two rivers join at mid-watershed.

The Llobregat River provides the Barcelona Metropolitan Region (pop. 3.5 million) with 45% of its drinking water supply (Mujeriego 2006). Approximately one quarter of the region's water is treated at the ATLL treatment facility in Abrera (max. capacity = 4 m^3/s). The average flow at the ATLL facility is 8 m^3/s. Two major dams hold back the Llobregat and the Cardener Rivers before they leave the Pyrenees Mountains. The size of the hypolimnetic releases from the dams is negotiated periodically between the hydroelectric dam operators, water suppliers and the regional water agency of Catalonia (ACA).

The study reach consists of 57.6 km between the stream gage at Balsareny, downstream of the lowermost dam, and the ATLL water treatment facility in Abrera. The entire river network could not be modeled because of the presence of the dams. The Llobregat River travels 27.8 km between Balsareny and the confluence with the Cardener. The river then travels another 29.8 km to the ATLL water treatment facility, located 29.0 km upstream from the river's mouth in the Mediterranean.

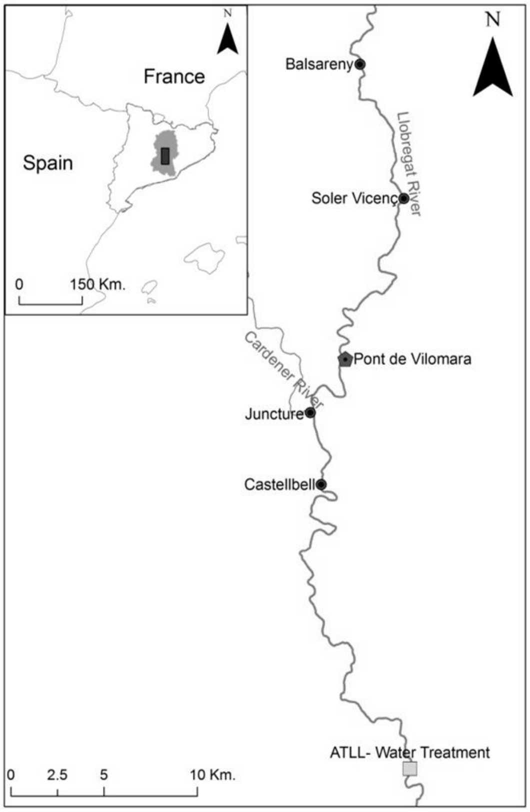


Figure 4.1 The study reach is 57.6 km between the town of Balsareny and the ATLL drinking water treatment facility in Abrera. Meteorological data was collected from a weather station at Pont de Vilomara.

4.3 Methods

SNTEMP Model

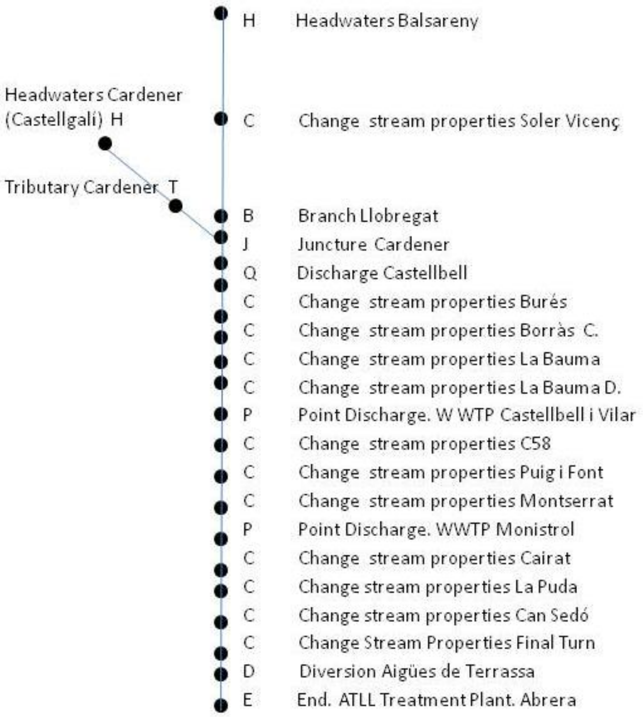
The Stream Network Temperature Model (SNTEMP) is a one-dimensional heat transport model for stream networks that predicts mean daily water temperatures based on heat flux equations (Theurer et al. 1984, Bartholow 2000). The mechanistic model was originally developed by the U.S. Fish and Wildlife Service (Theurer et al. 1984) and is now distributed by the United States Geological Survey (USGS). USGS has generated training materials for SNTEMP which has facilitated its widespread use (Hendrick and Monahan 2003; Norton and Bradford 2009). SNTEMP is a well characterized and tested model that can evaluate changes in both stream shading and discharge, with only moderate data requirements. The model calculates the heat gained or lost from a parcel of water as it passes through the various nodes in a stream network (Appendix E). The model simulates heat flux processes of convection, conduction, evaporation, direct solar radiation (short wave), atmospheric radiation, radiation from riparian vegetation (long wave), and back radiation released by the water (Bartholow 2000) (Appendix F). The model requires data on stream hydrology, stream geometry, meteorology and shading conditions (Table 4.1) (Appendix G). Given these inputs, the model predicts the stream temperature at the end of the segment (Appendix H). The stream network model was constructed using 22 nodes, each of which marks either a change in stream temperature, discharge, geographic or shading conditions or thermal mixing (Fig. 4.2). On average, SNTEMP models have 30 nodes (Bartholow 2000).

Table 4.1 Input data requirements for the SNTEMP Model

Stream Hydrology	Stream Geometry	Meteorology	Shading Conditions
Segment Inflow	Node Latitude	Mean Daily Air Temp	Topographic Shade
Temperature Inflow	Node Elevation	Relative Humidity	Vegetation Shade
Segment Outflow	Width A and B Terms	Wind Speed	
Accretion Temperature	Manning's N	Solar Radiation	
		Ground Temperature	
		Thermal Gradient	

The Llobregat River SNTEMP Model

I obtained meteorological data from the Catalan Meteorological Service that operates a weather station located at the center of the stream segment (km 37) in the town of el Pont de Vilomara (406310, 4617994 UTM) (Fig 4.1). Hydrologic and stream temperature data were obtained from the Catalan Water Agency (ACA). A complete data set for all nodes was available for the 2009 calendar year.



Node	**Distance (km)**	**Elevation (m)**	**Function**
H	57.6	285	Headwaters
C	49.1	175	Change Stream Properties
B	29.8	165	Branch
H	32.0	175	Headwaters
T	29.8	165	Tributary
J	29.8	165	Juncture
Q	23.9	148	Discharge
C	23.0	141	Change Stream Properties
C	21.8	141	Change Stream Properties
C	20.5	132	Change Stream Properties
C	19.6	127	Change Stream Properties
P	19.5	127	Point Discharge
C	18.9	125	Change Stream Properties
C	17.8	126	Change Stream Properties
C	16.9	119	Change Stream Properties
P	15.1	109	Point Discharge
C	11.0	80	Change Stream Properties
C	9.8	75	Change Stream Properties
C	6.8	70	Change Stream Properties
C	3.0	63	Change Stream Properties
D	2.6	62	Diversion
E	0	57	End

Figure 4.2 A schematic representation of the modeled stream network between Balsareny and the ATLL drinking water treatment facility in Abrera, Spain. Data on stream discharge is required for Headwaters (H), Discharge Verification (Q), Point Discharges (P), and End (E) nodes. Temperature data is input at Headwaters (H), Tributaries (T), Branch (B), and Point Discharges (P) nodes.

I measured vegetative and topographic shade on 8 and 9 May 2011 following the field work guidelines outlined in Bartholow (1989) (Appendix I). I verified the location of stream gages, diversions, returns and point sources, and identified sites where the properties of the stream changed (C nodes). I also evaluated if the restoration of riparian forests was viable given current soil quality or topographic conditions. I annotated the location of sites where extreme slopes (cliffs), or the absence of soils (large stones and boulders) would make any proposal to reforest unrealistic. Forest coverage estimates collected in the field were compared with satellite imagery available from Google Earth. In stream segments where field measurements were not taken I relied on satellite imagery.

Shading Scenarios

I divided the Llobregat into multiple segments according to topographic and forest conditions. I defined a stream segment as “restorable” if it had less than 30% forest cover along its bank and did not have an obvious impediment to forest restoration such as poor soil quality, or steep topography.

I tested five shading scenarios. The first three scenarios increased shade only in the subset of river segments defined as “restorable” (<30% cover and favorable soil quality and topography). Shading was increased from its existing condition (<30%) to 40%, 60% and 80% forest cover. The next shading scenario increased shade for the entire stream segment to 100% coverage. This scenario serves as an upper boundary estimate of shading’s potential impact. In the final scenario, I removed all existing riparian forest to estimate the contribution of current shade in moderating stream temperatures.

Discharge Scenarios

I tested five discharge scenarios that increased stream flow by 5%, 25%, 50%, and 100% of historic monthly means. Monthly mean discharge values were computed from a historic data set of six years (2004-2009).

Model Calibration

The calibration of predicted to observed temperatures was accomplished by adjusting calibration parameters built into the model and following recommended procedures (Bartholow 1991). In this case I only adjusted the coefficient for air temperature across seasons. During winter months, from November to February, the air temperature calibration coefficient was 0.25. During the peak summer months of June to September it was 0.9. In the remaining months the air temperature calibration coefficient was 0.5

(Appendix J). It was important to ensure that the model's predictions approximated observed outcomes. Although for my purposes, it was even more important that the model help me accurately estimate the impact of the various management scenarios on stream temperature.

Value of Ecosystem Services

Managers at the ATLL treatment plant begin to add EDR modules in March of each year when stream temperatures surpass 12°C. At peak summer temperatures all nine EDR modules are in operation. Since one EDR module is in operation year round, there are eight additional modules that may be added in warm months. This generates eight temperature thresholds in which the costly EDR treatment modules are added. Although the precise protocol for adding EDR modules has not been formalized by ATLL, a linear relation to temperature provides a reasonable decision rule (personal communication, Valero 2010). In this study, I assume an EDR module is added for every 2°C rise in temperature beyond 12°C (14°, 16°, 18°, etc...). Each module consumes approximately 12,000 kWh per day for a cost of €1,000/day (personal communication, Barceló 2010). Value is generated when ecosystem processes delay the exceedance of one of the eight critical temperature thresholds by at least one day and therefore allow water treatment managers to avoid turning on an additional module.

Riparian Reforestation Costs

I collected information on riparian restoration projects in order to estimate the costs associated with the increasing stream shade along the Llobregat Rivers and conduct a cost-benefit analysis of the restoration projects over a 20 year period. ACA has financed projects that remove invasive species of cane (*Arundo donax*) and replaced them with native species of Willow (*Salix alba*), Ash (*Fraxinus agustifolia*) and Poplar (*Populus Alba*). These projects were executed along the Llobregat and Cardener

Rivers, and therefore offer a useful precedent to help gage future restoration costs (Consell Comarcal del Bages and Phragmites SL 2010 and 2011). Given the initial investment, I calculated the net present value of the project over a 20 year period with a discount rate of 4%. Since we cannot expect that the full benefits associated with shading will materialize until the trees reach maturity, I estimated annual savings that were proportional to the growth rate of riparian trees (Wanatabe et al 2005).

Robustness Tests

While the SNTEMP model has already been validated (Bartholow 1991, Bartholow 2000), the model does not provide users with estimates of uncertainty or error. Therefore I tested the robustness of my results to assumptions concerning estimated parameters (Manning's N) and their sensitivity to measurement error (relative humidity, stream width, stream height). In the stream shading scenarios, I modified relative humidity (+/- 10%), stream width (+/- 20%), vegetation height (+/- 25%) and tested Manning's N at 0.045 and 0.025. For the stream discharge scenarios, I re-calculated the results with changes in relative humidity (+/- 10%), stream width (+/- 20%) and vegetation height (+/- 25%). The percent +/- variation was chosen to be conservative, or approximate the maximum potential deviance, and therefore serve as an upper and lower boundary of expected error. To test each parameter I ran the model 20 times, testing for variation by a given percentage under two new baseline scenarios (+/-), and then running every vegetation and discharge scenario separately (9 scenarios total, each run twice +/-) and comparing the new results to the respective baseline scenarios (2). I also tested for robustness to assumptions pertaining to model calibration and to the location of EDR thresholds.

4.4 Results

SNTEMP produced satisfactory water temperature predictions during the spring, summer and fall of 2009 (R^2=0.93, N=255, Pearson correlation=0.94) (Fig 4.3). The calibrated model predicted stream temperatures with a mean error of 0.53°C, overestimating observed temperature. Forty percent of the model's predictions fell within 1°C of the observed value. The maximum error was 4.6°C. To remove the effects of this systematic overestimate in my valuation of ecosystem services, I regressed modeled versus observed temperature and adjusted model output accordingly (Fig 4.4).

Figure 4.3 Observed and predicted temperature values for the Llobregat River during the warmer months of 2009 in which EDR modules are in operation at the drinking water facility.

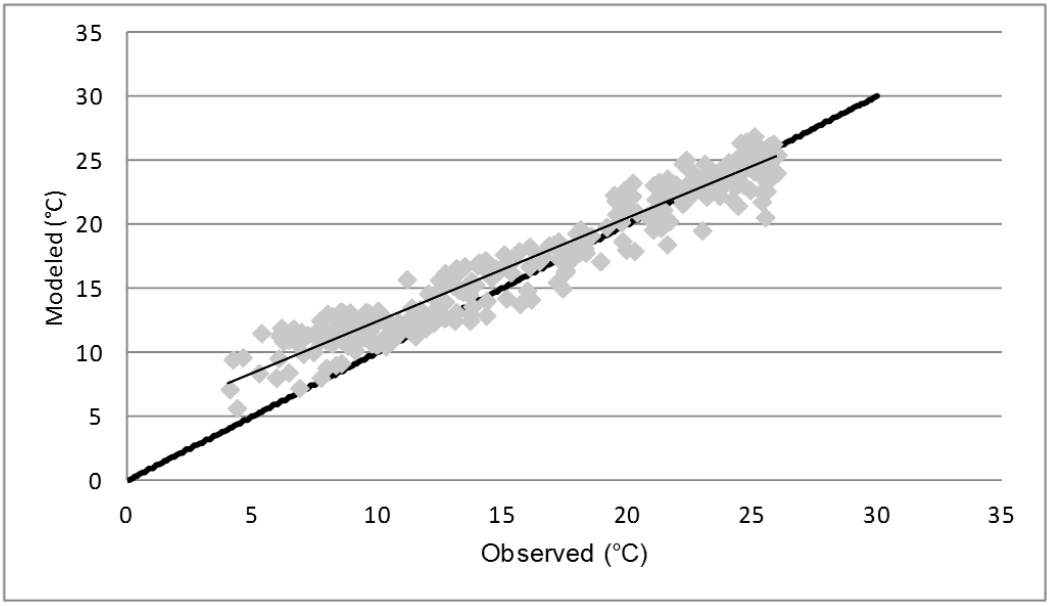


Figure 4.4 Observed and modeled temperatures for all dates in 2009. EDR water treatment modules are only used when temperatures surpass 12°C. At these warmer temperatures the SNTEMP model better predicts observed temperature. (R^2=0.933) T= 0.8068(observed temp) + 4.335. The bold line marks the 1:1 relationship.

Robustness of Temperature Estimates

When testing the sensitivity of temperature predictions to changes in humidity, stream width, and vegetation height, mean annual temperature values changed modestly, and always within 1°C. As expected, the predicted values were always bounded within the higher and lower estimates (+/-) (Fig 4.5 & 4.6). For both the vegetation and discharge scenarios, temperature results were most sensitive to changes in humidity.

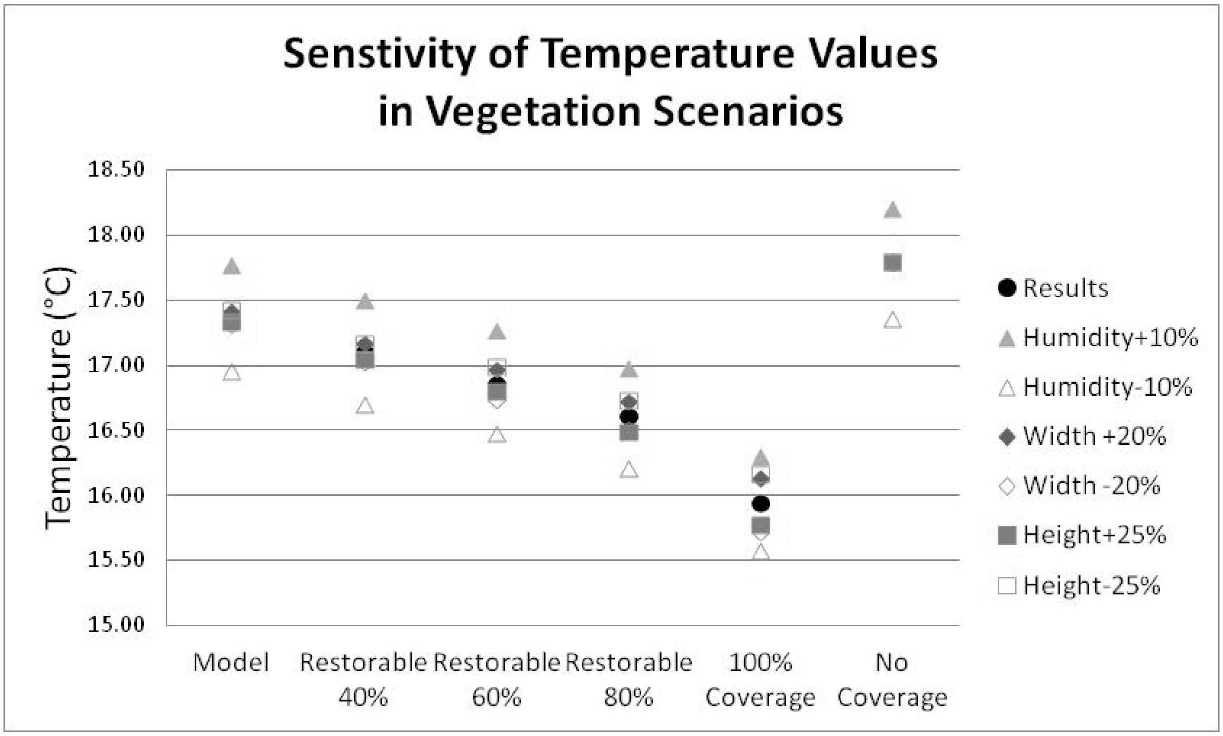


Figure 4.5 The sensitivity of temperature estimates (mean annual) in the different vegetation scenarios when looking at changes in humidity (+/- 10%), stream width (+/-20%) and vegetation height (+/-20%). In all cases, the results were bracketed by the higher and lower estimates. The variation was always slightly below 1°C.

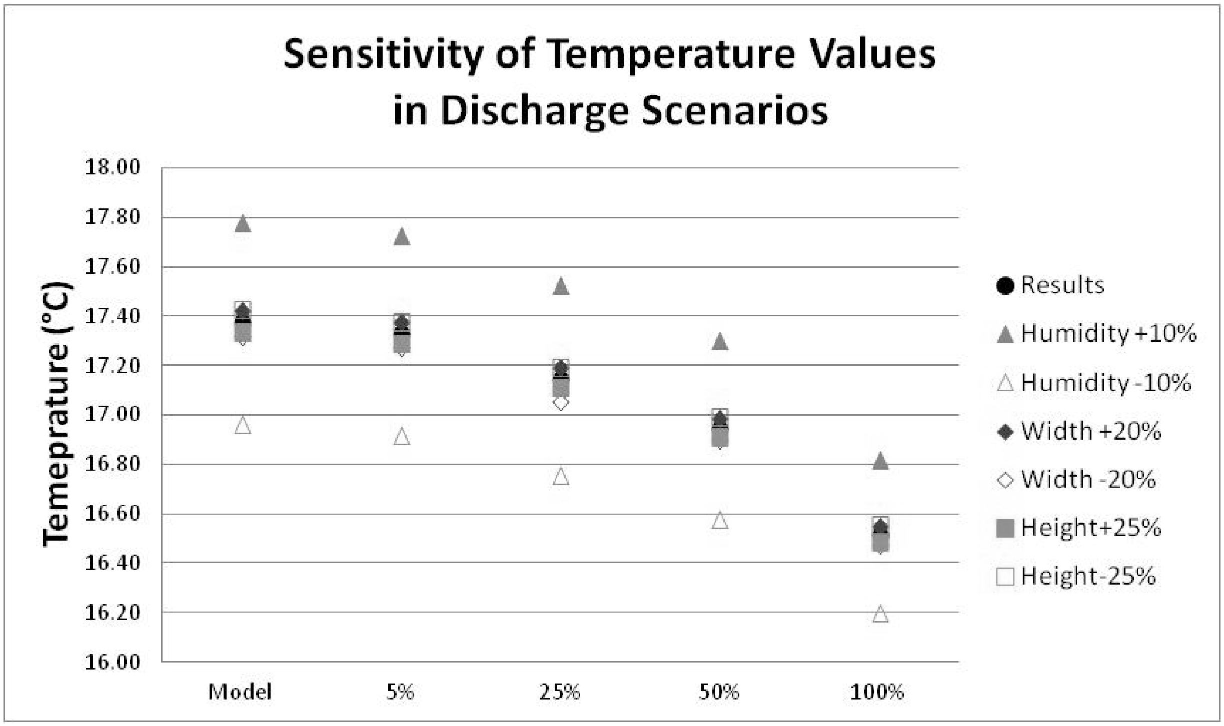


Figure 4.6 The sensitivity of temperature estimates in the different discharge scenarios when looking at changes in humidity (+/- 10%), stream width (+/-20%) and vegetation height (+/-20%).

Effect of shading and discharge on temperature

An increase in shade over the Llobregat River showed reduced temperatures throughout the stream segment, while the scenario in which all vegetation was removed increased water temperature. Shade produced a stronger effect in warmer months (Fig 4.7). The most modest shading scenario (restorable areas to 40%) reduced mean annual stream temperature at the intake of the ATLL water treatment facility by 0.34°C (0.006°C/km), while a simulated forest coverage of 100% on all segments showed a mean annual reduction of 1.84 °C (0.03°C/km) (Appendix K). The removal of existing riparian vegetation increased stream temperature at the ATLL treatment plant by over 0.5°C between May and October.

