THE WATER METABOLISM OF SOCIO-ECOSYSTEMS

EPISTEMOLOGY, METHODS AND APPLICATIONS

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The Water Metabolism of Socio-Ecosystems

Epistemology, Methods and Applications

by

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Para Felipe y Toñi

“¿Qué gigantes? dijo Sancho Panza.

Aquellos que allí ves, respondió su amo, de los brazos largos, que los suelen tener algunos de casi dos leguas.

Mire vuestra merced, respondió Sancho, que aquellos que allí se parecen no son gigantes, sino molinos de viento, y lo que en ellos parecen brazos son las aspas, que volteadas del viento hacen andar la piedra del molino.”

(El Ingenioso Hidalgo Don Quijote de la Mancha, Miguel de Cervantes)

Für Martijn

“Drum hab’ ich mich der Magie ergeben,
Ob mir durch Geistes Kraft und Mund
Nicht manch Geheimniß würde kund;
Daß ich nicht mehr mit sauerm Schweiß,
Zu sagen brauche, was ich nicht weiß;
Daß ich erkenne, was die Welt
Im Innersten zusammenhält”

(Faust, Wolfgang vom Goethe)

Abstract

The research line presented in this dissertation is a first attempt to provide a bridge for the communication between Hydrological studies and Social Metabolism. It was born from the observation that water is neglected in Social Metabolism and that current water science, while certain about the need of evolving towards a more interdisciplinary field, still faces challenges in the connection of social and ecosystem analyses. The contribution made here is the definition of an analytical framework –the Water Metabolism of Socioecosystems- where this connection can be established and which is formed by a conceptual proposal and a methodological toolkit. The document is divided in three parts where the epistemological, the methodological and the formal novelties of the framework are discussed.

Part I covers the epistemological reflections related to the analytical framework. It begins in Chapter 1 with the explanation of the challenges faced by current water science and which are related to the need of finding analytical frameworks that contribute useful inputs to integrated management of the water resources (IWRM). As with the case of other resources, IWRM requires the analytical connection of the social and ecosystem dynamics. As a key piece within Sustainability Science the analogy of the metabolism of societies can be used to establish this connection. However, the metabolism concept needs a close examination before its joint use with other conceptions of the relations between humans and nature. After highlighting the need of considering the societal and ecosystem metabolism of socio-ecosystems as two separate but connected processes, a conceptual scheme is proposed in Chapter 2 to describe the metabolic relations between them. In Chapter 3, this scheme is adapted to the specifics of water using some of the most relevant concepts in socio- and eco-hydrology. In this way the water metabolism of socio-ecosystems is defined as the metabolism of the coupled water-human systems.

Part II describes the methodological framework. In Chapter 4 the Multi-Scale Assessment of the Societal and Ecosystem Metabolism (MuSIASEM) is presented as an established framework able to deal with the scale issues and the integration of narratives. MuSIASEM is adapted to the analyses of coupled water-human systems. Since water presents some differences with the previous energy-focus analyses, its adaptation requires the inclusion of new scales of analysis –problemshed and watershed- and new definitions of water as a metabolite –as flow and fund. In Chapter 5 the differences and synergies between MuSIASEM and the water footprint analysis –as one of the tools of the IWRM- are highlighted.

In part III four case studies are presented with two objectives. First, Chapter 6 assesses the sustainability of the metabolic patterns I Punjab and Mauritius in order to test the adaptation of MuSIASEM to water and to show how this type of analyses is made functional. Second, Chapter 7 shows how the water footprint accounting methods can complement the analysis of the water flows in MuSIASEM and how MuSIASEM, in turn and provide a space for their contextualization.

Keywords: Agriculture, Complex Systems, Integrated Water Resources Management, Flow/Fund Model, Grammar, Multilevel Matrixes, MuSIASEM, Scale Issues, Socio-Ecological System, Social Metabolism, Virtual Water, Water, Water Footprint, New Water Culture.

Resumen

La línea de investigación presentada en esta tesis representa un primer acercamiento entre los estudios sobre Hidrología y Metabolismo Social. La línea nace de la observación de que el agua es evitada en los estudios que tratan el metabolismo y de que la ciencia del agua –si bien reconoce la necesidad de evolucionar hacia la interdisciplinariedad- todavía no ha conseguido conectar los análisis enfocados en la sociedad y en los ecosistemas. La contribución que se hace en este trabajo es precisamente la definición de un marco analítico –el Metabolismo Hídrico de los Socio-ecosistemas- donde se puede establecer esta conexión y que está formado por una propuesta conceptual y un set de herramientas metodológicas. El documento se divide en tres partes donde se discuten las novedades epistemológicas, metodológicas y formales del marco.