Increasing stream discharge also reduced stream temperature. A 5% increase in discharge had a very small effect on stream temperature (mean reduction = 0.048°C), whereas a 25% increase in discharge reduced temperature 0.2°C during warm months (Fig 4.8). An increase in discharge by 50%

reduced stream temperatures by 0.4°C during warm months. The doubling of discharge (100%) had a greater effect in the spring and fall, when stream discharge is largest. I hypothesize that the doubling of discharge in the summer made little difference because the summer base flows are already small.

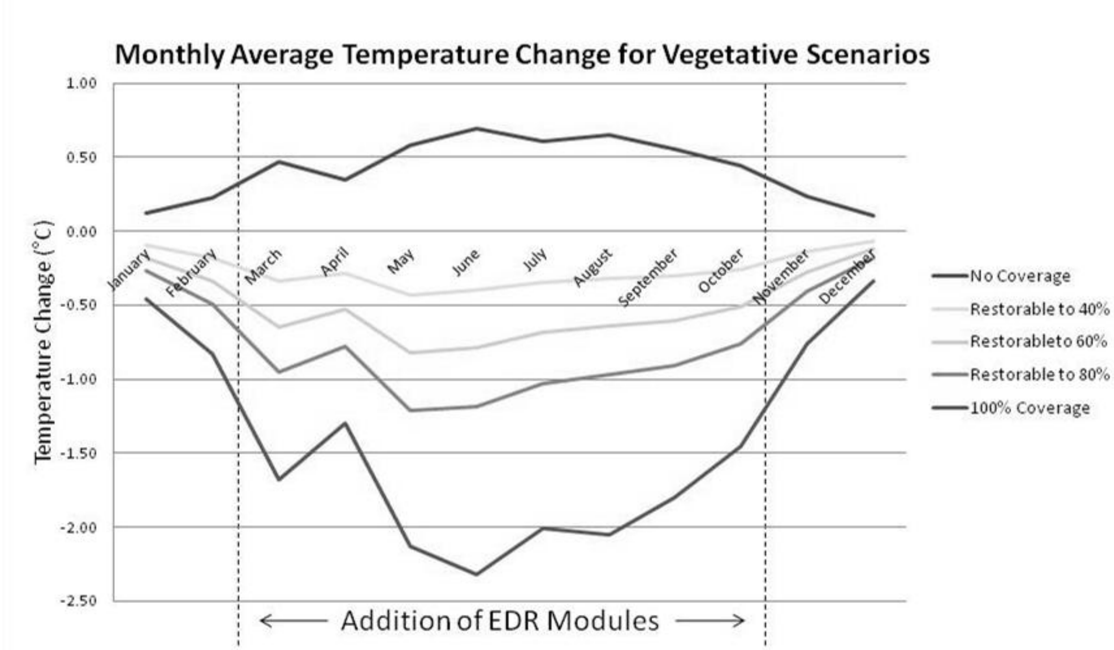


Figure 4.7 Mean monthly temperature changes simulated by SNTEMP in the five shading scenarios: (1) existing vegetation coverage removed, (2) riparian forest in restorable areas increased to 40% coverage, (3) riparian forest in restorable areas increased to 60% coverage, (4) riparian forest in restorable areas increased to 80% coverage, (5) 100% coverage in the entire stream reach.

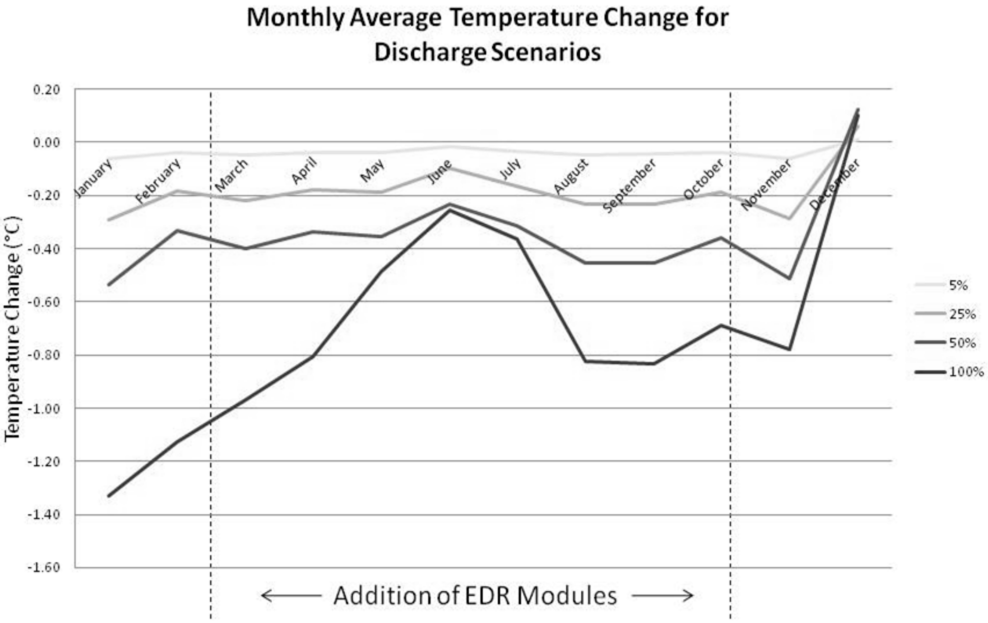


Figure 4.8 Mean monthly temperature changes simulated by SNTEMP in the four discharge scenarios: (1) increasing discharge 5% of monthly mean, (2) 25% of monthly mean, (3) 50% of monthly mean, and (4) 100% of monthly mean.

Longitudinal Temperature Profile

The simulated reductions in stream temperature could prevent the Llobregat River from crossing critical temperature thresholds, and therefore save water managers from adding EDR modules on particular days. Each day in which water managers avoid adding an additional EDR module would save them €1000. The temperature profile on a particular day allows us to visualize the induced changes in stream temperature projected by each management scenario. For example, on 26 August 2009, one of the warmest days of the year, the stream temperature rose rapidly in the first half of this segment and then more gradually between Castellbell (km 24) and the ATLL treatment plant (Fig 4.9). On this day modest changes in riparian shading and discharge were insufficient to maintain stream temperatures below the critical threshold of 26°C. Only the most aggressive measures, such as the doubling of discharge or restoring 100% coverage would have kept temperatures below the critical threshold. In contrast, removing existing vegetation would have increased stream temperature to 27.72°C at the intake of the ATLL water treatment plant.

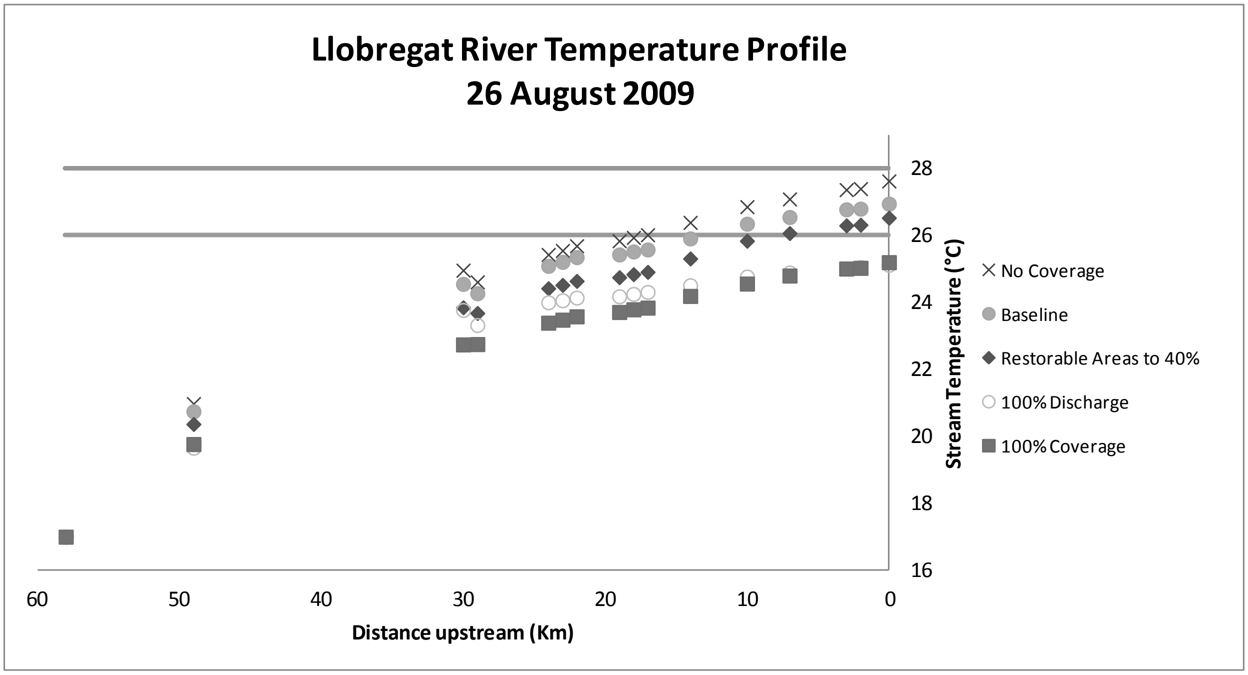


Figure 4.9 The temperature profiles under different simulated management scenarios on 26 August 2009. The horizontal lines represent temperature thresholds. On this day, the waters of the Cardener River had a slight cooling effect that can be appreciated by a dip in stream temperature at the river confluence (km 29).

On other days, modest management actions were sufficient to prevent the stream temperature from exceeding critical thresholds. For example on 25 May 2009 increasing forest cover to 40% in restorable areas would have reduced stream temperature by 0.45°C and maintained stream temperature below the 20°C threshold at the end of the segment (Fig 4.10). For this date, then, water managers would have operated without an additional EDR module, saving them €1000 in this management scenario.

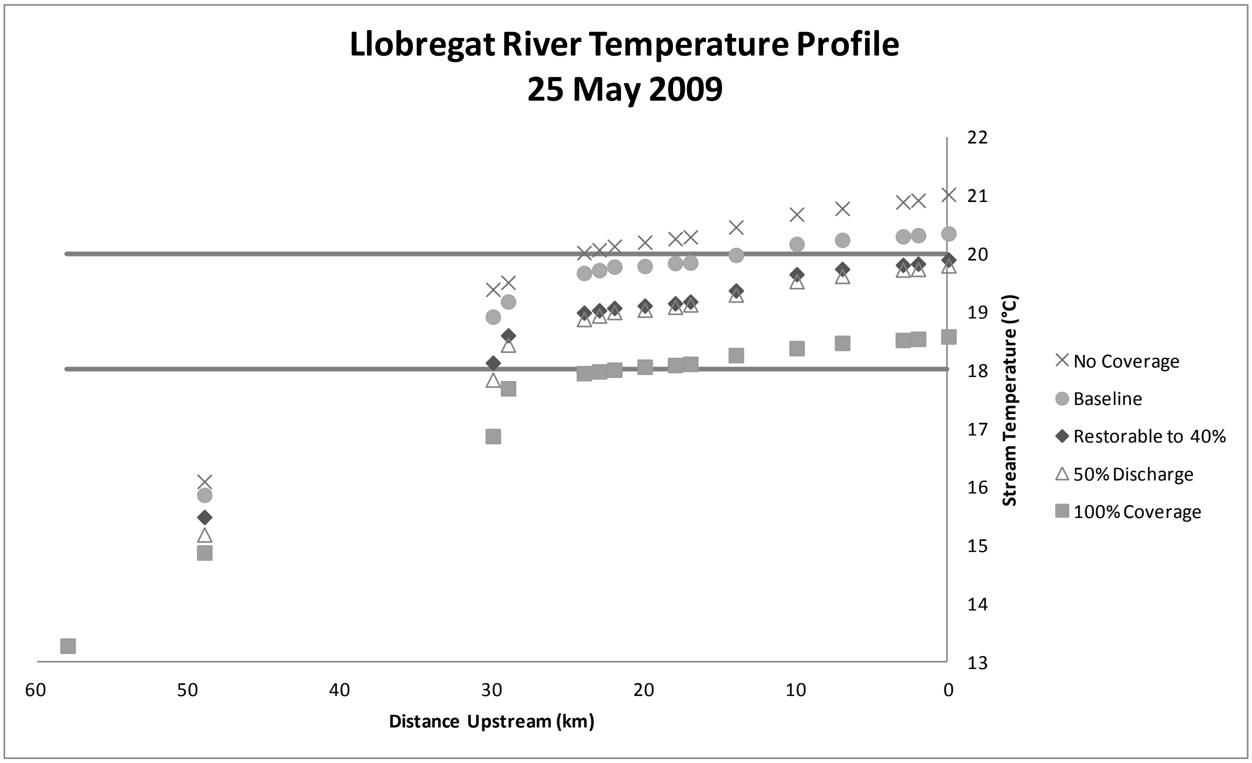


Figure 4.10 The temperature profiles under different simulated management scenarios on 25 May 2009. The dashed lines represent the temperature thresholds. The horizontal lines represent temperature thresholds.

In both longitudinal profiles, temperatures rose faster in the first half of the stream segment, between the stream headwaters and the confluence with the Cardener (29.8 km). This rapid thermal heating in the upper parts of the watershed has been documented elsewhere in the literature (Chan et al. 1998).

Avoided Threshold Crossings

As expected, large increases in shade and discharge are predicted to prevent more threshold crossings (Fig 4.11 and 4.12). The shading scenarios would prevent between 57 and 283 threshold crossings, while the discharge scenarios would prevent between 7 and 120 threshold crossings.

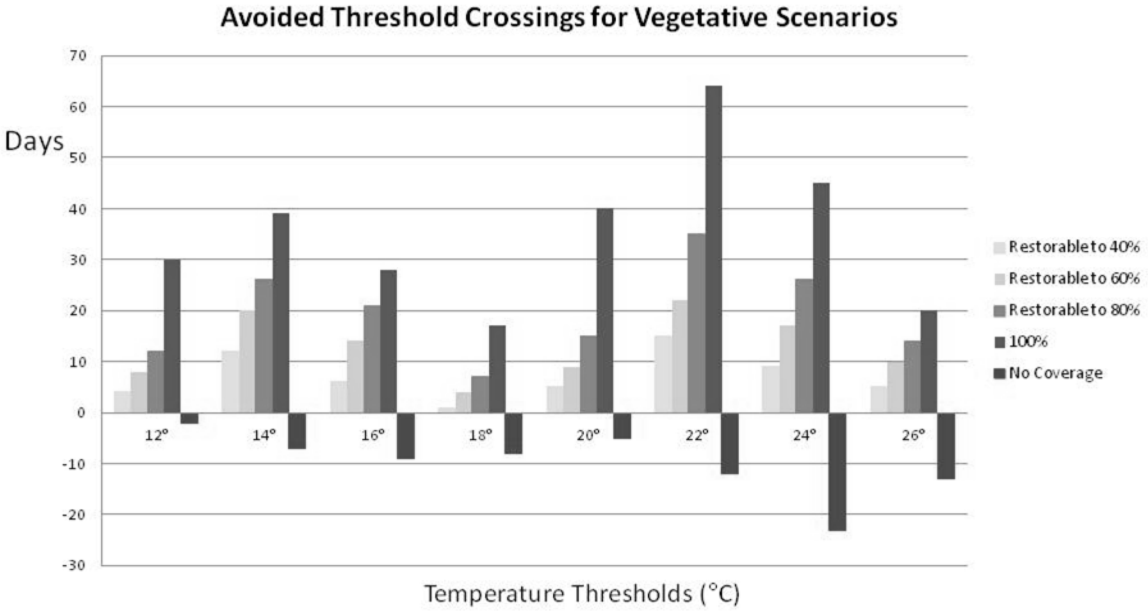


Figure 4.11 Avoided threshold crossings associated with riparian restoration scenarios measured in days. Positive values are days in which the water treatment plant could avoid operating an additional EDR module. Negative values are days in which the treatment plant would need to operate an additional EDR module, which is only the case in the scenario when existing revegetation is hypothetically removed.

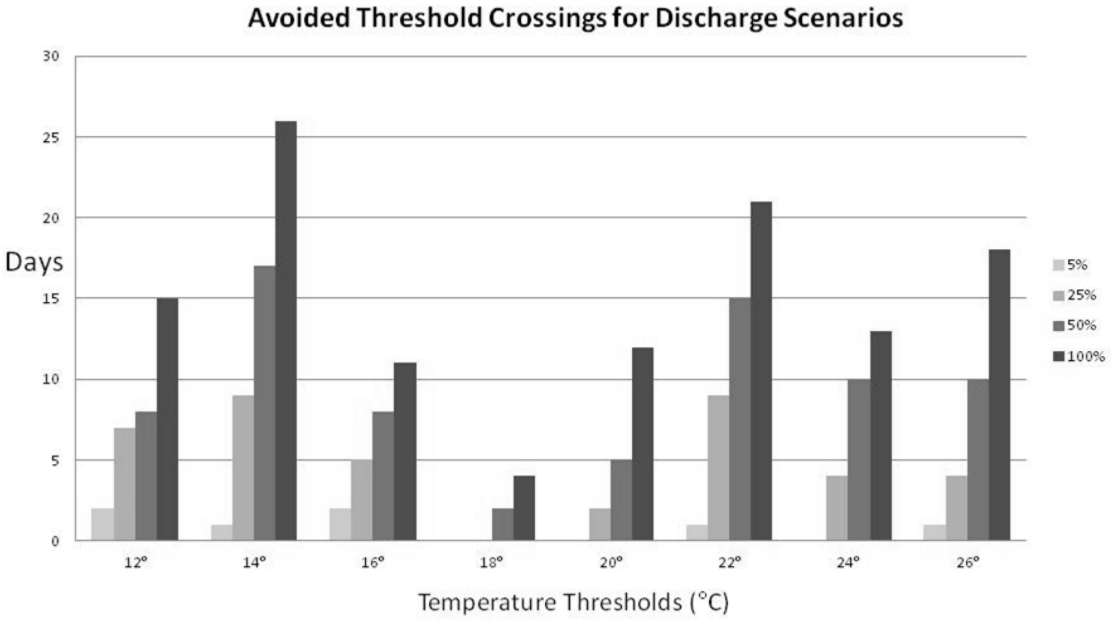


Figure 4.12 Avoided temperature threshold crossings, measured in days, associated with a percent increase in stream discharge: 5%, 25%, 50%, and 100%.

Ecosystem services associated with stream shading

By adding the number of days in which threshold crossings are prevented, the five shading scenarios could generate savings in the range of €57,000 to €283,000 per year (Fig 4.13). Our model also allowed us to quantify the value of the services provided by the existing vegetation, which is estimated by the scenario in which vegetation is removed. Removing the existing vegetation would require treatment managers to switch on EDR modules an additional 79 days during the year, for an annual cost of €79,000.

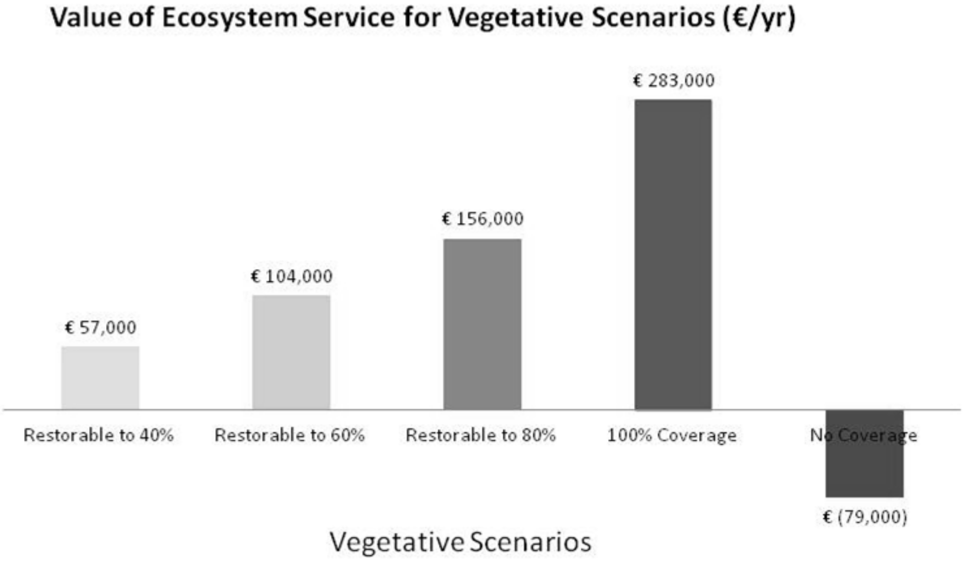


Figure 4.13 Value of ecosystem service for the ATLL water treatment plant of various riparian restoration options.

Ecosystem services associated with increased discharge

Increasing stream discharge by 5% had a nearly negligible impact on stream temperature, preventing threshold crossings on only 7 days for a savings of €7,000 annually. In contrast a 25% increase in discharge would prevent 40 threshold crossings per year, saving the drinking water facility €40,000 annually. Increasing discharge by 50% would prevent threshold crossings on 75 days, saving water treatment managers €75,000 annually, while the doubling of discharge (100%) would prevent threshold crossings on 120 days, saving water treatment managers €120,000 annually (Fig 4.14).

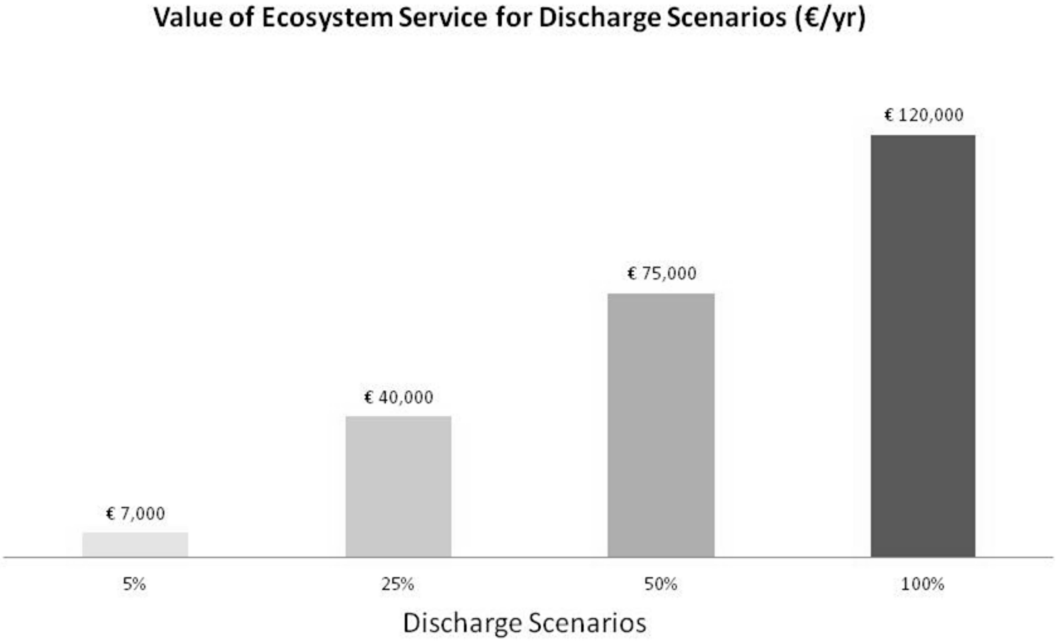


Figure 4.14 Value of ecosystem service for the ATLL water treatment plant for increases in stream discharge (% of monthy mean).