La Parte I cubre las reflexiones epistemológicas relacionadas con el marco analítico. Éstas comienzan en el Capítulo 1 con la explicación de los restos a los que la ciencia del agua se enfrenta y que están relacionados con la necesidad de encontrar marcos analíticos que puedan proporcionar inputs relevantes para la gestión integrada de los recursos hídricos (GIRH). Al igual que para el caso de otros recursos, la GIRH requiere el establecimiento de una conexión analítica de las dinámicas sociales y de los ecosistemas. La analogía del metabolismo de la sociedad, como una de las piezas claves de la Ciencia de la Sostenibilidad, es una buena opción para establecer esta conexión. Sin embargo, el concepto de metabolismo necesita ser examinado de cerca antes de su uso combinado con otras concepciones de las relaciones entre el ser humanos y la naturaleza. Tras subrayas que el metabolismo de las sociedades y los ecosistemas son dos procesos distintos per conectados, en el Capítulo 2 se propone un esquema para la descripción de las relaciones metabólicas entre ellos. En el capítulo 3, este esquema es adaptado a las condiciones específicas del agua, usando algunos de los conceptos más relevantes en socio- y eco-hidrología. De esta forma, el metabolismo hídrico del socio-ecosistema es definido como el metabolismo del sistema agua-ser humano.

La Parte II describe el marco metodológico. Como un marco ampliamente establecido que es capaz de tratar los problemas de escala y de integrar narrativas, el Capítulo 4 presenta el Análisis Integrado Multi-Escala del Metabolismo Social y de los Ecosistemas (MuSIASEM). MuSIASEM se ha seleccionado como raíz y ha sido adaptado al análisis de sistemas complejos agua-ser humano. Dado que el agua presenta importantes diferencias con respecto a los análisis previos en energía, esta adaptación requiere la inclusión de nuevas escalas de análisis –el 'problemshed' y el

'watershed'- y nuevas definiciones del agua como metabolito –como flujo y fondo. En el capítulo 5 se señalan las diferencias y sinergias ente MuSIASEM el análisis de la huella hídrica –como una de las herramientas de la GIRH.

En la Parte III se presentan cuatro casos de estudio con dos objetivos. En primer lugar, el Capítulo 6 analiza a sostenibilidad de los patrones metabólicos en el uso del agua en Punjab y Mauricio para testear la aplicación de MuSIASEM a los estudios de agua y para mostrar cómo este tipo de análisis de formaliza. En segundo lugar, el Capítulo 7 muestra como los métodos de contabilidad del agua del análisis de la huella hídrica complementan el análisis de flujos de agua en MuSIASEM, encontrando además una referencia para su contextualización.

Palabras clave: Agua, Agua Virtual, Agricultura, Gestión Integrada de Los Recursos Hídricos, Gramática, Huella Hídrica, Metabolismo Social, Modelo de Flujo/Fondo, Matrices Multinivel, MuSIASEM, Nueva Cultura del Agua, Problemas de Escala, Sistemas Complejos, Sistema Socio-Ecológico.

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Acronyms

AG: agriculture production, 117; agriculture-social compartment, 200
AG*: rest of the agriculture, 200
APP: Appropriation, 152
CWR: crop water requirement (, 183
DU: direct use, 153; direct use of water, 199
EEIO: Environmentally Extended IO, 200
EF: ecological footprint, 122
ELP: economic labor productivity, 167
EM: energy and mining, 117, 158
EnU: End use, 154
ES: ecosystem service, 44
ET: evapotranspiration, 183
EXT: extraction, 153
F&V: fruits and vegetables, 188
GIS: geographical information system, 183; geographical information systems, 135
GWS: Global Water System, 68
HA: human activity, 112, 198
HH: households, 116; Households, 113
ILA: impredicative loop analysis, 120
IO: input-output, 130
IWRM: Integrated Water Resource Management, 39
LCA: life cycle analysis, 128
MFA: material flow accounting, 128
MRIO: multi-regional input-output, 134
MSP: Minimum Support Price, 162
MuSIASEM: multi-scale integrated assessment of societal and ecosystem metabolism, 84
PS: Productive Sectors, 113
PW: paid work, 117, 205; Paid Work, 113
PW*: other paid work, 117
REC: Recharge, 152
SDW: specific water demand, 182
SEH: socio-eco-hydrology, 39
SES: *socio-ecological system*, 52
SG: Services and Government, 113
SOHO: self-organizing hierarchical open (systems), 54
SU: Supply, 152
SWD: specific water demand, 128
THA: total human activity, 199
VW: virtual water, 71
WA: water *availability*, 135
WF: water footprint, 121; Water Footprint, 15
WFA: water footprint assessment, 121
WFD: EU Water Framework Directive, 41
WHS: coupled water-human systems, 70
WMD: water metabolic density, 187
WMR: water metabolic rate, 175, 187
WMS: water metabolism studies, 65
WOS: water observation system, 64
WSI: water *scarcity*, 135

Preface

Evolution of the research line

This research line began with the calls for a 'new water culture' that rose in Spain in the mid 2000s. At that point, discussions about the multidimensionality of water were on vogue. Substantial criticism against the reductionist definition of water just as a productive asset came from academia. The fundamental role of water for the maintenance of ecosystems was highlighted. Interdisciplinary studies of water issues were born, bringing ideas like the definition of water as an eco-social asset to students. Water management rooted on an ever-increasing supply was questioned bringing policies like the EU Water Framework Directive.

In 2004, when I was in the last year of my BSc studies in Environmental Science, the proceedings of an International expert meeting on 'Virtual Water Trade' held in Delft, The Netherlands, in February 2003 fell in my hands. It was my first approach to Virtual Water (VW) and its quantification. The interdisciplinary methods used for the assessment of VW flows associated to the trade of agricultural products called my attention. Unitary water requirements per ton or ha of production were estimated using physiological models and combined with trade data to assess the dimension of the flows. I decided to focus my final BSc project on the topic and performed an assessment of the VW associated to the tomato trade from Andalusia to the rest of the world. Amazed by the potential of the VW concept I decided to do a PhD on the topic.

I moved from Sevilla to Barcelona and enrolled in the 'Ecological Economics and Environmental Management' specialization of the joint MSc-PhD program of ICTA. Having studied in a not-so-international city and attended only to Environmental Economics lectures during my BSc, the international, interdisciplinary environment of ICTA was a first epistemological breakdown. I attended MSc courses like Ecological Economics or Complex Systems, which brought to me not only new knowledge but also the need of questioning conventional principles.

Particularly the works on Social Metabolism and Water Footprint (WF) were a real discovery for me during those first years in ICTA. I decided to focus my MSc dissertation on the combination of both and designed a first version of the water metabolism which, now I see, was very naïve. The novelty of the work was the combination of water and monetary indicators, in the same way that metabolism studies did for other materials. This article was published in the *Revista*

Iberoamericana de Economía Ecológica and, to the best of my knowledge, it is the first scientific publication about virtual water in Spanish.

Water was, already (still?) in 2007, a challenge for metabolism studies and the water flows analysis of the WF studies seemed the perfect way of complementing my description of the water metabolism. With the purpose of learning more about WF, I decided to apply for a visiting stay with Arjen Hoekstra. During the eight months I spent at the University of Twente I discovered the importance of classifying water flows according to their end use, particularly the distinction between blue and green water. Also, I learnt the specifics of the volumetric method for the WF assessment, including top-down and bottom-up approaches. Back then, this was the only method used for the assessment of the WF. Shortly before my stay in Twente, I had won the FPU fellowship to develop my PhD research at the department of Applied Economics (UAB). Guided by Vicent Alcántara I had started to explore IO analysis as a method for the assessment of biophysical flows able to deal with truncations issues and I clearly saw that IO could be used to link WF and economic structure improving the indicators I used for my MSc and avoiding these truncation errors of the process-driven methods.

This stay brought me the contact with researchers that understood water as a multi-scale issue. On the one hand, I met the colleagues of the Global Water System Project in Bonn and, on the other hand the group of the UNESCO IHE in Delft –where that first virtual water expert meeting took place. In Delft, I attended for the first time a lecture by Tony Allan and discovered that there was an epistemological discussion behind the quantitative indicators of VW. It was then when I realized that I had advanced a lot in the quantification of the water metabolism, but that the conceptual side was still very weak.