Robustness of the Value of Ecosystem Services

I also found that the value of the ecosystem services were highly robust to changes in modeling assumptions or possible measurement error (Fig 4.15 and Fig 4.16). The significant changes in estimated or measured parameters show relatively modest changes in the results of the economic valuation. The sign and direction of the values remained similar in all the scenarios tested. However unlike the sensitivity tests on temperature values (Fig 4.5 and 4.6), the economic valuation estimates were not evenly bounded because economic value was only generated when thresholds were crossed.

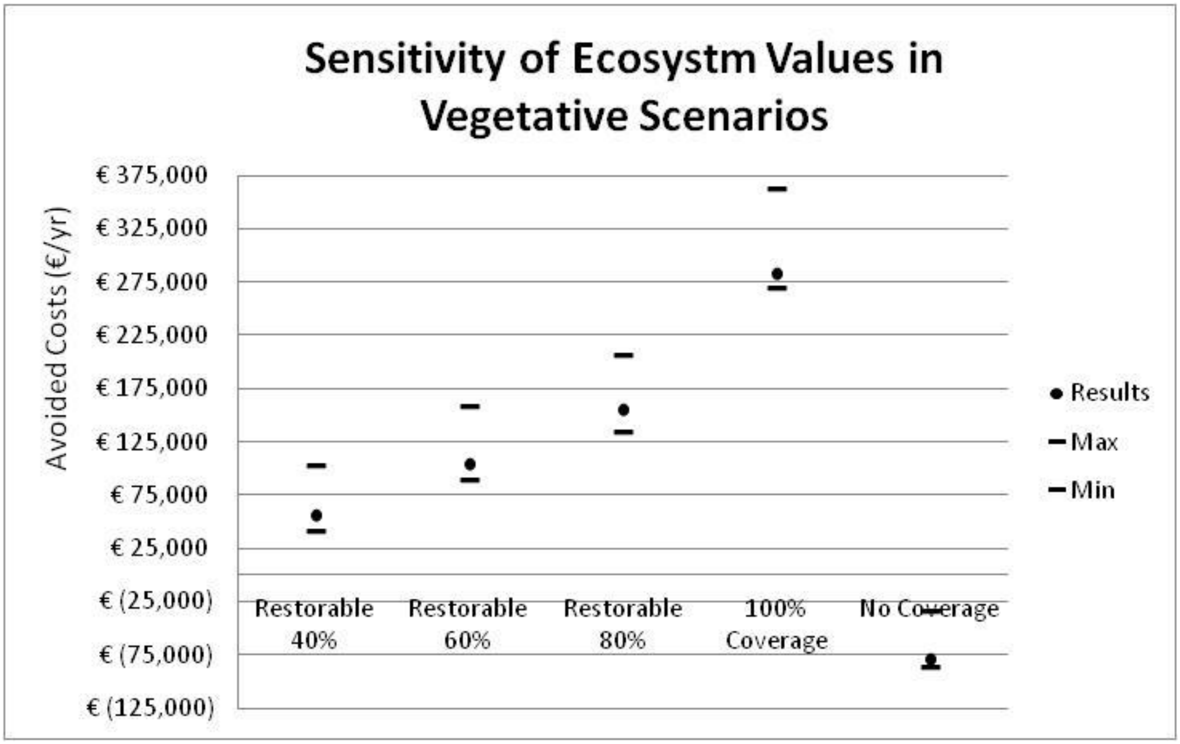


Figure 4.15 The upper and lower boundary results in the vegetative scenarios when testing for possible error in relative humidity (+/-10%), , stream width (+/- 20%), vegetation height (+/-25%), and Manning's N (0.0025 & 0.0035).

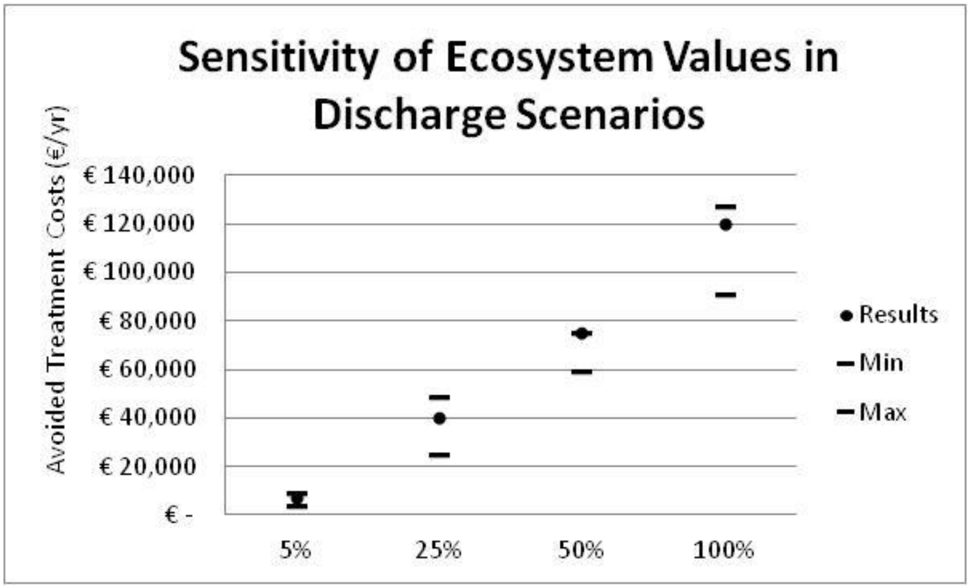


Figure 4.16 The upper and lower boundary results in the discharge scenarios when testing for possible error in relative humidity (+/-10%), stream width (+/-20%) and vegetation height (+/-25%).

I also tested if the results were sensitive to model calibration (Fig 4.17). The uncalibrated model showed values very similar to the final results. The insensitivity of the results to model calibration is explained by how the economic values are calculated. Value is created for water treatment managers when thresholds are crossed, therefore even temperature models that over- or under-estimates temperature values (uncalibrated) will still predict temperature reductions, and therefore threshold crossings. The similarity of the results between the calibrated and uncalibrated models gives me considerable confidence that my final results are robust to changes in model calibration.

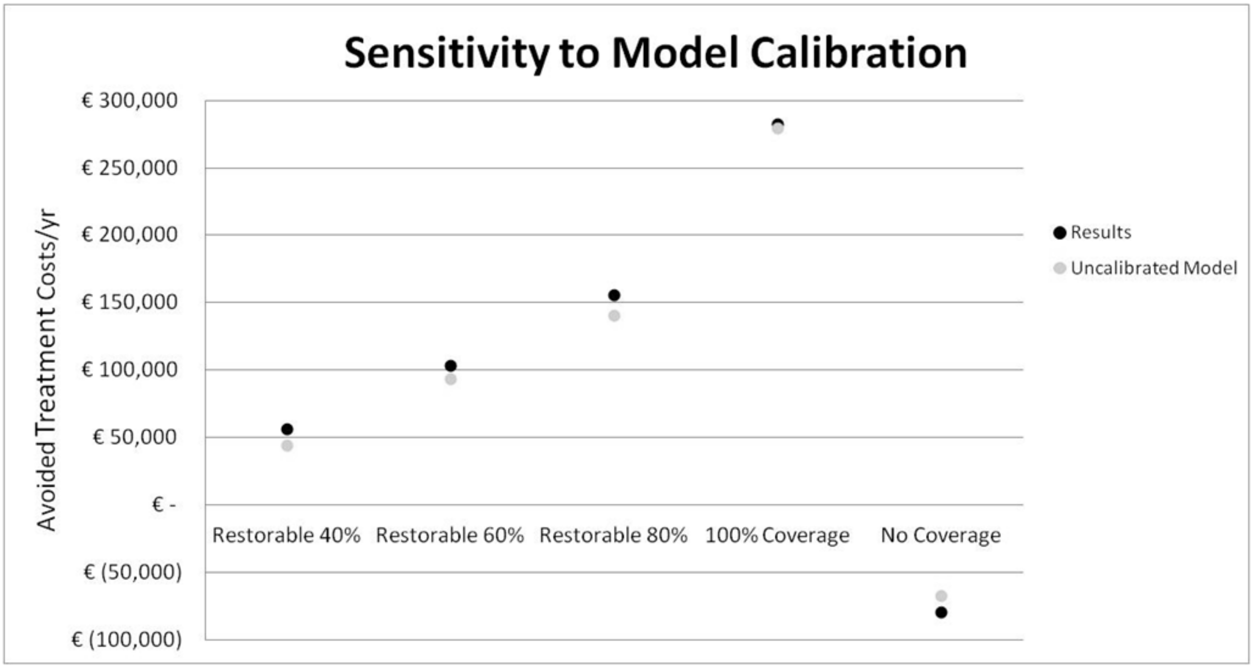


Figure 4.17 Comparison of results between the calibrated and uncalibrated models.

Finally, I tested if the results were sensitive to the placement of thresholds at particular temperature values. Recall that the temperature thresholds for adding an additional EDR model were uniformily distributed every 2°C after 12°C (12°C, 14°C, 16°C, 18°C, 20°C, 22°C, 24°C, 26°C). I tested how the results might change if these thresholds were 1°C lower (11°C, 13°C, 15°C, 17°C, 19°C, 21°C, 23°C, 25°C) as well as thresholds that were randomly generated (12.8°C, 13.9°C, 15.7°C, 18.6°C, 21.8°C, 22.4°C, 23.7°C, 24.7°C). The results are not hugely sensitive to these changes (Fig 4.18), suggesting that even if water managers modify the temperature thresholds for turning on EDR modules, the value of the ecosystem services are unlikely to change significantly.

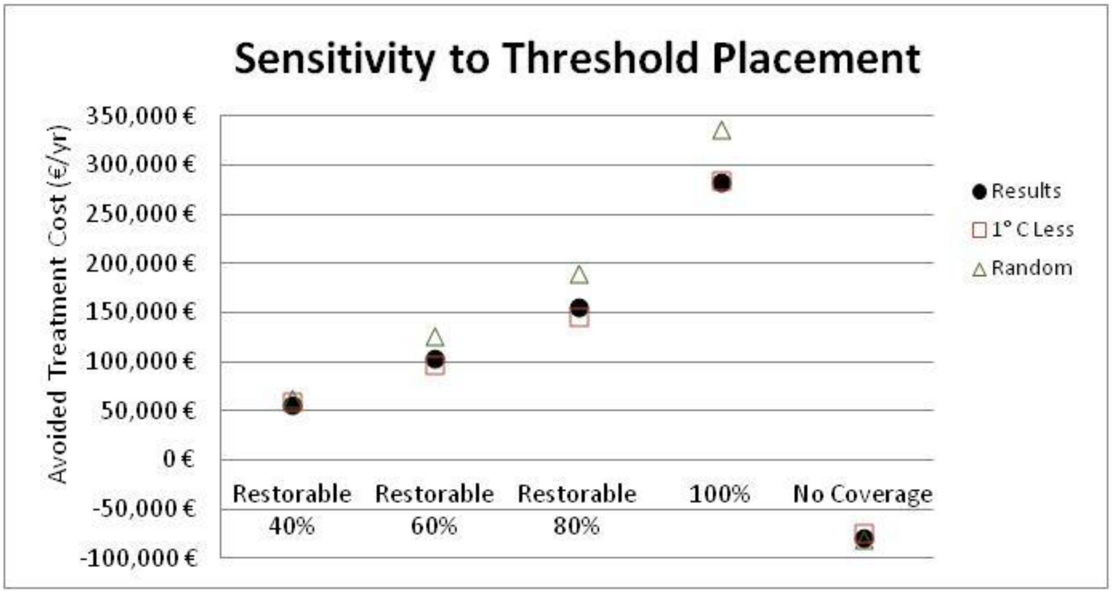


Figure 4.18 The results were largely insensitive to the placement of the EDR thresholds. When reducing the thresholds uniformly by 1°C, the results changed only slightly. Nor did the results change substantially when the temperature thresholds were selected randomly.

Forest Restoration Projects

Past restoration projects along the Llobregat and Cardener Rivers suggest that restoration costs are approximately €120,300 per kilometer (both sides), or €6.02/m^2. At this rate, the restoration cost for each scenario is €1,082,700; €1,624,050; €2,165,400 and €3,464,640 respectively. These upfront investment costs would be partially recovered through savings in reduced water treatment costs. In each of the restoration scenarios, at least one third of the initial investment is recovered within a 20 year period (Table 4.2). The most ambitious restoration scenario recovered up to 46% of the investment. Each of these projects would have a positive net benefit in 20 years if restoration costs could be lowered to €20,000 per kilometer, or €2.0/m^2 (Appendix O).

Table 4.2 Summary of restoration costs and % investment recovered after 20 years.

Restoration Scenarios	Segment (Km)	Cost (€)	% Investment Recovered
Recoverable Areas to 40%	18	€ 1,082,700	33%
Recoverable Areas to 60%	27	€ 1,624,050	41%
Recoverable Areas to 80%	36	€ 2,165,400	46%
All areas 100%	57.6	€ 3,464,640	46%

Increases in Discharge

Dam releases in two reservoirs (Sant Ponç and Baells) in the Llobregat watershed could increase water flow at a low cost. Moreover, in contrast to riparian restoration, the reductions in stream temperature associated with dam releases would materialize immediately. The critical tradeoff is the loss of water storage. When water supplies are low, the dam releases may not be a viable option. But if temperatures are rising and water supplies are abundant, dam releases may be an effective measure to postpone the use of expensive EDR water treatment.

4.5 Discussion

The existing stream vegetation along the Llobregat River already provides valuable ecosystem services for the ATLL water treatment plant, and by extension, for the residents of Barcelona, by maintaining the Llobregat River cool and avoiding the use of EDR modules on approximately 79 days per year, saving €79,000 per year in water treatment costs. Restoring the Llobregat River with more riparian trees or increasing discharge could provide even greater benefits.

The least ambitious shading option would generate services worth €57,000 per year, while the most ambitious scenario, the restoration of vegetation along the entire stream segment (100% coverage), could save water managers €283,000 per year. This last scenario serves as an upper boundary estimate and also shows that ecosystem processes have the potential to generate substantial value for downstream users.

Increases in stream discharge also have the potential to generate additional savings for water treatment managers. The timing of discharge increases is particularly important (Fig 4.8). Greater flows are most likely to reduce stream temperature the months of March, April, May, August, September and October.

These results have implications for water managers in Catalonia as they seek to comply with the Water Framework Directive (WFD) that requires that all water bodies obtain “good ecological status” (Directive 2000). In an effort to comply with the WFD, the Catalan Water Agency has drafted a plan of measures, published in 2010, that budgeted €8.67 million for riparian restoration along the Llobregat River (ACA 2010). This research shows that some of these costs can be recovered. This is useful information as policy makers must decide which measures to execute and which measures might be postponed because of their financial cost. Recall that governments may be excempt from the European Union’s requirement to restore water bodies to “good ecological status” if they can justify that the costs associated with ecological restoration are disproportionately large. However these economic assessments frequently only focus on the costs of the restoration measure and not the associated environmental and economic benefits, as presented here. Therefore this research helps quantify some of the benefits associated with ACA’s program of measures. At the same time, the WFD seeks to invert our economic logic by putting the objective of “good ecological status” at the center of policymaking. Following this logic, the restoration benefits quantified in this paper are in addition to our policy objective of “good ecological status” – rather than a justification for them.

The model does not include the inputs from all waste water treatment plants along this river segment. However when two waste water treatment plants were included in the lower reach they had a negligible impact on downstream temperature. The model also does not consider the effect of successive river impoundments which hold back the water on its journey between Balsareny and Abrera.

The longitudinal profiles suggest that the location of riparian shading matters. In this case, the increased shading between Balsareny and Castellbell would be especially important since the river gains the most heat in this segment. As a result, it is here where management is likely to have the most impact (Appendix L). Other watersheds have also shown a pattern of streams heating up faster in the upper parts of the watershed (Chen et al. 1998).

None of the restoration scenarios could offer projects with a positive net present value after 20 years because of the high initial investment and low initial returns that do not become more substantial until the trees reach full maturity. If the restoration projects were to plant older trees they would provide more benefits earlier, and the projects would have higher returns.

Increasing stream flow through strategic dam releases would allow water managers to realize benefits within a shorter time frame. These releases would need to be negotiated with the Catalan Water Agency and the electrical company that captures energy from the hydroelectric dams. The institutional structures already exist to allow this negotiation to develop. Additional releases would be most realistic when reservoirs are near full capacity and air temperatures are rising rapidly. For example, if reservoirs were full in late May due to spring rains, and temperatures were to rise abruptly, the additional discharge could help maintain cooler stream temperatures, and prevent the ATLL treatment plant from turning on additional EDR modules for several days or weeks.

This chapter has applied a deterministic model of biophysical processes to simulate alternative management options in the watershed. And yet the biophysical model alone could not have generated the reliable valuation estimates of the ecosystem services related to stream temperature. The technological and decision making conditions downstream dictated the terms under which valuation estimates could be made. This implies that different technologies or alternative management protocols would alter the value associated with ecosystem services that moderate stream temperature. From the perspective of the water treatment managers, the ecosystem service was created by the new technology and the treatment protocol that centered decision making on stream temperature values.

I have calculated a value for the ecosystem services by focusing on how these services could help treatment managers meet specific water quality targets. Focusing on how ecosystem services could contribute to meeting policy objectives allowed me to avoid thorny questions concerning non-use valuation. Of course, streams provide both use and non-use values. However, non-use values can be difficult to quantify. And even when these controversial methods are accepted, there are still concerns that valuation exercises are inappropriate or misguided (Venkatachalam 2004, McCauley 2006, Gómez-Baggethun et al. 2010, Kosoy and Corbera 2010, Sangenberg and Settele 2010). To avoid some of these controversial issues associated with non-use valuation, in this chapter I did not seek to value the ecosystem structures in their entirety (use and non-use), but merely quantified the use-values generated for a specific downstream users. Thus the results presented here offer a lower boundary estimate of the value provided by riparian ecosystems.

Managing ecosystem services in order to meet specific objectives has several advantages. It simplifies the valuation process, engages decision makers, and facilitates the implementation of ideas about ecosystem services in practice. This approach may not be viable for all ecosystem services studied, especially when non-use values are involved. However it does highlight that new opportunities to manage and restore ecosystem services may arise if we scrutinize the decision making context of those who depend on nature's services. By focusing on the end users, we will be more likely to harness the benefits that ecosystems provide.

4.6 Acknowledgements

This research has been funded by the Water Technology Center (CETaqua) and the Catalan Water Agency (ACA) in a collaborative agreement with the Catalan Water Research Institute (ICRA), Aigües-Ter Llobregat (ATLL) and Aigües de Barcelona (AGBAR). Results were obtained with data from the Meteorological Service of Catalonia (Meteocat), Aigües Ter Llobregat (ATLL), and ACA. ACA also provided the HEC-RAS model to calculate the width A and B constants, with valuable assistance from Rosana Aguilera at ICRA and Ramón Batalla from the University of Lleida. I thank Maria Jou from Mina-Sorea for providing data on discharge and temperature from the wastewater treatment plants. John Risley and John Bartholow from the United States Geological Survey (USGS) provided valuable assistance developing the Stream Network Model. I thank Francesc Solana for meteorological data used to produce preliminary results for Stream Segment Model. Èric Esclassans and Héctor Oliva loaned me equipment to conduct the field work.

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APPENDICES

Appendix A. Osmotic Pressure, Total Dissolved Solids, & Energy Efficiency at AGBAR

Appendix B. Electrodialysis Reversal (EDR), Conductivity, & Energy Efficiency at ATLL

Appendix C. Summary of the Value of Ecosystem Services Following Technological Change

Appendix D. Additional Reflections on Ecosystem Services and Technology

Appendix E. Heat Fluxes Modeled in the Stream Network Temperature Model (SNTEMP)

Appendix F. Stream Network Model Operation

Appendix G. Input Files for the Stream Network Model (SNTEMP)

Appendix H. Output File for Data Verification Program TDATCHK

Appendix I. Field Work for Shading Estimates

Appendix J. Calibration of SNTEMP

Appendix K. Full Results for SNTEMP

Appendix L. Notes on Scale Selection for SNTEMP

Appendix M. Stream Segment Model (SSTEMP)

Appendix N. Stream Network Model from Castellbell to Abrera

Appendix O. Riparian Vegetation and Restoration Costs

Appendix A. Osmotic Pressure, Total Dissolved Solids, & Energy Efficiency at AGBAR

AGBAR spends between €1.8 and €2.2 million per year on energy to desalinate water from the Llobregat River with reverse osmosis technology. This estimate only covers energy expenses associated with the reverse osmosis membranes and excludes other energy use associated with ultrafiltration or water elevation. Given these high energy expenses, a reduction in salinity concentrations in the Llobregat River could generate considerable financial savings. In the main text I calculated these savings using the Reverse Osmosis System Analysis (ROSA) software distributed by Dow Chemical.

Underlying these calculations are the physical laws that govern osmotic pressure. To remove dissolved solids from a solution, the reverse osmosis process must apply a pressure that surpasses the osmotic pressure (Elimelech and Phillip 2011). A higher concentration of the solute will increase the osmotic pressure and therefore increase the energy needed to desalinate. Osmotic pressure (Π) is a function of the molar concentration of total dissolved solids (c), the gas constant (R), and temperature (T) (Equation 1).