In 2009 I did a second research stay at King's College London with Tony Allan with the purpose of learning more about how VW was born. It was there when I discovered that the conceptual side of the VW was at least as relevant as its role as indicator. I not only deepened my knowledge of the VW but also, I learnt how what I consider a virtual water theory was inserted within the process of formation of the dominant water discourse. Part of these reflections about the meaning of the virtual water concept is published in the journal *Water Resources Management*.

During my first years at ICTA I had had a first interaction with local water and agriculture policy makers and other stakeholders through my work in some projects, but I had never had the chance of interacting with national policy makers. In London Tony Allan put me in contact with the Department of Environment, Food and Rural Affairs of the UK Government, where I was invited to present the work I developed during my MSc on the –back then- water metabolism of the fruits and vegetables sector in Andalusia, Spain. Moths later, also the Spanish Ministry of Environment of Spain invited me to show these results. This interaction with the non-academic world put me back on the track of applied research, as I realized that pure epistemology was not going to contribute much to improving water management.

After my stay in London I spent a considerable amount of time struggling with theory and numbers as ways to describe the water metabolism. I would be probably still in that debate if Jesús Ramos-Martín, who had followed the developments of my PhD, would not have spent a couple of afternoons discussing it with me and recommended me some readings about MuSIASEM. When I started testing MuSIASEM for the analysis of the water metabolism of Spain with Mario Giampietro, I could not understand its specifics very well, but it seemed to be a way to integrate my theories and my numbers. When in 2011 Mario and Jesús accepted to co-supervise my –already quite advanced– PhD journey and included me in the IASTE group I experienced my second epistemological breakdown. Deconstructing all the learnings of the last years was a difficult but most enriching experience and I can now tell that it was exactly what I needed.

MuSIASEM is a framework that puts together bioeconomics principles and complex systems theory and which has been mostly used for energy analysis. It is rooted in a complex definition of metabolic systems. When I decided to face the challenge of adapting the framework for water, I thought the work was only about removing energy flows and using water flows. However this was not the case and together with Violeta Cabello –a colleague from the University of Sevilla- we soon realized that neither the analytical levels, nor the semantic categories defined for the analysis of energy were valid for water. It took us a one-year discussion with Mario to integrate water within the MuSIASEM framework and almost another year to write it down in the paper now published in *BioScience*.

This discussion has enriched the description of the water metabolism –now accepted for publication in the *Journal of Industrial Ecology*– in several ways. Through it I have learnt how the analyst choices reflect the connection between epistemology and numbers, which is the way in which the water discourse materializes in academia, and feeds itself. MuSIASEM has provided a way to analyze the water metabolic patterns and to integrate the natural and the social perspectives that so important are regarding water issues. With this scope, it has been difficult to frame the dissertation within the discourse of water scarcity –or water availability and use- because the metabolic patterns are much more. In the last instance, this is a research about water availability and use, but not only that. There is water supply, and recharge and extraction, and appropriation. There are scarcity issues, and human rights, production chains, ecosystem components, etc. There is also land, and labor, and energy.

When I began my PhD research I thought that water was the most important issue in the world. I am now aware that water is just one (really really important) part of the picture of the metabolism of SES. This idea has come clearly during my work in the last years in nexus-related projects with FAO and the government of Ecuador. In the attempt to design a national water accounting system for Mauritius, Punjab and Ecuador, one realizes how difficult is to fit the specifics of water, energy and land together in the field of metabolism studies. This might be the reason why I now feel that my focus in agriculture is too narrow and decided to open the scope of future case studies to the analysis of the water-food-energy-land nexus. My plans for the assessment of the fracking activities in the US has been funded by a Marie Curie Fellowship, which I would like to use to fine tune the framework of the water metabolism. I would like that it once leaves the academic journals and becomes a decision tool for integrated water resources management. This will be, I hope, my little piece of contribution towards the development of the 'new water culture'.

With the adaptation of MuSIASEM for water analyses, this research is an effort to integrate hydrology methods within metabolism studies. It has been developed with the firm belief that they can enrich each other. My aim has not been to depreciate current research in any of the fields, but to highlight their complementarity and contribute a bridge for their communication. I hope I have succeeded.

Barcelona, October 27th 2014

Acknowledgments

Now that I can see the writing of this dissertation coming to an end I cannot help but to think that –after all– I will miss my PhD period. It has been an exciting journey. Contrary to what I was told at the beginning, the PhD has not been a lonely path. It has been an individual challenge, but not a lonely one. There have been many people who crossed my way shaping the results of this journey and I would like to take a couple of pages to acknowledge their valuable contributions.