(1) Equation for osmotic pressure: $\Pi = cTR$

Where:
c = the molar concentration of the solute;
R= the gas constant 0.082 (liter·bar)/(deg·mol);
T= temperature (Kelvin)

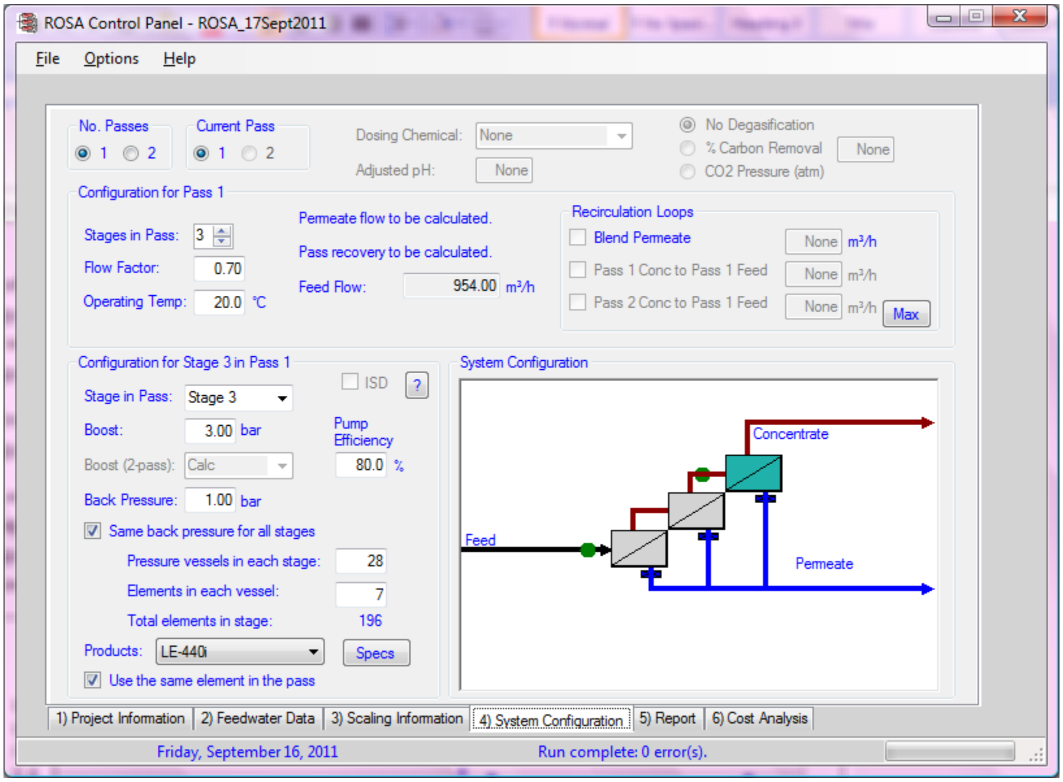
Higher concentrations of dissolved solids need more osmotic pressure for the same output water quality (Elimelech and Phillip 2011). However it difficult to calculate the energy TDS-energy efficiency relationship directly because RO systems have three phases, and the pressure that must be applied must surpass the osmotic pressure in all three desalination phases. With three phases and seven membranes in each phase, one molecule of water will have gone through 21 membranes before it exits the system. At each phase, the rejected water that does not pass the membrane begins to accumulate salts. Hence the minimum pressure needing application in each membrane increases as dissolved solids accumulate.

AGBAR treats approximately 44 million m^3 of water per year at the Sant Joan Despí water treatment facility. According to a water characterization of the Llobregat River by the treatment plant, the mean concentration of total dissolved solids in the Llobregat is 1,397 mg/L (Table A.1). Another source from the AGBAR treatment facility reports a similar, although slightly lower mean level of total dissolved solids at 1,150 mg/L (Pedraz-Yañez 2007). However when one calculates the TDS from the mean conductivity value (1500 uS/cm) of the Llobregat River with a conversion factor of 0.7 uS/cm per mg/L TDS, the then TDS value is much higher at 2,140 mg/L.

Ions	mg/L
Ammonium (NH4)	0.15
Potassium (K)	31.40
Sodium (Na)	216.90
Magnesium (Mg)	50.80
Calcium (Ca)	162.30
Strontium (Sr)	2.00
Barium (Ba)	0.05
Carbonate (CO3)	1.55
Bicarbonate (HCO3)	370.00
Nitrate (NO3)	11.50
Chloride (Cl)	402.00
Flouride (F)	0.172
Sulfate (SO4)	292.00
Silica (Si02)	8.78
Boron	0.233
Total Dissolved Solids	1,397

Table A.1 Water quality characteristics of the Llobregat River

ROSA is a computer assisted tool for designing and operating reverse osmosis and nanofiltration systems (Fig A.1). The software was created to assist water treatment managers operate the desalination systems provided by the Dow Chemical Company (Dow Chemical 2011).



No. Passes: ● 1 ○ 2

Current Pass: ● 1 ○ 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 1

Stages in Pass: 3
Flow Factor: 0.70
Operating Temp: 20.0 °C

Permeate flow to be calculated.
Pass recovery to be calculated.
Feed Flow: 954.00 m³/h

Recirculation Loops
☐ Blend Permeate None m³/h
☐ Pass 1 Conc to Pass 1 Feed None m³/h
☐ Pass 2 Conc to Pass 1 Feed None m³/h

Configuration for Stage 3 in Pass 1

Stage in Pass: Stage 3
☐ ISD
Boost: 3.00 bar
Pump Efficiency 80.0 %
Boost (2-pass): Calc
Back Pressure: 1.00 bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 28
Elements in each vessel: 7
Total elements in stage: 196
Products: LE-440i
☑ Use the same element in the pass

Friday, September 16, 2011
Run complete: 0 error(s).

Figure A.1 Configuration of the AGBAR reverse osmosis system in ROSA.

As described in the Main Text, I ran ROSA with different feed water qualities and then observed the associated reduction in energy efficiency (kWh/m³). I used a conversion factor of 0.7 to transform values reported in ROSA in Total Dissolved Solids to conductivity. The results of these simulations are presented in the table below. As presented in the Main Text, we observe an exponential relationship between TDS values and specific energy efficiency (kWh/m^3) with the expression $Y=0.315e^{0.00034x}$

TDS	Conductivity (µS/cm)	Average Net Driving Pressure (bar)	Power (kW)	Specific Energy (kWh/m³)	Total Energy (kWh)	Total Energy Expense (€)	Savings per reduction in 100 mg/L TDS [Model Values]	Savings per reduction in 100 mg/L TDS [Trendline]
1000	700	6.18	355.12	0.443	19,508,153	1,755,734 €	39,903 €	61,074 €
1100	770	6.05	357.04	0.458	19,951,520	1,795,637 €	79,806 €	63,187 €
1200	840	5.92	358.89	0.474	20,838,255	1,875,443 €	39,903 €	65,372 €
1300	910	5.79	360.69	0.490	21,281,622	1,915,346 €	79,806 €	67,633 €
1400	980	5.65	362.43	0.507	22,168,356	1,995,152 €	79,806 €	69,972 €
1500	1050	5.52	364.13	0.525	23,055,090	2,074,958 €	79,806 €	72,392 €
1600	1120	5.39	365.78	0.543	23,941,824	2,154,764 €	79,806 €	74,895 €
1700	1190	5.26	367.39	0.561	24,828,559	2,234,570 €	79,806 €	77,486 €
1800	1260	5.14	368.96	0.581	25,715,293	2,314,376 €	79,806 €	80,166 €
1900	1330	5.01	370.49	0.601	26,602,027	2,394,182 €	79,806 €	82,938 €
2000	1400	4.88	371.99	0.622	27,488,761	2,473,989 €	79,806 €	85,806 €

Table A.2 TDS, energy, cost relationships.

AGBAR reports that they desalinate approximately 44,336,712 m^3 per year and consume nearly 24 GWh to sustain this desalination. They pay approximately 0.09€/kWh for a total expense of approximately €2 million per year only for energy expenses in the reverse osmosis system.

Volume treated by reverse osmosis	44,336,712	m³/year
Specific Energy	0.54	kWh/m³
Energy Consumption	23,941,824	kWh
Energy Price	0.09	€/kWh
Energy Expense	2,154,764	€/year

Table A.3 Volumes, energy expenses and costs at the AGBAR treatment facility.

The theoretical minimum amount of energy needed to remove salts from sea water is 1.8 kWh/m^3. As of yet, no technology has been able to reach this theoretical minimum, although new systems are starting to reach values below 2 kWh/m^3 (Elimelech and Phillip 2011).

Appendix B. Electrodialysis Reversal (EDR), Conductivity, & Energy Efficiency at ATLL

The calculations in the Main Text pertaining to energy use and conductivity at the ATLL facility are made with observed data. The technological specifications of the EDR system provided by the vendor (AWWA 1995) also show that lower conductivity in the feed water would reduce energy demand (Table B.1). Using these values from General Electric, a improvement in feed water quality from <1500 μS/cm to <1000 μS/cm would increase energy efficiency from 0.68 kWh/m^3 to 0.52 kWh/m^3. Maintaining production volume and energy costs constant, this would imply a reduced expenditure of €425,288 per year.

Table B.1 Energy consumption (kWh/m^3) at ATLL Treatment Facility at different levels of conductivity. Source

<1000 μS/cm	<1500 μS/cm	<2000 μS/cm	<2500 μS/cm
0.52	0.68	0.87	1.02

Appendix C. Heat Fluxes Modeled in the Stream Network Temperature Model (SNTEMP)

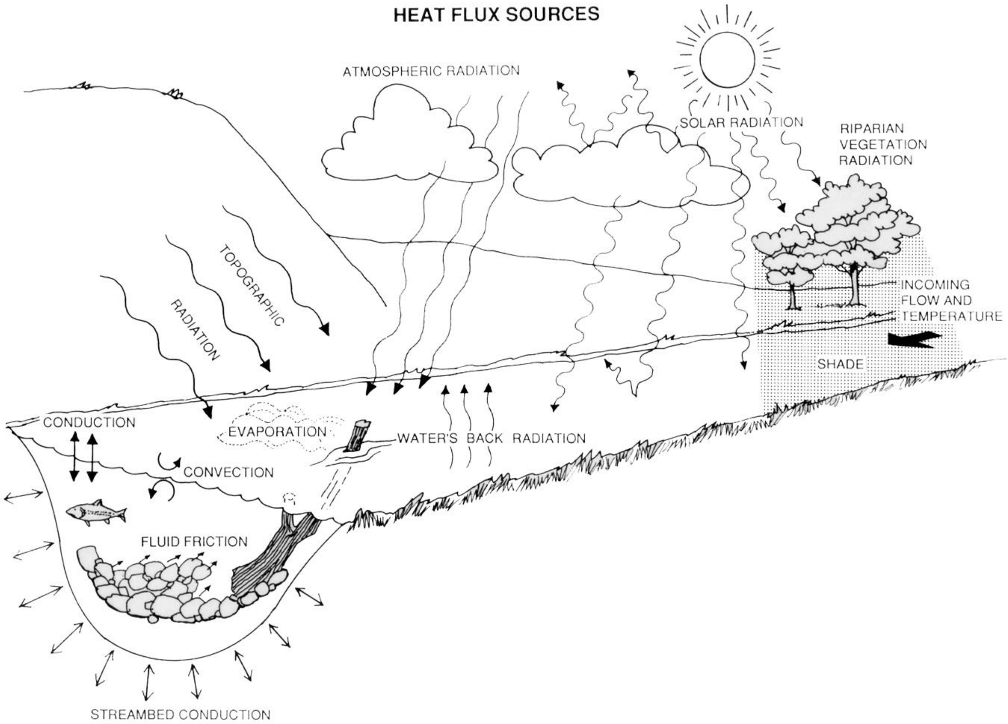
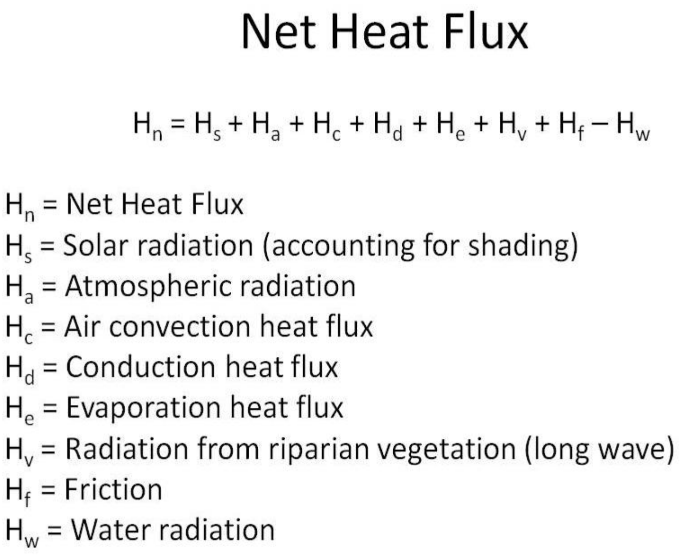


Figure C.1 Heat fluxes in a stream ecosystem. Reproduced from Bartholow (2000)



Net Heat Flux

$$H_n = H_s + H_a + H_c + H_d + H_e + H_v + H_f - H_w$$

H_n = Net Heat Flux
H_s = Solar radiation (accounting for shading)
H_a = Atmospheric radiation
H_c = Air convection heat flux
H_d = Conduction heat flux
H_e = Evaporation heat flux
H_v = Radiation from riparian vegetation (long wave)
H_f = Friction
H_w = Water radiation

Figure C.2 Net Heat Flux equation used in SNTEMP Model

Appendix D. Stream Network Model Execution

Model Input Files

The Network Model operates with seven input files and a job control file.

(1)	Stream Geometry File	KVRFSTR.DAT
(2)	Time Period File	KVRFTME.DAT
(3)	Meteorology File	KVRFMET.DAT
(4)	Study Node File	KVRFSTD.DAT
(5)	Hydrology Node File	KVRFHDR.DAT
(6)	Hydrology Data File	KVRFHYD.DAT
(7)	Shade File	KVRFSHD.DAT
(8)	Job Control File	KVRFJOB.DAT

Input Data Verification

Before running SNTEMP it is advisable to run a data check program that searches for inconsistencies or errors in the input tables. The DOS command is: TDATCHK KVRFJOB.DAT KVFCHK.OUT. The ouput file describes any inconsistencies detected.

Run Command

The model runs with the DOS command SNTEMP. The program will then request the Job Control file: KVRFJOB.DAT, and the user is asked if any modifications are desired in the Job Control. Modifications may include the alteration of calibration coefficients or changing the period in which outputs are requested. If no modifications are made, the Network Model will run through the seven sub-programs: STRGEM or Stream Geometry, which updates elevations, latitudes and slopes for each node; HYDROL or Hydrology, which computes missing flows and adds lateral temperatures; METROL or meteorology, which computes time specific meteorology; REGTWO, which fills in missing temperature values using a regression model; TRNSPT, which computes water temperatures using physical processes, and VSTATS, which computes validation statistics (not applicable because no Validation or Calibration nodes used).

Model Output

The model produces eleven output tables. The temperature predictions are in table VIII located in the output file KVRTRNS.DAT. Users cannot control the names of the output files.

Troubleshooting Issues

SNTEMP would not run unless the input files were formatted precisely. Therefore several issues arose that prevented the model from running to completion.

(1) Time Period. The model would not run unless each time period (one year) had exactly the same number of days. This prevented me from using data in 2010 data because I only had data through November 2010. My period of analysis was revised to 1-January-2004 to 31-December-2009 (later it was reduced further with the need to incorporate the Cardener River for which only data in 2009 was available). Furthermore, all years needed to have exactly 365 days. The 29th of February in 2004 and 2008 were eliminated even though data was available.

(2) Regression Program. The regression program that fills in missing temperature values did not run successfully, and produced a Run Time Error M6201: MATH, which implied that a negative square root was found in the computations. This was resolved by filling all missing temperature values with average values from the day prior and after.

Table D.1 Network nodes for the Llobregat Temperature Model

ID	River	Node	Distance (m)	Name	Elevation	Function	UTM_X	UTM_Y
1	Llobregat	H	57,612	Headwaters Balsareny	285	Headwaters	407107	4633667
2	Llobregat	C	49,080	Soler Vicenç	175	Change Stream Geometry	409434	4626515
3	Llobregat	B	29,810	Llobregat Branch	165	Branch	404459	4615146
4	Cardener	H	32,000	Castellgalí (Cardener H)	175	Headwaters	403929	4616981
5	Cardener	T	29,810	Tributary Cardener	165	Tributary	404459	4615146
6	Llobregat	J	29,810	Juncture Cardener	165	Juncture	404459	4615146
7	Llobregat	Q	23,932	Castellbell	148	Discharge	405776	4610500
8	Llobregat	C	23,010	Bures	141	Change Stream Geometry	404926	4610700
9	Llobregat	C	21,752	Borras	141	Change Stream Geometry	404411	4609660
10	Llobregat	C	20,462	La Bauma Desviacio	132	Change Stream Geometry	405562	4609180
11	Llobregat	C	19,641	La Bauma	127	Change Stream Geometry	405443	4608670
12	Llobregat	P	19,547	Castellbell i Vilar WWTP	127	Point Discharge	405366	4608730
13	Llobregat	C	18,919	C58	125	Change Stream Geometry	404801	4608890
14	Llobregat	C	17,805	Puig i Font	126	Change Stream Geometry	404388	4607880
15	Llobregat	C	16,879	Monistrol	119	Change Stream Geometry	403990	4607380
16	Llobregat	P	15,054	Monistrol WWTP	109	Point Discharge	404488	4605950
17	Llobregat	C	11,048	Cairat	80	Change Stream Geometry	405714	4602760
18	Llobregat	C	9,844	La Puda	75	Change Stream Geometry	406672	4602550
19	Llobregat	C	6,827	Can Sedo	70	Change Stream Geometry	406079	4599920
20	Llobregat	C	2,974	Final Turn	63	Change Stream Geometry	409259	4598810
21	Llobregat	D	2,556	D Aigues de Terrasa	62	Diversion	409283	4598400
22	Llobregat	E	0	Abrera Treatment Plant	57	End	409757	4596230

Appendix E. Input Files for the Stream Network Model

STUDYFILE [KEY]

River Name   Node   Distance Upstream   Description

```
STUDYFILE: BALSARENY TO ABRERA 27 JULY 2011
LLOB     H    57.612   HEADWATERS BALSARENY
LLOB     B    29.81    BRANCH LLOBREGAT
CARD     H    32.00    HEADWATERS CARDENER
CARD     T    29.81    TRIBUTARY CARDENER
LLOB     J    29.81    JUNCTURE CARDENER
LLOB     E     0        END ABRERA
```

HYDROLOGY NODE FILE [KEY]

River name;   Node; Output flag; Regression model instructions; Distance Upstream; Description
Hydrology linkage instructions (first line only)

```
HYDROLOGY NODE FILE: BALSARENY TO ABRERA 27 JULY
LLOB     H    57.612   HEADWATERS BALSARENY
LLOB     B    29.81    BRANCH LLOBREGAT
CARD     H    32.00    HEADWATERS CARDENER
CARD     T    29.81    TRIBUTARY CARDENER
LLOB     J    29.81    JUNCTURE CARDENER
LLOB     Q    23.932   CASTELLBELL
LLOB     P    19.547   POINT DISCHARGE CAS WWTP
LLOB     P    15.054   POINT DISCHARGE MON WWTP
LLOB     D    2.556    AIGUES DE TERRASSA
LLOB     E    0        END ABRERA
```

STREAM SHADE FILE [KEY]

River Name; Node; Output flag; Hydrology model linkage; Local Shade Linkage; Distance Upstream; Description
Site Latitude (Radians); Stream Reach Azimuth (radians); Stream Width (m)
Eastside topographic altitude (radians); vegetation crown (m); height(m); offset (m); ***vegetation density***
Westside topographic altitude (radians); vegetation crown (m); height(m); offset (m); ***vegetation density***

STREAM SHADE FILE: CASTELLBELL TO ABRERA 29 JULY 2011

```
LLOB         H1S2    57.612   C0 HEADWATERS BALSARENY
0.7303  0.1745  25
0.1745  20      20      5      0.15
0.1745  20      20      5      0.15

LLOB         C       49.080   CA SOLERVICENC
0.7293  0.0873  30
0.1745  20      20      5      0.15
0.1745  20      20      5      0.15

CARD         H1S2    32.000   HEADWATERS CARDENER
0.7292  1.5708  20
0.1745  20      20      5      0.10
0.1745  20      20      5      0.10

LLOB         J       29.81    JUNCTURE CARDENER
0.7274  0.1745
0.1745  20      30      5      0.10
0.1745  20      20      5      0.10

LLOB         C       23.010   C1 BURES
0.7267  0.0873  30
0.2618  20      20      5      0.2
0.1745  20      20      5      0.05

LLOB         C       21.752   C2 BORRAS CANYON
0.7266  -0.7854 30
0.6109  20      20      5      0.1
0.5236  20      20      5      0.8

LLOB         C       20.462   C3 LA BAUMA DES
0.7265  -0.2618 25
0.2618  20      20      5      0.25
0.2618  20      20      5      0.1

LLOB         C       19.641   C4 LA BAUMA
0.7265  0.7854  30
0.1745  20      20      5      0.4
0.2618  20      20      5      0.4

LLOB         C       18.919   C5 C58
0.7263  0.1745  60
0.2967  20      20      5      0.3
0.5236  20      20      5      0.1

LLOB         C       17.805   C6 PUIG I FONT
0.7263  0.0873  35
0.2618  20      20      5      0.5
0.5236  20      20      5      0.6

LLOB         C       16.879   C7 MONTSERRAT
0.7262  0.7854  25
0.5236  20      20      5      0.2
0.5236  20      20      5      0.2

LLOB         C       11.048   C8 CAIRAT
0.7255  -0.349  30
0.4363  20      20      5      0.15
```

```
0.4363  20      20      5       0.1

LLOB            C       9.844    C9 LA PUDA
0.7255  0.1745  40
0.2618  20      20      5       0.4
0.3491  20      20      5       0.2

LLOB            C       6.827    C10 CAN SEDO
0.7252  -0.0873 30
0.2618  20      20      5       0.25
0.3491  20      20      5       0.3

LLOB            C       2.974    C11 FINAL TURN
0.7249  0.1745  30
0.1745  20      20      5       0.4
0.1745  20      20      5       0.35
```

STREAM GEOMETRY FILE [KEY]

River Name; Node; Distance upstream; Description

Site latitude (radians); elevation; Manning's N; Stream Width Coefficient; Width Exponent; Min Shading; Max Shading; Ground Temperature; Streambed thermal gradient (J/m2/sec/C) default 1.65

```
STREAM GEOMETRY FILE: BALSARENY TO ABRERA 27 JULY 2011

LLOB        H     57.612   HEADWATERS BALSARENY
0.73036 285    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     49.080   CA SOLERVICENC
0.7293  175    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        B     29.81    BRANCH LLOBREGAT
0.72746 165

CARD        H     32.00    HEADWATERS CARDENER
0.72749 175    0.035   24.73   0.2061  0.01    0.90    10      1.65

CARD        T     29.81    TRIBUTARY CARDENER
0.72746 165

LLOB        J     29.81    JUNCTURE CARDENER
0.72746 165    0.035   23.552  0.2061  0.01    0.90    10      1.65

LLOB        C     23.010   C1 BURES
0.72678 141    0.035   23.552  0.2061  0.01    0.90    10      1.65

LLOB        C     21.752   C2 BORRAS CANYON
0.72661 140    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     20.462   C3 LA BAUMA DES
0.72654 132    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     19.641   C4 LA BAUMA
0.72646 127    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     18.919   C5 C58
0.72649 125    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     17.805   C6 PUIG I FONT
0.72634 126    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     16.879   C7 MONTSERRAT
0.72626 119    0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     11.048   C8 CAIRAT
0.72553 80     0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     9.844    C9 LA PUDA
0.72550 75     0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     6.827    C10 CAN SEDO
0.72510 70     0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        C     2.974    C11 FINAL TURN
0.72492 63     0.035   24.73   0.2061  0.01    0.90    10      1.65

LLOB        E     0        END ABRERA
0.72452 57     0.035   24.73   0.2061                  10      1.65
```

TIME PERIOD FILE [KEY]

Time Period Name; First Day of Simulation Period; Last Day of Simulation Period; Number of points in time period average (usually 1); Dust Coefficient for simulation period; Ground reflectivity for simulation period; Calibration Factors by Time Period: Air temperature calibration constant, Air Temperature calibration coefficient, Wind speed calibration constant, Wind speed calibration coefficient.

```
TIME PERIOD FILE
  1-Jan    1    1    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  2-Jan    2    2    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  3-Jan    3    3    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  4-Jan    4    4    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  5-Jan    5    5    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  6-Jan    6    6    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  7-Jan    7    7    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  8-Jan    8    8    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
  9-Jan    9    9    1  0.1607  0.2269  0.0000  0.0000  0.0000  0.0000
 …
```

METEOROLOGY FILE [KEY]

Latitude (radians); elevation (m); Average annual air temp (°C); Description

Year; Time period name; Mean air temp; Mean wind speed; Relative humidity; %sunshine (no data); Solar radiation)

```
METEOROLOGY FILE: LLOBREGAT WATERSHED - 26 MAY 2011
          0.73032 210    14.1    Pont de Vilomara
   2009   1-Jan    6.7    0.7  0.916          50.2
          2-Jan    6.7    0.5  0.940          31.1
          3-Jan    7.7    0.9  0.859          28.8
          4-Jan    3.4    1.0  0.865          84.6
          5-Jan    2.4    1.7  0.819          72.2
          6-Jan    2.1    0.8  0.899          28.3
          7-Jan    0.5    1.0  0.863          70.3
          8-Jan   -1.2    0.8  0.830          84.0
          9-Jan    3.0    1.0  0.917          41.2…
```

HYDROLOGY DATA FILE [KEY]

River Name; Node; Distance upstream; Description

Year; Time Period Name; Discharge for time period; Temperature

```
HYDROLOGY DATA FILE: LLOBREGAT BASIN

LLOB         H        57.612 HEADWATERS BALSARENY
   2009   1-Jan   4.79   7.25
           2-Jan   4.84   7.10
           3-Jan   4.71   7.32
           4-Jan   4.63   6.66
           5-Jan   4.58   5.78
…
```

JOB CONTROL FILE [KEY]
Line 1. Title

Line 2. Subtitle

Line 3. Verification Tables. T if requested. F if otherwise.
Tables I-IX; I-III; I; III after M merged; III after O merged; III; IV-V, IV with missing hydrology flows added; V with lateral flows added; VI; VII; ***VIII Water Temperature Data****; IX Validation statistics; X Job Control; XI; All skeleton nodes; hydrology nodes; geometry nodes; composite network; B nodes; C;D;E;H;J;K;M;O;P;Q;R;S;T;V; Hydrology warning message suppression flag; Shade data file present; Global Shade model used; Regression need flag.*

Line 4. General Numeric Information
Number of years of historical data; years of synthetic data; First year (use 0); First year of historical data (use 0); Number of time periods per year; number of shade nodes; stream geometry nodes; hydrology nodes; study nodes; total number of nodes; number of nodes requiring regression analysis

Line 5. Node count information
Number of B nodes; C nodes; D nodes; E nodes; H nodes; J nodes; K nodes; M nodes; O nodes; P nodes

Line 6. Node count information and Time Period Output Sequence Numbers
Number of Q nodes; R nodes; S nodes; T nodes; V nodes; Starting year sequence number of output; Last year sequence number of output; First time period number (always 1); Last time period sequence number (365)

Line 7. Use-Supplied Parameters
User supplied evaporation factor EFA (default =40); User supplied evaporation factor EFB (default =15); User supplied evaporation factor EFC; User supplied Bowen ratio; 1st maximum daily air temperature regression coefficient; 2nd maximum daily air temperature regression coefficient; 3rd maximum daily air temperature regression coefficient; 4th maximum daily air temperature regression coefficient; Starting time period sequence number for air temperature correction; Last time period sequence number for air temperature correction

Line 8. Global Calibration Factors
Air temp calibration constant; air temp calibration coefficient; wind speed calibration constant; wind speed calibration coefficient; humidity calibration constant; humidity calibration coefficient; sunshine calibration constant; sunshine calibration coefficient; solar calibration constant; solar calibration coefficient

Line 9. Air Temperature Correction Factors
1st elevation; 1st factor; 2nd elevation; 2nd factor; 3rd elevation; 3rd factor; 4th elevation; 4th factor; 5th elevation; 5th factor

Line 10. Input File Names
Time period file name; Meteorology file name; Skeleton; Stream geometry file name; Study file name

Line 11. Input File Names
Hydrology node file name; Hydrology data file name; Shade file name

Line 12. Spatial Output Request by Stream Name
Local stream name for output; Starting distance for output; Ending distance for output

Lines 13-21. Template (unused)

```
JOB CONTROL FILE: LLOBREGAT  28 July
TEMPERATURE MODEL
TFFFFFFFFFFFTFFFFFFF                       FFFFTFFFFFFFFFFFFFFFFTTTT
     1.     0.     0.   365.     15.     18.     10.     6.     21.     0.
     1.    12.     1.     1.     2.     1.     0.     0.     0.     2.
     1.     0.     0.     1.     0.     1.     1.     1.   365.     0.
   0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000
   0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000
   0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000
KVRFTME.DAT    KVRFMET.DAT    dummy        KVRFSTR.DAT    KVRFSTD.DAT
KVRFHDR.DAT    KVRFHYD.DAT    KVRFSHD.DAT
LLOB              57.6    29.8
CARD              29.8   132.0
 STR. NAME #   3     0.0     0.0
 STR. NAME #   4     0.0     0.0
 STR. NAME #   5     0.0     0.0
 STR. NAME #   6     0.0     0.0
 STR. NAME #   7     0.0     0.0
 STR. NAME #   8     0.0     0.0
 STR. NAME #   9     0.0     0.0
 STR. NAME #  10     0.0     0.0
```

Output File for Data Verification Program TDATCHK

```
DATCHK Version 3.4 Results     Jul 28 2011   11:28
 Job Control File: kvrfjob.dat

 Checking Job Control File ***************************
 Successfully read   21 lines of   21 with    0 warnings.

 Checking Time Period File ***************************
 Successfully read  366 lines of  366 with    0 warnings.

 Checking Meteorology File ***************************
 Successfully read  367 lines of  367 with    0 warnings.

 Checking Stream Geometry File ***********************
 Successfully read   55 lines of   55 with    0 warnings.

 Checking Study File ********************************
 Successfully read    7 lines of    7 with    0 warnings.

 Checking Hydrology Node File ***********************
 Successfully read   11 lines of   11 with    0 warnings.

 Checking Hydrology Data File ***********************
 Successfully read  3671 lines of  3671 with    0 warnings.

 Checking Shade File ********************************
 Successfully read   76 lines of   76 with    0 warnings.

 Cross Checking Nodes *******************************

 CARD       H    32.0 HEADWATERS CARDENER              OK
 CARD       T    29.8 TRIBUTARY CARDENER               OK
 LLOB       B    29.8 BRANCH LLOBREGAT                 OK
 LLOB       C    49.1 CA SOLERVICENC                   OK
 LLOB       C    23.0 C1 BURES                         OK
 LLOB       C    21.8 C2 BORRAS CANYON                 OK
 LLOB       C    20.5 C3 LA BAUMA DES                  OK
 LLOB       C    19.6 C4 LA BAUMA                      OK
 LLOB       C    18.9 C5 C58                           OK
 LLOB       C    17.8 C6 PUIG I FONT                   OK
 LLOB       C    16.9 C7 MONTSERRAT                    OK
 LLOB       C    11.0 C8 CAIRAT                        OK
 LLOB       C     9.8 C9 LA PUDA                       OK
```

```
LLOB          C     6.8 C10 CAN SEDO                          OK
LLOB          C     3.0 C11 FINAL TURN                        OK
LLOB          D     2.6 AIGUES DE TERRASSA                    OK
LLOB          E     0.0 END ABRERA                            OK
LLOB          H    57.6 HEADWATERS BALSARENY                  OK
LLOB          J    29.8 JUNCTURE CARDENER                     OK
LLOB          P    19.5 POINT DISCHARGE CAS WWTP              OK
LLOB          P    15.1 POINT DISCHARGE MON WWTP              OK
LLOB          Q    23.9 CASTELLBELL                           OK

Node cross check completed with    0 warnings.

Cross Checking Time Periods ************************

Time period check completed with    0 warnings.
```

Appendix F. Field Work for Shading Estimates

The field work familiarized me with important stream features. For example, I learned that the stream temperature gage at Castellbell was not at the location of the UTM coordinates provided. Neither was the temperature gage, which was several hundred meters downstream from the Castellbell discharge gage.[124] Below is the template form used during the collection of field data.

Node/Waypoint	
Name	
UTM X	
UTMY	
Radians	
Comments	

C Node: ☐ Topographic ☐ Vegetation

Number & Description	
UTM X	
UTMY	
Latitude (radians)	
Stream width (m)	
Stream reach azimuth (radians)	

West Side

Topographic Altitude (degrees)	
Vegetation crown diameter (m)	
Vegetation height: water to top (m)	
Offset: trunk to water (m)	
Continuity of vegetation (%)	
Screening factor (%)	
Min/Max Density (%)	

East Side

Topographic Altitude (degrees)	
Vegetation crown diameter (m)	
Vegetation height: water to top (m)	
Offset: trunk to water (m)	
Continuity of vegetation (%)	
Screening factor (%)	
Min/Max Density (%)	

---

[124] For photographs during field work along the Llobregat River see: https://picasaweb.google.com/jhoney/LlobregatRiverSegment?authkey=Gv1sRgCIyulbGwtI613wE#

Appendix G. Calibration of SNTEMP Model

The uncalibrated model predicted stream temperatures that were too warm throughout the year. This indicated that a cool effect in the watershed was not accounted for. This might be from the Gavarresa tributary that flows into the Llobregat. The Gavarresa is the only significant tributary not accounted for in the model because temperature data was not available.

The air temperature coefficient was the only parameter used to calibrate the model. Calibration was coded into the time period file (KVRFTME.DAT) to allow for seasonal adjustments. During the winter, from November to February, the air temperature calibration coefficient was 0.25. During the peak summer months of June to September it was 0.9. In the remaining months the air temperature calibration coefficient was 0.5.

Figure G.1 Observed and predicted temperature values with calibrated and uncalibrated Stream Network Temperature Model for the Llobregat River in 2009.

Appendix H. Full Results for SNTEMP

In the period in which EDR modules operated (March to October) the calibrated model predicted stream temperatures with a mean error of 0.53°C, while for the entire year the model error was 1.23°C.

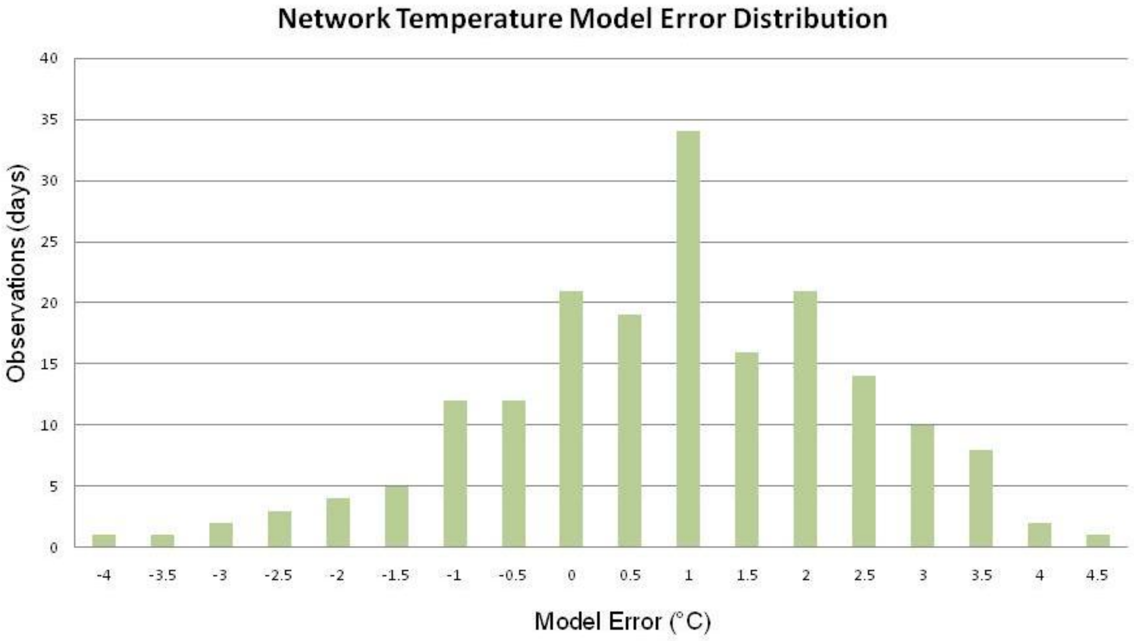


Figure H.1 Network Temperature Model Error Distribution.

	Restorable Areas to 40%	Restorable Areas to 60%	Restorable Areas to 80%	All Areas to 80%	All Areas to 100%	No Coverage
Mean	-0.264	-0.513	-0.764	-1.068	-1.427	0.424
Mean (°C/km)	-0.005	-0.009	-0.013	-0.019	-0.025	0.007
Minimum	-0.580	-1.090	-1.610	-2.190	-2.920	-0.160
Maximum	0.070	0.150	0.220	0.340	0.460	0.850
SD	0.147	0.286	0.427	0.612	0.821	0.247

Table H.1 Summary statistics of temperature changes from scenarios that modified riparian shading.

	5%	25%	50%	100%	200%
Mean	-0.048	-0.227	-0.293	-0.585	-0.773
Mean °C/km	-0.001	-0.004	-0.005	-0.010	-0.014
Minimum	-0.130	-0.580	-1.100	-2.400	-3.210
Maximum	0.100	0.510	0.870	1.030	1.220
SD	0.034	0.152	0.268	0.577	0.736

Table H.2 Summary statistics of temperature changes from scenarios that increased stream discharge.

	Restorable40%	Restorable60%	Restorable80%	80%	100%	No Coverage
Annual	-0.26	-0.51	-0.76	-1.07	-1.43	0.42
March-October	-0.34	-0.65	-0.97	-1.38	-1.84	0.54

Table H.3 Temperature change (°C) associated with vegetation scenarios.

	5%	25%	50%	100%
Annual	-0.04	-0.18	-0.35	-0.70
March-October	-0.04	-0.19	-0.36	-0.65

Table H.4 Temperature change (°C) associated with discharge scenarios

Threshold Crossings

I correct for bias in my tabulation of threshold crossings with the regression equation that gave me the relationship between modeled and observed observations (Fig 4.4). This quantified the bias of my model.

Equation (1): Modeled temperature=0.8068(observed temperature) + 4.335.

I solved for observed temperature:

(2) Observed temperature = (Modeled Temperature – 4.355)/ 0.8068.

These updated temperature (or predicted temperature) account for the model bias and therefore were more appropriate for my estimation of threshold crossings.

	Temperature Threshold (°C)									
	12°	14°	16°	18°	20°	22°	24°	26°	Total Days	Euros/ year
Restorable 40%	4	12	6	1	5	15	9	5	57	€57,000
Restorable 60%	8	20	14	4	8	22	17	10	104	€104,500
Restorable 80%	12	26	21	7	15	35	26	14	156	€156,000
100%	30	39	28	17	40	64	44	20	283	€283,000
No Coverage	-2	-7	-9	-8	-5	-12	-23	-13	-79	(€79,000)

Table H.5 Avoided threshold crossings (in days) and their estimated economic value (Euros) associated with each of the five shading scenarios increases in stream shading.

	Temperature Threshold (°C)									
	12°	14°	16°	18°	20°	22°	24°	26°	Total Days	Euros/ Year
5%	2	1	2	0	0	0	1	1	7	€6,250
25%	7	9	5	0	2	9	4	4	40	€40,000
50%	8	17	8	2	5	15	10	10	75	€75,000
100%	15	26	11	4	12	21	13	18	120	€85,000

Table H.6 Avoided threshold crossings (in days) and their estimated economic value (Euros) from increases in stream discharge.

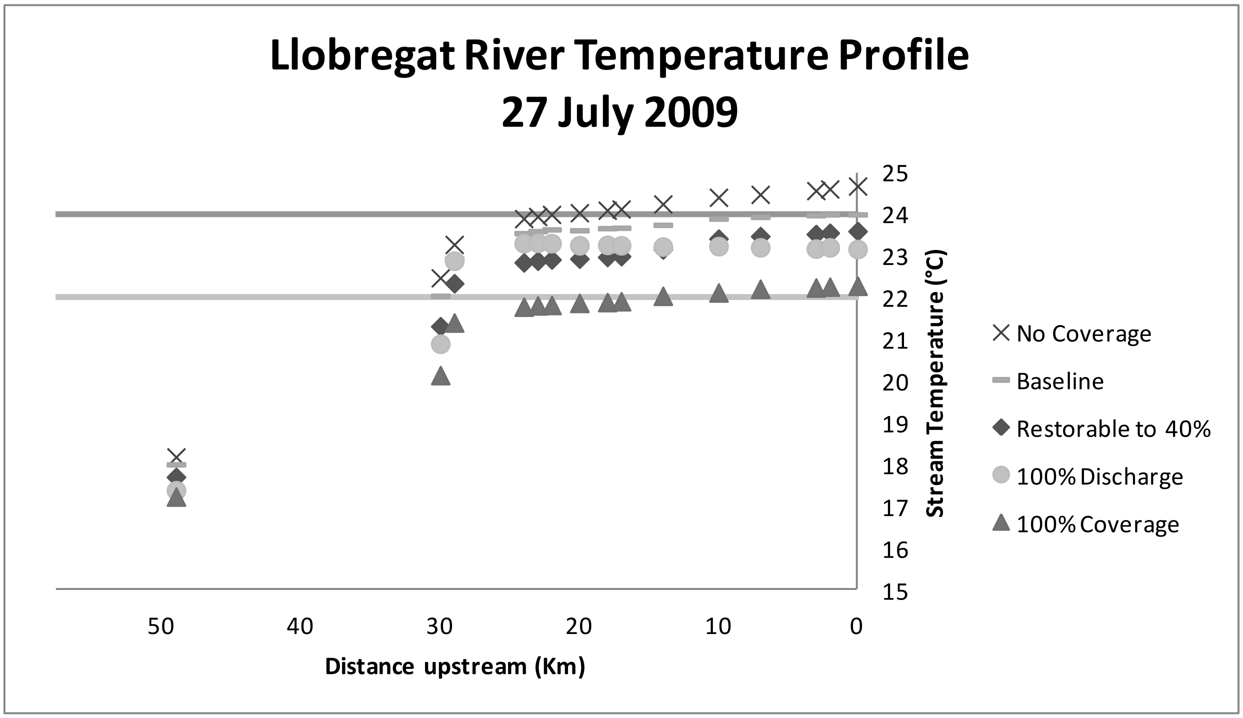


Figure H.2 Temperature Profile 27 July 2009.

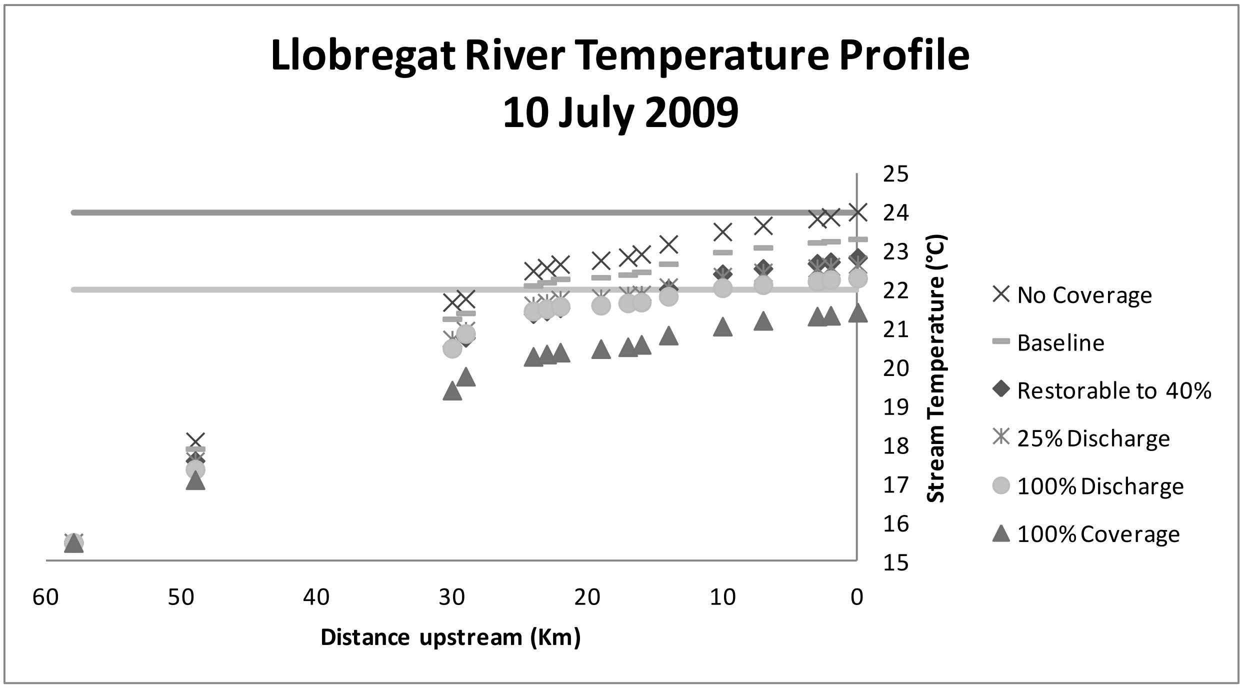


Figure H.3 Temperature Profile 10 July 2009.

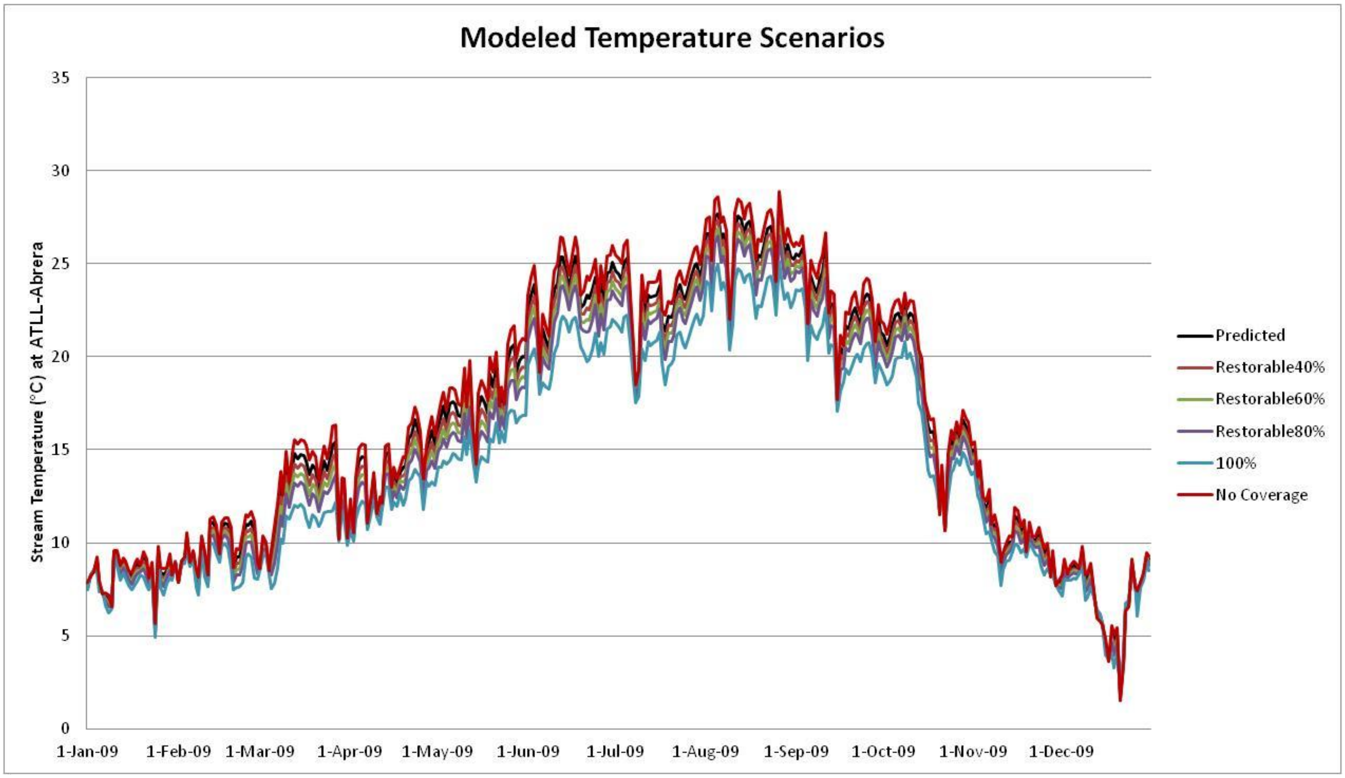


Figure H.4 Stream temperature according to the revegetation scenarios.

Appendix I. Notes on Scale Selection for SNTEMP

The results are sensitive to the length of stream segment studied, since most of the thermal heating occurs in the first half of the stream segment between Balsareny and the stream juncture with the Cardener. As noted in the Main Text, temperatures rise more rapidly at first, and then more gradually in the second half of the segment. In this second half, between Castellbell and Abrera temperatures rise an average only 1.35°C over this 29 km reach. This is an average of 0.06°C/km, which is the lowest of the reaches studied. In contrast, the upper segment between Sallent and Castellbell, temperatures rise on average 0.11°C/km -- nearly double the thermal change in the lower half.

Three factors probably amplify the effect of stream shading in the upper reaches of the watershed. First the stream width is narrower, which allows for shading to cover a larger proportion of the stream. Second, the stream volume is smaller, and larger streams are less sensitive to changes in shading conditions (Seedang et al. 2008, Chan et al. 1998). Third, temperatures higher in the watershed are cooler to begin with, so shading helps the stream remain cool. Once the warming has taken place, shading has a much smaller impact on downstream values. This implies that restoration in the upper half of the stream segment would yield greater thermal protection than restoration in the lower reaches.

It is worth mentioning that the temperature rise on the Llobregat River is relatively small when compared to other streams globally. The rate of increase for small streams has been reported as 0.6°C/km (Zwieniecki and Newton 1999), intermediate streams 0.2°C/km (Cassie 2006) while larger streams 0.09 °C/km (Torgerson et al. 2001). This would place the Llobregat with an average thermal gain per kilometer closer to large streams, even though its discharge is more like an intermediate, or small stream.

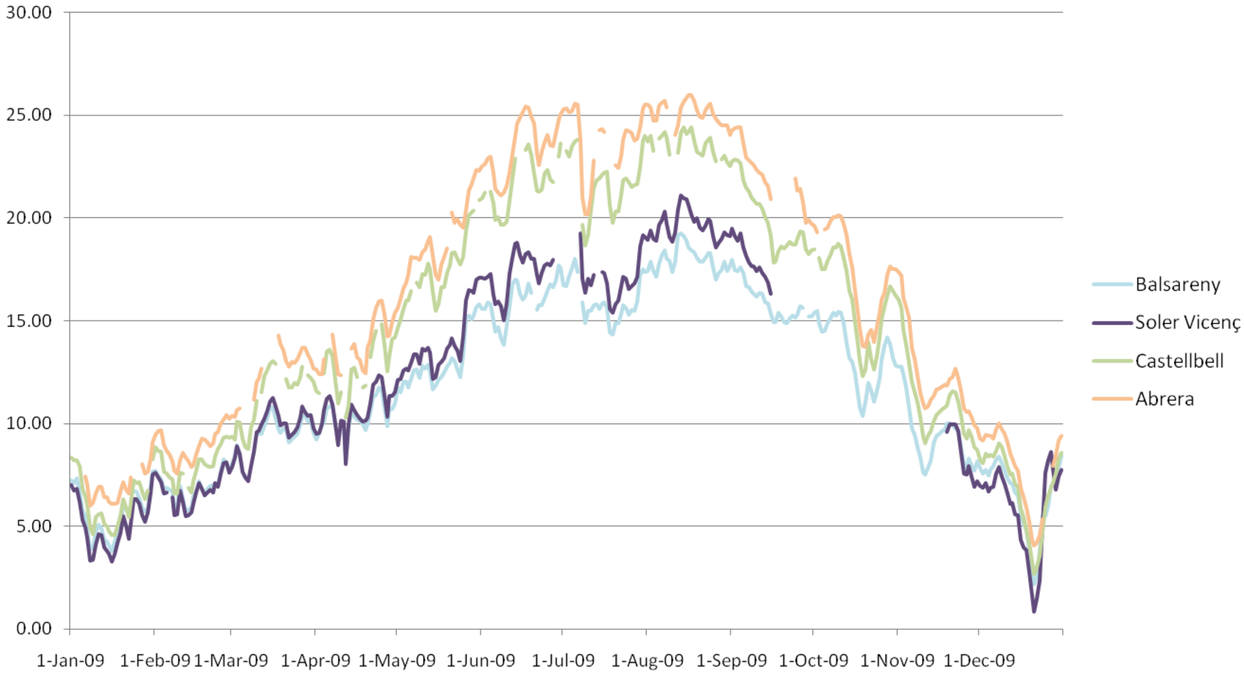


Figure I.1 Observed stream temperature values in the Llobregat River during 2009.

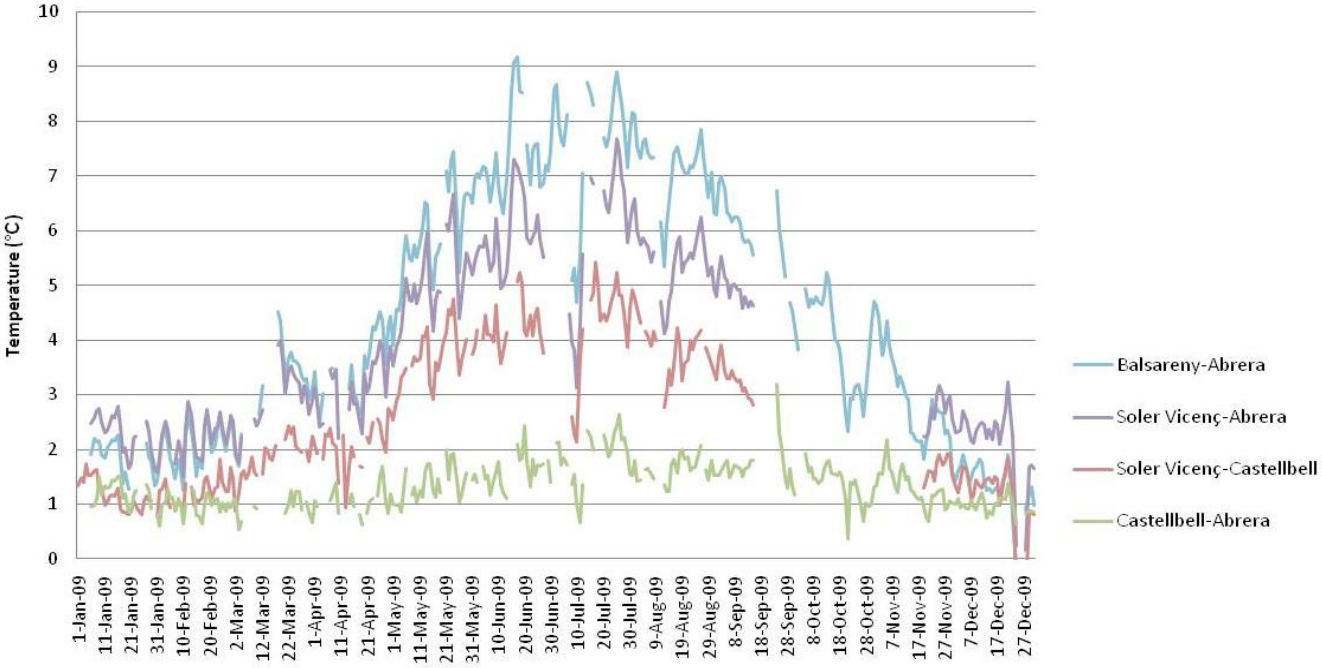


Figure I.2 Temperature differences between upstream and downstream gages.

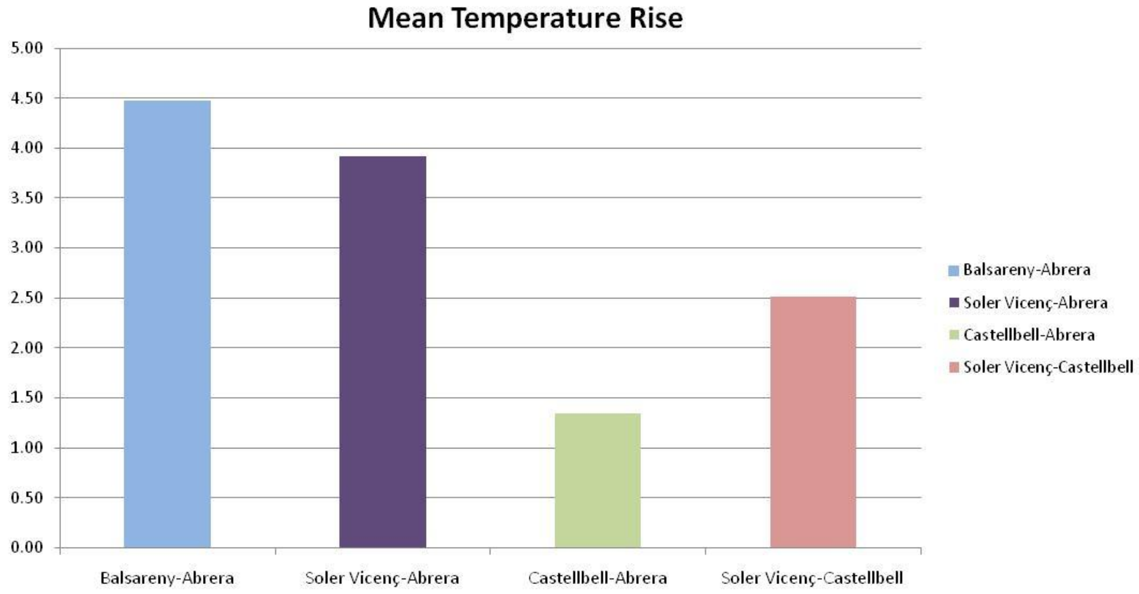


Figure I.3 Mean Temperature Rise (°C/km) between downstream and upstream gages.

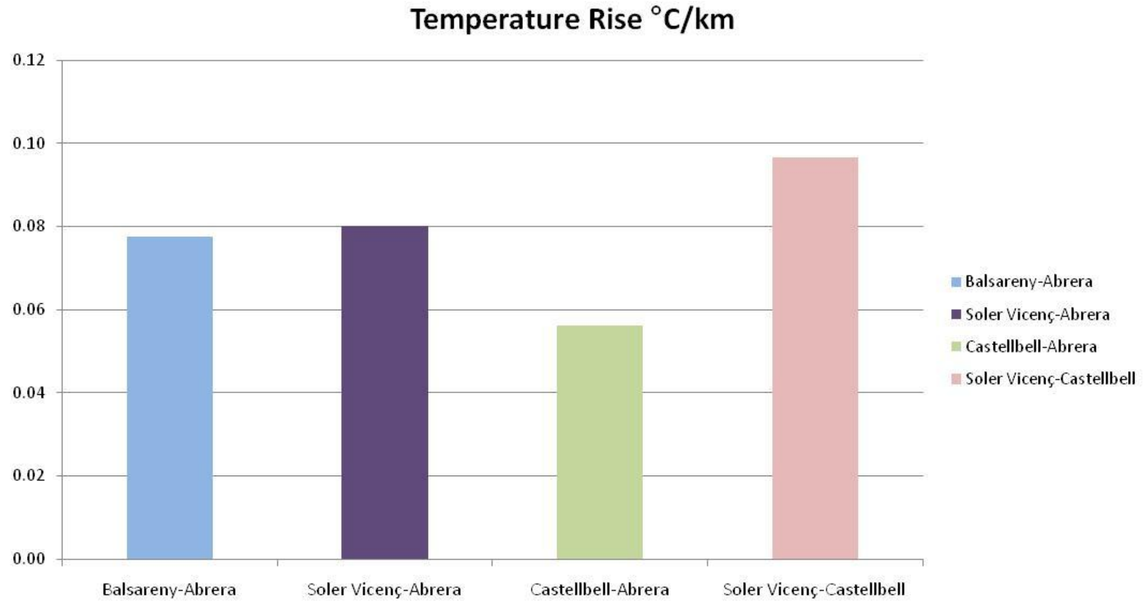


Figure I.4 Mean Temperature Rise (°C/km) between downstream and upstream gages.

Appendix J. Stream Segment Model (SSTEMP)

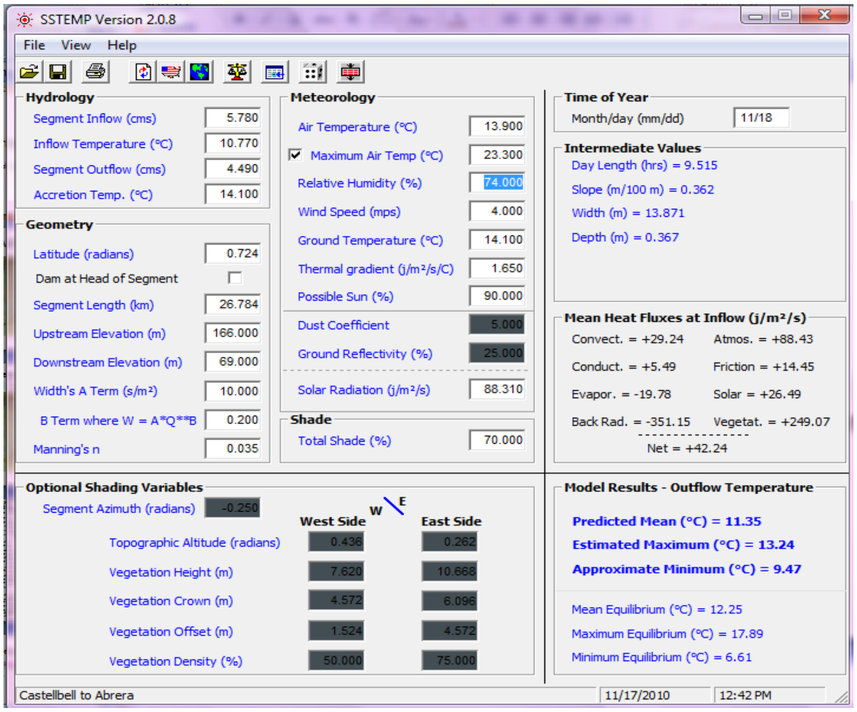
Prior to using the SNTEMP model as presented in the Main Text, I used the Stream Segment Model (SSTEMP) to make a preliminary approximation regarding the potential impact of increased shading and discharge on stream temperature. The Segment Model was designed to be a simplified and scaled down version of SNTEMP (Bartholow 2004). The Segment Model includes a Windows interface to that allows users to enter input variables and estimate downstream temperatures for a one day period. The Segment Model uses the same mathematical equations as the original Network Model but does not allow for mixing (tributaries, diversions or point source contributions), nor does it permit changes to geographic, topographic or vegetative conditions within the segment.

The stream segment studied in the SSTEMP model was shorter (23.932 km) than the studied reach in the Main Text. The segment began at the discharge measurement gage in Castellbell i el Vilar and ended at the ATLL drinking water treatment facility. This segment begins 53 km downstream of the Baells dam and 4.5 km downstream from the Llobregat's confluence with the Cardener River. This reach is fed by only small tributaries, most of which flow only during storm events. This segment has nine water diversions to hydroelectric generators. These diversions are, in order moving downstream: Burés, Borràs, La Bauma, Puig i Font, Comes, Gomis, El Cairat, Can Sedó, and Catex Moli. Two waste water treatment facilities discharge along this segment, one at Castellbell i el Vilar, and a second at Monistrol de Montserrat. The stream segment ends 29 km upstream of its terminus point in the Mediterranean.

Just like SNTEMP, SSTEMP calculates the heat gained or lost from a parcel of water as it passes through a stream segment. The model simulates heat flux processes such as convection, conduction, evaporation, direct solar radiation (short wave), heat from the air (long wave radiation), and radiation back from the water (see Main Text).

I collected data with a mean daily time step for the period 1 January 2004 to 15 November 2010 (n=2,526). Meteorological data was obtained from the same weather station in the town of el Pont de Vilomara (406310, 4617994 UTM), operated by the Catalan Meteorological Service, and 7.5 kilometers north of the river segment. Hydrologic and stream temperature data was downloaded from the Catalan Water Agency (ACA).

The Segment Model was designed to produce mean daily outputs one day at a time (Fig M.1). A utility allowed me to run several observations in a single operation, but only if all input parameters had data. When removing days in which information was incomplete, the final data set included 1,470 days.



Hydrology

Segment Inflow (cms) 5.780
Inflow Temperature (°C) 10.770
Segment Outflow (cms) 4.490
Accretion Temp. (°C) 14.100

Geometry

Latitude (radians) 0.724
Dam at Head of Segment ☐
Segment Length (km) 26.784
Upstream Elevation (m) 166.000
Downstream Elevation (m) 69.000
Width's A Term (s/m²) 10.000
B Term where W = A*Q**B 0.200
Manning's n 0.035

Meteorology

Air Temperature (°C) 13.900
☑ Maximum Air Temp (°C) 23.300
Relative Humidity (%) 74.000
Wind Speed (mps) 4.000
Ground Temperature (°C) 14.100
Thermal gradient (j/m²/s/C) 1.650
Possible Sun (%) 90.000
Dust Coefficient 5.000
Ground Reflectivity (%) 25.000
Solar Radiation (j/m²/s) 88.310

Shade

Total Shade (%) 70.000

Time of Year

Month/day (mm/dd) 11/18

Intermediate Values

Day Length (hrs) = 9.515
Slope (m/100 m) = 0.362
Width (m) = 13.871
Depth (m) = 0.367

Mean Heat Fluxes at Inflow (j/m²/s)

Convect. = +29.24
Atmos. = +88.43
Conduct. = +5.49
Friction = +14.45
Evapor. = -19.78
Solar = +26.49
Back Rad. = -351.15
Vegetat. = +249.07
Net = +42.24

Optional Shading Variables

Segment Azimuth (radians) -0.250

	West Side	East Side
Topographic Altitude (radians)	0.436	0.262
Vegetation Height (m)	7.620	10.668
Vegetation Crown (m)	4.572	6.096
Vegetation Offset (m)	1.524	4.572
Vegetation Density (%)	50.000	75.000

Model Results - Outflow Temperature

Predicted Mean (°C) = 11.35
Estimated Maximum (°C) = 13.24
Approximate Minimum (°C) = 9.47

Mean Equilibrium (°C) = 12.25
Maximum Equilibrium (°C) = 17.89
Minimum Equilibrium (°C) = 6.61

Castellbell to Abrera
11/17/2010
12:42 PM

Figure J.1 The user interface for the Segment Model (SSTEMP). Users adjust conditions concerning time of year, hydrology, geometry, meteorology, and shade. The model predicts mean temperature values at the end of the stream segment given these conditions (lower right).

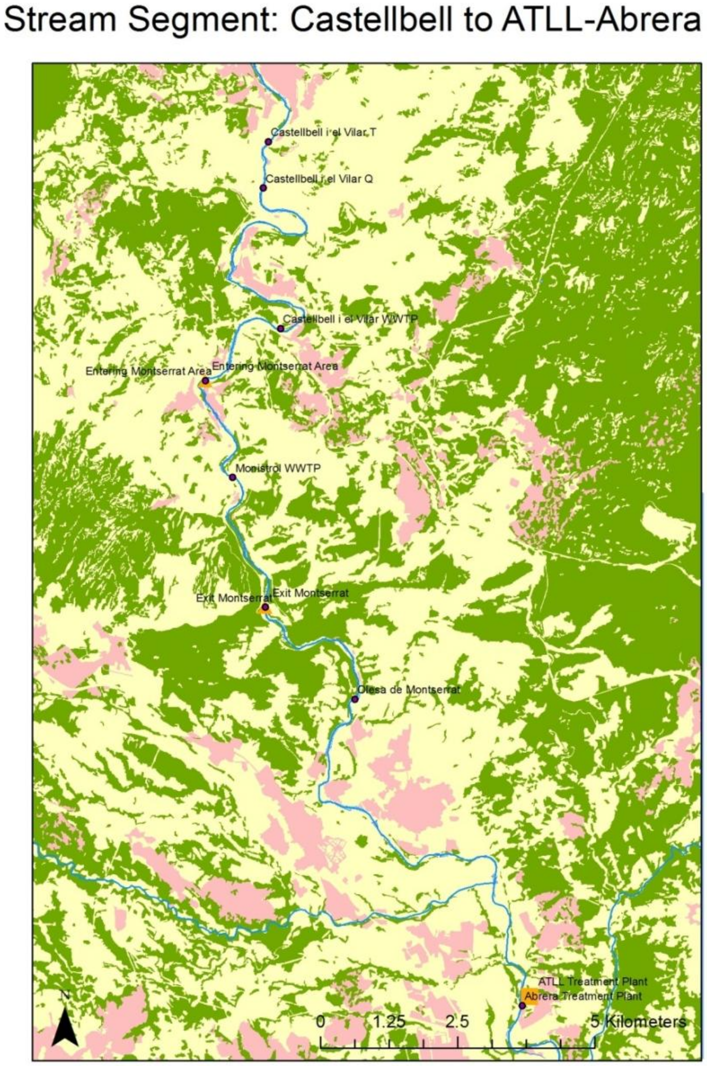


Figure J.2 Stream reach studied for the Stream Segment Temperature Model (SSTEMP).

SSTEMP Results

The Segment Model predicted downstream temperature with a mean error of -1.53 °C (Fig M.3). Over 40% of the predicted temperatures were within 1 °C of the observed values.

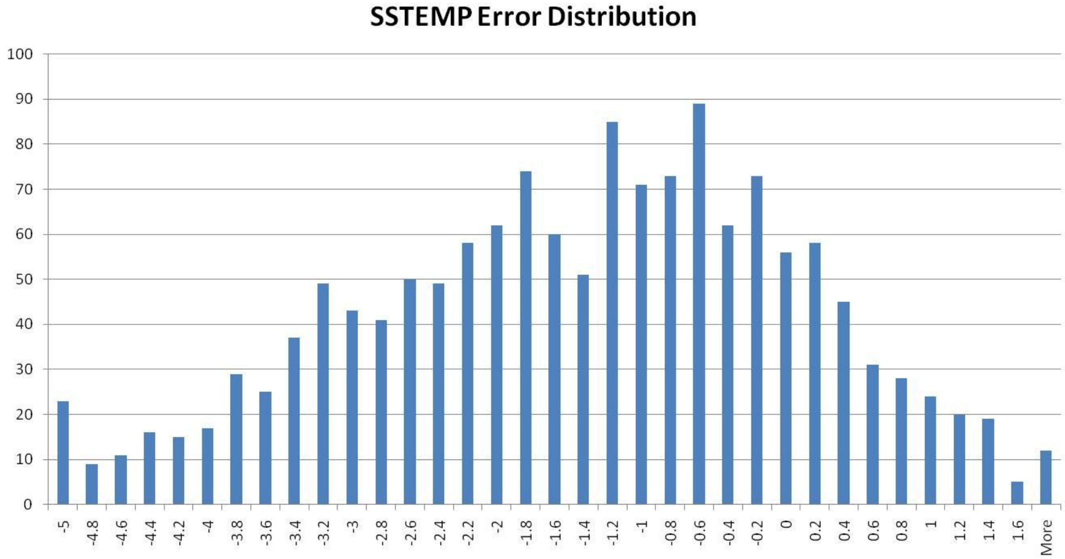


Figure J.3 The error distribution of the Segment Model during 2004-2010. Error measured in °C.

The Segment Model underestimated temperature values at the ATLL-Abrera water treatment facility, especially during summer months. The most accurate results were during 2009 and 2010, while the error increased in the earlier years (Fig M.4).

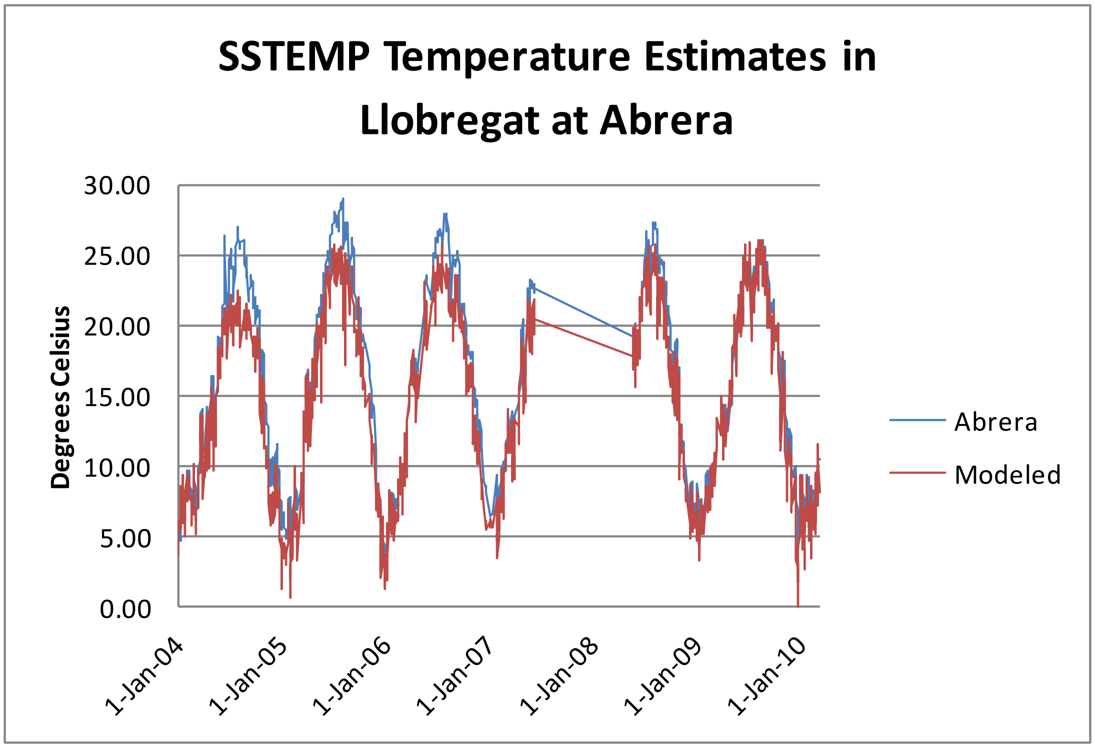


Figure J.4 Observed temperature (blue) and modeled values (red) with the Stream Segment Temperature model. Gaps show periods where input parameters were not available in the ACA water temperature data set, most notably in late 2007 and early 2008.

The Segment Model makes bold assumptions concerning the entire stream segment, and yet it succeeded in estimating downstream temperatures under a wide range of meteorological and hydrological conditions. The observed and modeled scatter plot shows a tight correlation (Pearson Correlation Coefficient= 0.975, R^2= 0.9249) albeit with a consistent underestimate (Fig M.5).

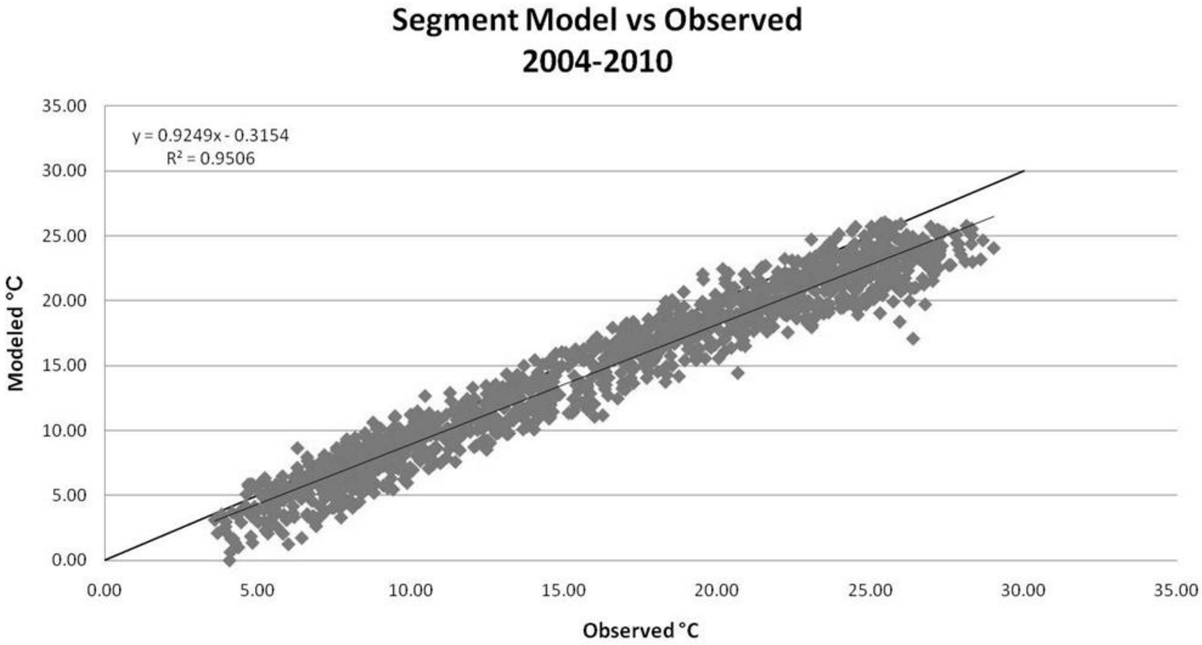
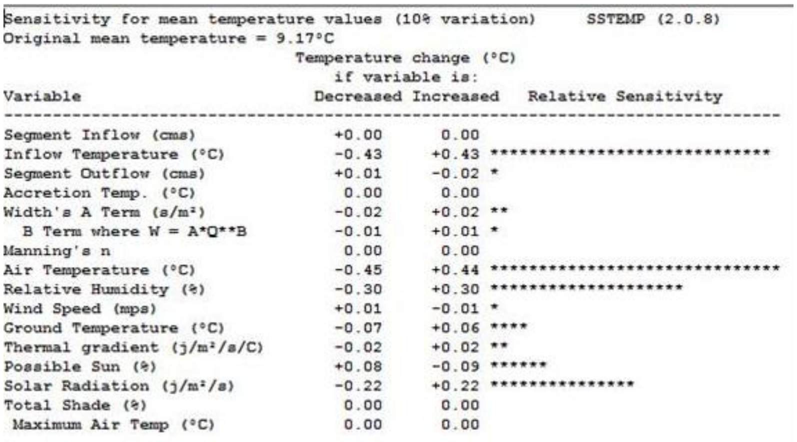


Figure J.5 The Segment Model underestimated downstream temperature values across a wide range of seasonal conditions.

The consistent underestimation by Segment Model suggests that certain factors contributing to stream heating which were not being incorporated into the model. These sources of heat may include the influx of urban waste water, or the diversion of water into the hydroelectric channels.

The Segment Model also includes a tool to conduct a sensitivity analysis. The Segment Model was most sensitive to inflow temperature, air temperature, relative humidity and solar radiation (Fig M.6). The model's sensitivity to these parameters is consistent with other stream temperature models (Bartholow 1989). In contrast, the parameters of most interest for this research, total shading and segment inflow, showed that they had little influence over temperature. A variation in 10% of both of these parameters made no difference in output temperature, according to the Segment Model sensitivity analysis.



```
Sensitivity for mean temperature values (10% variation)     SSTEMP (2.0.8)
Original mean temperature = 9.17°C
                              Temperature change (°C)
                                  if variable is:
Variable                        Decreased Increased   Relative Sensitivity
---------------------------------------------------------------------------------
Segment Inflow (cms)              +0.00       0.00
Inflow Temperature (°C)           -0.43      +0.43 ******************************
Segment Outflow (cms)             +0.01      -0.02 *
Accretion Temp. (°C)               0.00       0.00
Width's A Term (s/m²)             -0.02      +0.02 **
  B Term where W = A*Q**B         -0.01      +0.01 *
Manning's n                        0.00       0.00
Air Temperature (°C)              -0.45      +0.44 *******************************
Relative Humidity (%)             -0.30      +0.30 ********************
Wind Speed (mps)                  +0.01      -0.01 *
Ground Temperature (°C)           -0.07      +0.06 ****
Thermal gradient (j/m²/s/C)       -0.02      +0.02 **
Possible Sun (%)                  +0.08      -0.09 ******
Solar Radiation (j/m²/s)          -0.22      +0.22 ***************
Total Shade (%)                    0.00       0.00
 Maximum Air Temp (°C)             0.00       0.00
```

Figure J.6 Sensitivity Analysis for Segment Model showing that output results are most sensitive to inflow temperature, air temperature, relative humidity and solar radiation.

Riparian Shading in Segment Model

The Segment Model had a baseline shade estimate of 10% for the entire segment. To test the possible influence of riparian vegetation on stream temperature, I ran the Segment Model with the same conditions but with an increased total shading estimate of 30%. This modification simulated temperature values with an increase in riparian shading.

However the simulated temperatures influenced my modeled results, not observed values. To estimate the real temperature reduction on the observed values, I used the linear regression equation derived from Figure M.5 that plotted the relationship between observed and modeled values.

Equation (1) $Y=0.9249x - 0.3154$

I ran the modeled temperature values through equation (1) under both normal conditions and simulated conditions. The difference between these temperature values was my new estimate of temperature reductions. I then subtracted the temperature reductions from the observed temperature values. Finally, I counted the number of days the treatment facility would have remained below the temperature thresholds of 12°C, 14°C, 16°C, 18°C, 20°C, 22°C, 24°C and 26 °C.

The simulation suggests that increased shading moderated stream temperature sufficiently to prevent a temperature threshold crossing on 280 of 1,470 days (19%), with an average of 65.5 days per year. The simulation also suggests that an increase in shading would prevent the more threshold crossings in warmer conditions, especially around 24 °C.

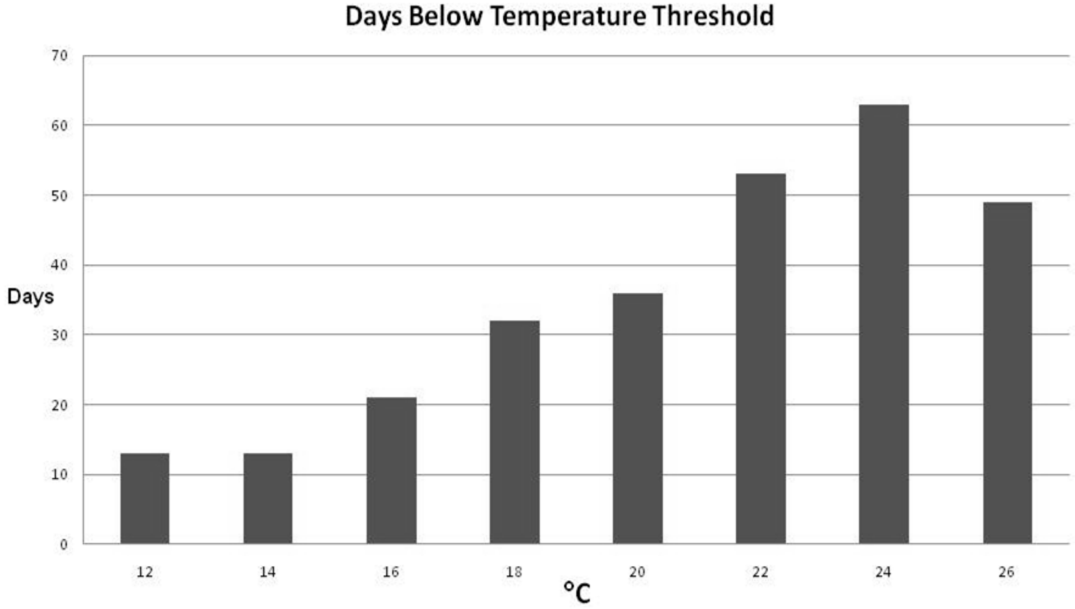


Figure J.7 Number of days water treatment facility will avoid crossing the temperature thresholds with an increase in riparian shading to 30%.

Simulating Increased Instream Flows in the Segment Model

Discharge volumes in the Llobregat River are regulated by three dams: Baells, Sant Ponç, and Llosa del Cavall. In addition, water flow is diverted to generate hydroelectric power at abandoned textile mills. These diversions reduce flows in the main channel of the Llobregat. The low flows are disruptive to the aquatic ecosystem and may contribute to thermal heating. Currently the Catalan Water Agency is taking steps to regulate minimum instream flows and oblige the owners of the hydroelectric generators to reduce their diversions.

With the Segment Model I simulated temperature values with increased flow through the main channel. For a first approximation, I simulated the doubling of discharge values. On a day by day basis, the model could also generate stream temperature profiles under various discharge conditions.

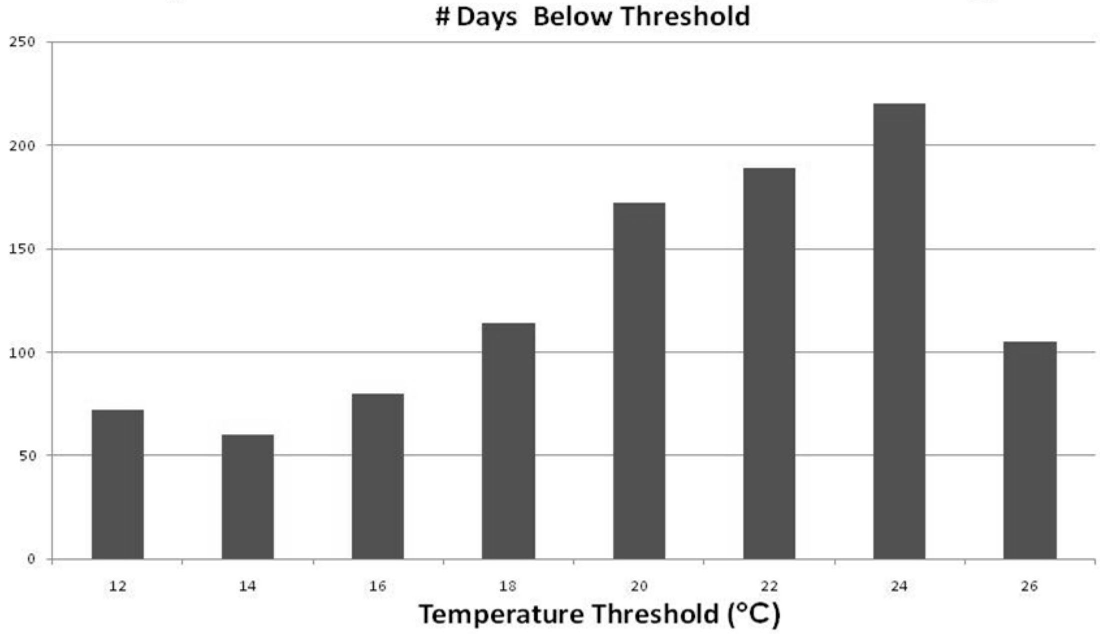


Figure J.8 Number of days in which simulated stream temperatures would not pass critical threshold values due to an increase in stream discharge.

The simulated increase in discharge moderated thermal heating, preventing threshold crossings on 1,012 days (68%), averaging 253 crossings avoided per year. Using the same assumptions as before, this simulated increase in discharge could generate savings of approximately €253,000 per year for the ATLL-Abrera water treatment facility.

Economic Value of Ecosystem Services

Each of the nine EDR modules at the ATLL-Abrera water treatment facility costs approximately €1,000 to operate per day.[125] We can approximate the value of the shading service ($V_{\text{Shading or Discharge}}$) by estimating the number of days (N) in which we avoid the cost an additional module (C_{Module}):

$$V_{\text{Shading or Discharge}} = N_{\text{Days}} * C_{\text{Module}}$$

The simulation suggests the ATLL-Abrera facility would avoid crossing the temperature threshold on average 70 days per year. An EDR module costs approximately €1,000 per day to operate, therefore the shading service under these conditions would be €70,000 per year.

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[125] The modules consume approximately 12,000 kWh per day, at a rate of 0.09 €/kWh.

Appendix K. Stream Network Model from Castellbell to Abrera

Before running the final version of the Stream Network Model presented in the Main Text, I ran a Stream Network Model that considered a smaller reach between Castellbell and Abrera (23.9 km). This model also originally included the nine water diversions by the various hydropower generators. This iteration of the Network Model consisted of 34 nodes when including all the hydroelectric diversions (Appendix 10 Figure 1). When the hydroelectric diversions were removed, the simplified network contained 13 nodes. Data on stream discharge must be provided for nodes Headwaters (H), Diversion (D), Point Source (P), and End (E). Temperature data must be provided for Headwaters (H), and Point Source (P).

Figure K.1 A schematic representation of the complete and simplified Stream Network Model between the headwaters in Castellbell i el Vilar to the ATLL Water Treatment Plant in Abrera.

Figure K.2 Restorable stream segments. Areas in Red have less than 30% stream cover and have the topographic conditions that would make riparian restoration plausible.

Results SNTEMP Model: Castellbell to Abrera

The simplified Network Model overestimates downstream temperature by an average of 2.14 °C. During the months in which the EDR system operates, from March to October, the overestimate is reduced to 1.37 °C. The overestimate is particularly strong in the winter months, which are less relevant for this study.

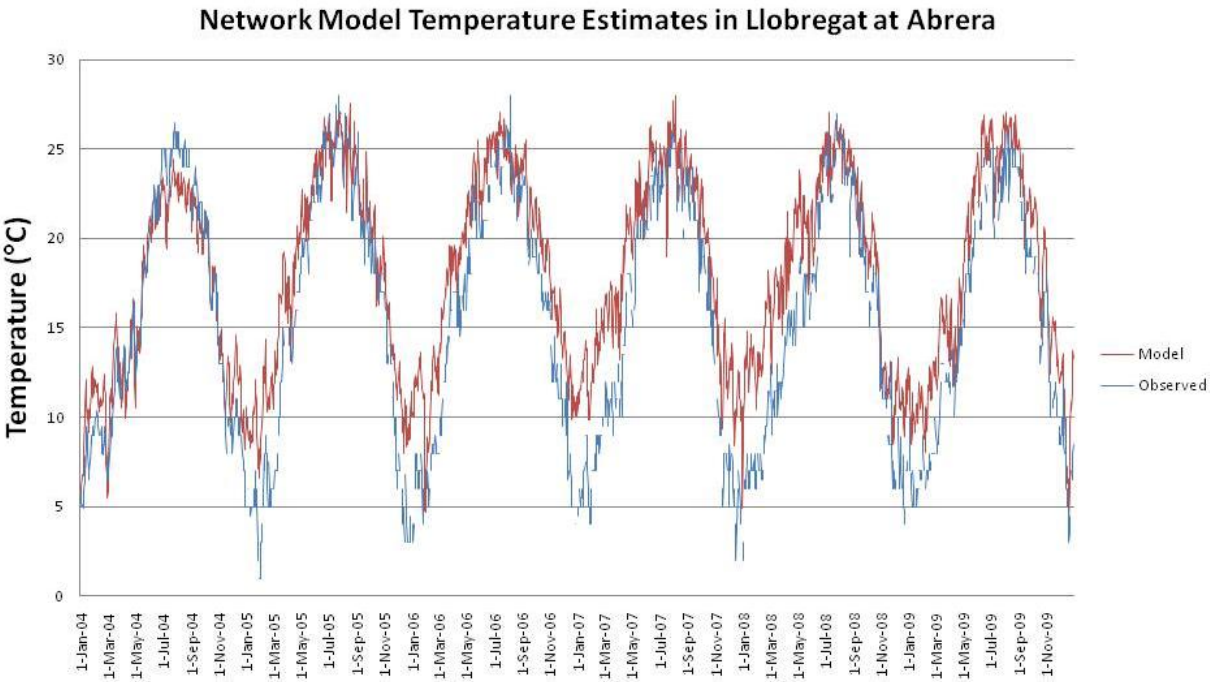

Figure K.3 Modeled and observed temperature values during the period 2004-2009

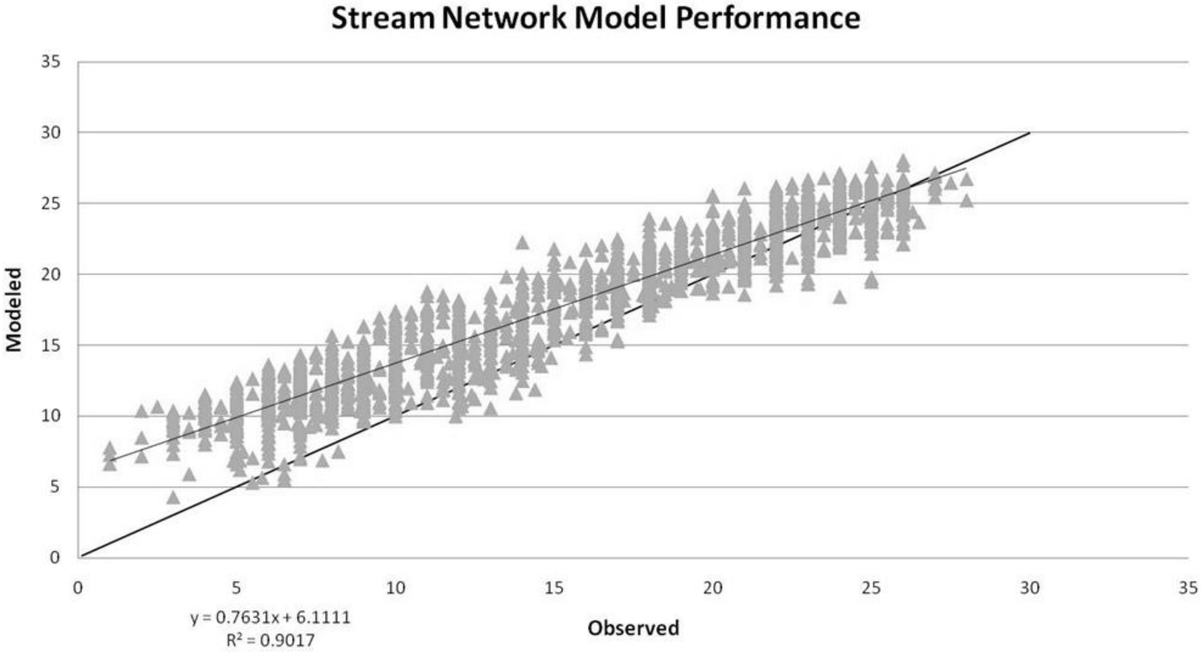

Figure K.4 A comparison of observed temperature values with modeled values predicted by Network Model at the end of the stream network. The Network Model shows a tight correlation but also overestimates values.

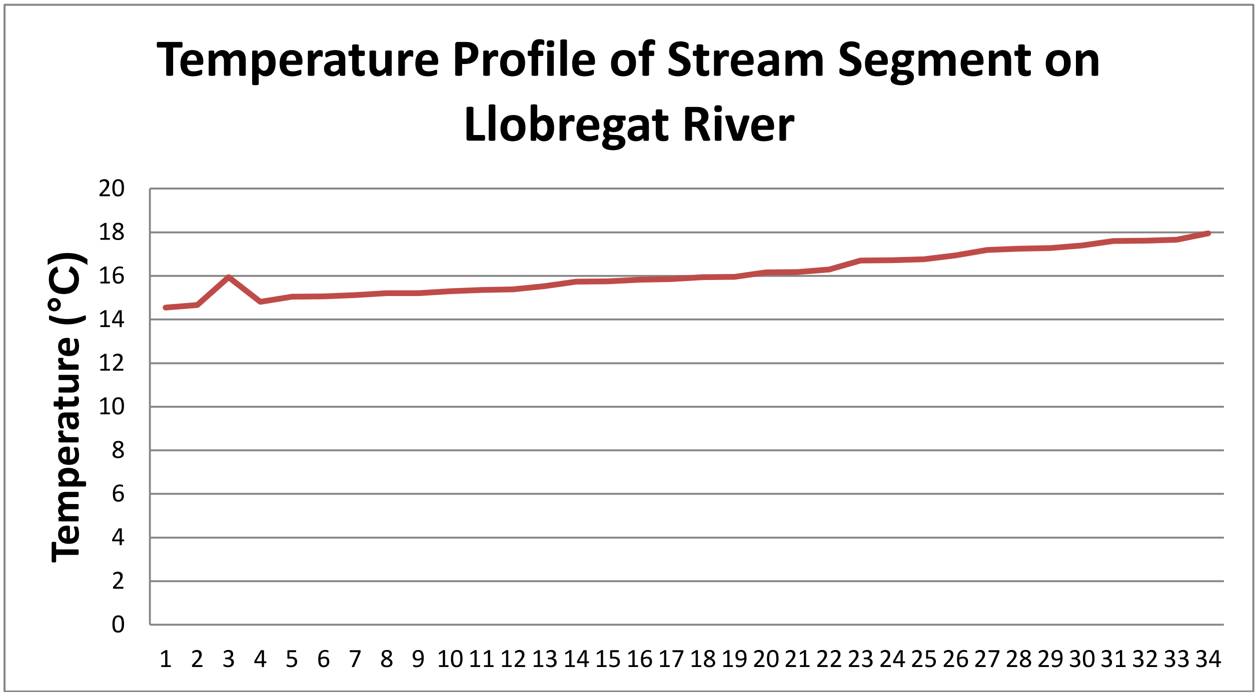

Figure K.5 Temperature profile of the SNTEMP model moving downstream from the first node H to the end node. The spike at point 3 is attributable to a node located after a water diversion. At this location there is little discharge in the main channel and the model estimates a high stream temperature. This high temperature disappears once the diverted water is returned to the main channel. I have verified that the rise in temperature on node 3 only occurs when the diversion upstream takes nearly all the flow from the main channel.

Table K.1 Changes in Riparian Shading

Scenario	**Vegetation Change**	**Mean Temperature Change (°C)**	**Mean Temperature Change (°C) From March to October**
1	Restorable segments increased to 40% coverage (most realistic scenario)	-0.08	-0.10
2	All segments at least 40% coverage	-0.14	-0.17
3	All segments increased to 80% vegetation coverage	-0.55	-0.69
4	All segments increased to 100% vegetation coverage	-0.77	-0.96
5	Stream vegetation removed or 0% coverage	0.32	0.40

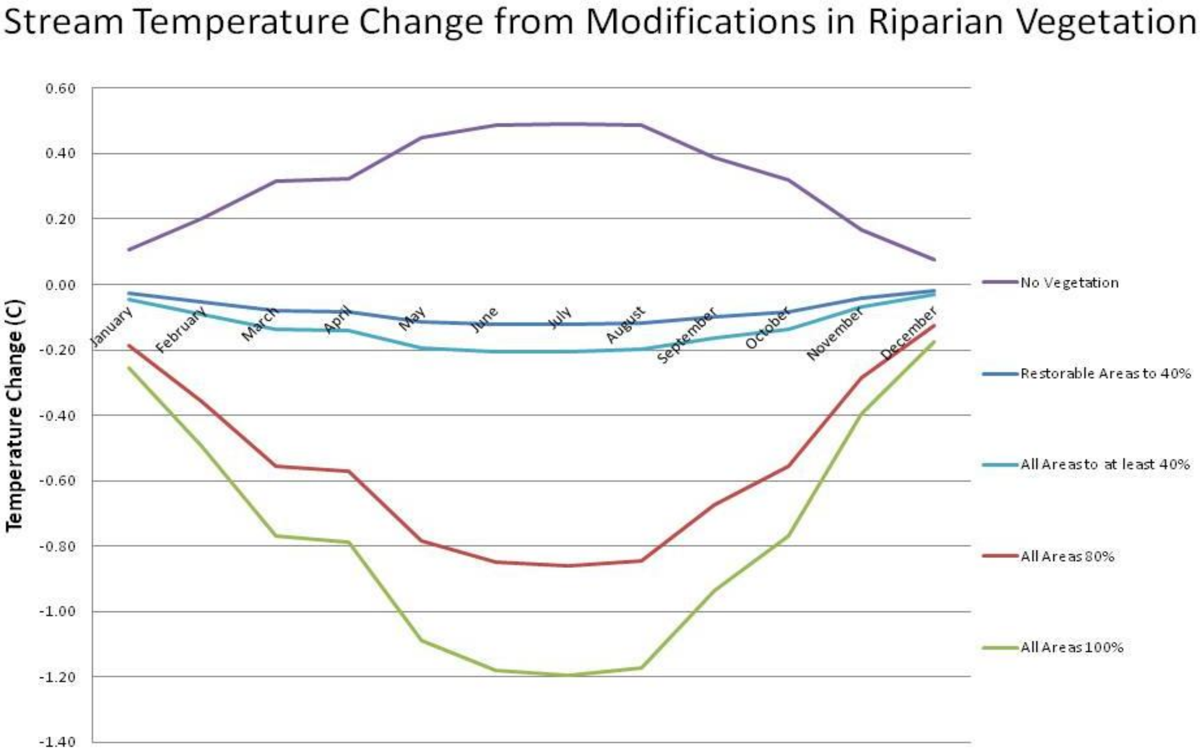

Figure K.6 Stream Temperature Change from Modification in Riparian Vegetation for the SNTEMP model between Castellbell and Abrera.

Table K.2 Network Nodes for the SNTEMP model between Castellbell and Abrera

ID	River	Node	Name	Elevation	Function	UTM_X	UTM_Y	NodeID	Upstream (m)
1	Llobregat	H	Headwaters	148	Headwaters	405776	4610500	H	23932.10
2	Llobregat	D	Bures	147	Diversion	405385	4610500	D1	23552.10
3	Llobregat	C	Bures	141	Change Stream	404926	4610700	C1	23010.50
4	Llobregat	R	R Bures	141	Return	404673	4610510	R2	22662.80
5	Llobregat	C	Borras	141	Change Stream	404411	4609660	C2	21752.60
6	Llobregat	D	Can Borras	139	Diversion	404486	4609650	D2	21674.30
7	Llobregat	R	R Borras	132	Return	405116	4609280	R1	20942.40
8	Llobregat	C	La Bauma Desviacio	132	Change Stream	405562	4609180	C3	20462.90
9	Llobregat	D	La Bauma	132	Diversion	405547	4609130	D3	20427.90
10	Llobregat	R	R La Bauma	127	Return	405661	4608820	R3	19907.40
11	Llobregat	C	La Bauma	127	Change Stream	405443	4608670	C4	19641.30
12	Llobregat	P	Castellbell i Vilar	127	Point Discharge	405366	4608730	P1	19547.90
13	Llobregat	C	C58	125	Change Stream	404801	4608890	C5	18919.50
14	Llobregat	C	Puig i Font	126	Change Stream	404388	4607880	C6	17805.60
15	Llobregat	D	Puig i Font	126	Diversion	404375	4607890	D4	17789.10
16	Llobregat	R	R Puig i Font	119	Return	403957	4607530	R4	17036.90
17	Llobregat	C	Monistrol	119	Change Stream	403990	4607380	C7	16879.10
18	Llobregat	D	Comes	118	Diversion	404210	4607020	D5	16466.10
19	Llobregat	R	R Comes	112	Return	404317	4606920	R5	16303.30
20	Llobregat	D	Colonia Gomis	111	Diversion	404401	4605970	D6	15152.80
21	Llobregat	P	Monistrol WWTP	109	Point Discharge	404488	4605950	P2	15054.30
22	Llobregat	R	R Gomis	106	Return	404403	4605240	R6	14142.60
23	Llobregat	D	El Cairat	106	Diversion	405380	4603030	D7	11480.40
24	Llobregat	R	R El Cairat	80	Return	405464	4602940	R7	11378.10
25	Llobregat	C	Cairat	80	Change Stream	405714	4602760	C8	11048.90
26	Llobregat	C	La Puda	75	Change Stream	406672	4602550	C9	9844.90
27	Llobregat	D	Can Sedo	75	Diversion	406198	4600790	D8	7786.30
28	Llobregat	R	R Can Sedo	70	Return	406068	4600150	R8	7050.40
29	Llobregat	C	Can Sedo	70	Change Stream	406079	4599920	C10	6827.40
30	Llobregat	D	Catex Moli	70	Diversion	407124	4599570	D9	5716.10
31	Llobregat	R	R Catex Moli	63	Return	409111	4598890	R9	3138.20
32	Llobregat	C	Final Turn	63	Change Stream	409259	4598810	C11	2974.30
33	Llobregat	D	D Aigues de Terrasa	62	Diversion	409283	4598400	D10	2556.90
34	Llobregat	E	ATLL-Abrera	57	End	409757	4596230	E	0.00

Appendix L. Riparian Vegetation and Restoration Costs

Starting in 2006, the Catalan Water Agency has collaborated with municipalities to restore riparian habitat along the Cardener and Llobregat Rivers. Projects have been executed at 16 sites in which invasive species of cane (*arundo donax*) has been removed, and native trees and shrubs were planted. The planted tree species include willows (*Salix alba*), black alder (*Alnus glutinosa*), white poplar (*Populus alba*), narrow leafed ash (*Fraxinus angustifolia*) and black poplar (*Populus nigra*). They also have planted native shrubs such as the rosemary willow (*Salix elaeganos*), the purple willow (*Salix purpurea*), the common dogwood (*Cornus sanguinea*), the European Privet (*Ligustrum vulgaris*), the common Hawthorn (*Crataegus monogyna*), and the black thorn (*Prunus spinosa*).

As an example of what is planted at these riparian restoration projects, the table below provides a list of what was planted at Monistrol de Montserrat.

Common Name	Species	Trees Planted	Height
White Poplar	*Populus alba*	30	16-27 m.
Narrow leafed Ash	*Fraxinus angustifolia*	15	20-30 m.
Willow	*Salix alba*	15	10-30 m.

Table L.1 Tree Species planted along the Llobregat River in Monistrol de Montserrat.

The average heights for these tree species reach up to 27-30 meters. However my shading estimates were conservative and only assumed heights of 20 m.

Figure L.1 Signage of the riparian restoration project at Monistrol de Monsterrat.

A cost-benefit analysis make assumptions pertaining to: (a) discount rate, (b) tree growth rate, (c) shading-value relationship.

(a) Discount rate. Cost benefit analysis often use discount rates in the range of 4-6%. In this case, I have chosen a discount rate of 4%. Higher discount rates imply that present generations place less value on future costs and benefits. Lower discount rates imply that present generations place a greater value future costs and benefits.

(b) Tree growth rate. I found tree growth rates for riparian species in another study that estimated the effect of riparian restoration on stream temperature (Wanatabe et al. 2005). In the Llobregat River, the restoration projects also planted species of cottonwoods, making these growth rates particularly useful. These growth curves tell us that cottonwoods will reach a height of 20 m at some point between 20 and 25 years. Since the trees planted in these restoration projects are already several years old, I assume that 20 years after planting, the trees will be 20 m in height (Fig L.2). For my shading model, 20 m is full maturity, because that was the maximum height used in the model.

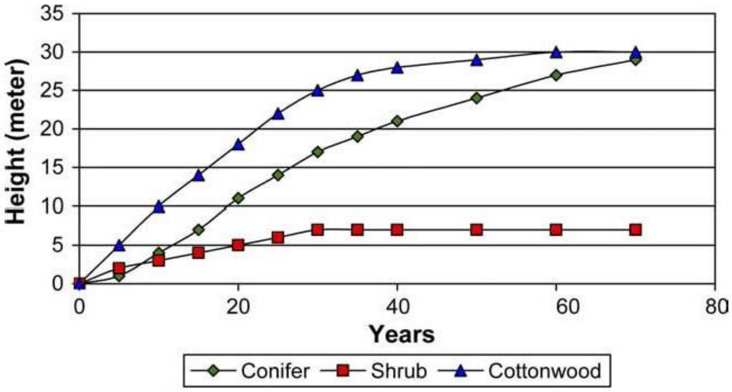

Figure L.2 Tree growth of cottonwoods and other vegetation used for riparian restoration (Wanatabe et al. 2005).

The temperature model assumed a maximum height of only 20 m. The tree growth rate used in the cost/benefit analysis was adjusted accordingly, so that after 20 years, the trees reached 100% of its expected height.

(c) Shading-value relationship

One critical assumption concerns how the shading effects are translated into economic value. In this case, we assume that the economic value of the shading effect is exactly proportional to the percent maturity of the tree (% Growth – with 20m being 100% maturity). To calculate the precise relationship between economic value and ecosystem structure I would need to run the model for each year with the trees at different heights. For each year, I would need to calculate the number of avoided threshold crossings. Note that I am assuming a linear relationship between ecosystem growth and net benefit for the water treatment plant. As pointed out in the introduction, this linear assumption may not always be the case (Aburto-Oropeza et al. 2008, Barbier et al. 2008, Koch et al. 2009).

Cost per km	60,150 €								
Discount Rate	0.04								
		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
		Restorable Areas to 40%		Restorable Areas to 60%		Restorable Areas to 80%		100 % Coverage	
	Reach Length (km)	18		27		36		57.6	
	Initial Investment	1,082,700 €		1,624,050 €		2,165,400 €		3,464,640 €	
% Tree Growth	Year	Future Value	Present Value	Future Value	Present Value	Future Value	Present Value	Future Value	Present Value
0.05	1	2,850 €	2,740 €	5,200 €	5,000 €	7,800 €	7,500 €	14,150 €	13,476 €
0.1	2	5,700 €	5,270 €	10,400 €	9,615 €	15,600 €	14,423 €	28,300 €	25,669 €
0.15	3	8,550 €	7,601 €	15,600 €	13,868 €	23,400 €	20,803 €	42,450 €	36,670 €
0.2	4	11,400 €	9,745 €	20,800 €	17,780 €	31,200 €	26,670 €	56,600 €	46,565 €
0.27	5	15,390 €	12,649 €	28,080 €	23,080 €	42,120 €	34,620 €	76,410 €	59,869 €
0.3	6	17,100 €	13,514 €	31,200 €	24,658 €	46,800 €	36,987 €	84,900 €	63,354 €
0.35	7	19,950 €	15,160 €	36,400 €	27,661 €	54,600 €	41,492 €	99,050 €	70,393 €
0.4	8	22,800 €	16,660 €	41,600 €	30,397 €	62,400 €	45,595 €	113,200 €	76,618 €
0.45	9	25,650 €	18,021 €	46,800 €	32,881 €	70,200 €	49,322 €	127,350 €	82,091 €
0.56	10	31,920 €	21,564 €	58,240 €	39,345 €	87,360 €	59,017 €	158,480 €	97,293 €
0.58	11	33,060 €	21,475 €	60,320 €	39,183 €	90,480 €	58,774 €	164,140 €	95,969 €
0.6	12	34,200 €	21,361 €	62,400 €	38,975 €	93,600 €	58,462 €	169,800 €	94,551 €
0.65	13	37,050 €	22,251 €	67,600 €	40,599 €	101,400 €	60,898 €	183,950 €	97,553 €
0.7	14	39,900 €	23,041 €	72,800 €	42,040 €	109,200 €	63,060 €	198,100 €	100,054 €
0.77	15	43,890 €	24,371 €	80,080 €	44,466 €	120,120 €	66,698 €	217,910 €	104,818 €
0.8	16	45,600 €	24,346 €	83,200 €	44,421 €	124,800 €	66,632 €	226,400 €	103,716 €
0.85	17	48,450 €	24,873 €	88,400 €	45,382 €	132,600 €	68,073 €	240,550 €	104,951 €
0.9	18	51,300 €	25,323 €	93,600 €	46,204 €	140,400 €	69,305 €	254,700 €	105,833 €
0.95	19	54,150 €	25,702 €	98,800 €	46,895 €	148,200 €	70,342 €	268,850 €	106,393 €
1	20	57,000 €	26,014 €	104,000 €	47,464 €	156,000 €	71,196 €	283,000 €	106,660 €
	Undiscounted Benefits	605,910 €		1,105,520 €		1,658,280 €		3,008,290 €	
	Net Benefits		361,683 €		659,913 €		989,869 €		1,592,497 €
	Net Cost		1,082,700 €		1,624,050 €		2,165,400 €		3,464,640 €
	Net Present Value		- 721,017 €		- 964,137 €		- 1,175,531 €		- 1,872,143 €
	Percent Recovery		33%		41%		46%		46%

Table L.2 Cost-Benefit Analysis for each of the restoration scenarios.

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