First of all I have been gifted with three great supervisors. Three complementary people whom I want to thank their dedication, faith, support and patience. Vicente has been the person who would accept that I take my own decisions and put my interest before his. He has been there from the beginning supporting my application to the PhD program at ICTA and to the FPU fellowship at the Department of Applied Economics of UAB (DEA).

Mario and Jesús arrived to my PhD later, giving me the chance of a re-start and showing me that falls are part of the journey. Jesús has been the older academic brother that every PhD student should have. An active and constantly-updated scholar that has made time to listen to my worries every single time I needed him. I am very grateful to him for opening the doors to apply the methods developed in this thesis in collaboration with the Government of Ecuador.

Mario is the person that has made this dissertation possible. He is the one who would put some intellectually-addictive piece in my hands, just to make me aware that something exists, and then guide me through my own process of deconstruction and reconstruction. To his guidance I own my interest in epistemology and the ability of questioning things without fear. Since he included me as one more in the IASTE team incredible options have been at my reach, particularly the experience of working with FAO and the award of a Marie Curie Fellowship.

The second gift has been a great group of colleagues from ICTA and DEA, Cristina, Mariana, Loli, Luci, Bea, Francisco, Emilio, Laia, Jordi… with whom I have shared wonderful moments. I am very happy to have an answer for Rafa now. Yes, I have submitted ;-). I am particularly grateful to Lourdes for that very good piece of advice; and to my new sister, Lidia, for many worthy years of everyday's sweet and sour. Also, a piece of this achievement results from my interaction with my IASTEs, from the spirit of Alev, the revolutionarism of Tarik, the joy of Rosi, the serenity of Zora, the good vibes of Pedro, the humanity of Sandra, the quietness of Juan, the intellect of Tiziano, the enthusiasm of François and the sweetness of Raúl.

The third gift has been the possibility of sharing academic space with people that have made a difference. I would not be in the intellectual and academic place I am today without the early year teachings of David Tábara and the support of Joan Martínez Alier, Jordi Roca and Kozo Mayumi. I am very grateful to Arjen Hoekstra and Tony Allan, who welcomed me in Twente University and King's College London and are always open to my requests and proposals.

During these years I have enjoyed the financial support of the FPU fellowship; the BE grant; the groups 2005SGR-177, 2009SGR-600, 2009SGR-594, ECO2009-10003, and the XREPP (Xarxa de Referència en Economia i Polítiques Públiques), which have given me the chance of doing my PhD, completing a couple of visiting stays and attending to many conferences.

I have enjoyed a good relation in the administrations I have contacted. I am grateful to the Andalusian Ministry of Agriculture; to Fernando Celestino Rey from the Spanish Statistic Institute, water accounts section and to Joan Anglada of the Catalan Water Agency. They have been very valuable contacts for reaching information.

Last, I do not want to end these lines without dedicating some words to those who are out of academia.

Mi último agradecimiento es para vosotros, que estáis fuera del mundo académico y que me habéis acompañado con vuestro cariño. A Mari por estar ahí sin estar aquí. A Ivana y Anna, por tantos cafés, y por los que nos quedan. A Sonia, perquè mai se t'oblida preguntar. A los Lopez por las fiestas. A Verónica, por las peleas y las reconciliaciones.

A vosotros, mis padres, por enseñarme a distinguir los molinos de los gigantes.

Martijn, für die Freundschaft, die Liebe und die Wertschätzung. Voor het verleden en de toekomst. For being the other holon of the holarchy.

Introduction

"We have seen already –and it will be a recurring theme– that people everywhere are deeply deluded in their relationship with water"

(Allan 2011, 116)

The issue(s)

The complexity of water

We are slowly accepting that the complexity of water is extremely difficult to handle. The dominant water discourse has for many years followed a paradigm in which water issues were defined and solved in a simplistic manner. Water shortages were considered an availability issue and faced with pharaonic hydraulic works. We have seen how these 'ultimate' management strategies have not succeeded in reducing the global shortage of water or in improving the situation of the heavily impacted water bodies around the world.

On the contrary, with stable water endowments, a growing world population, and consumption patterns developing towards more water demanding ways of life; it seems that the problem is worsening. The population who does not have access to regular water sources not only faces limitations in their ways of life but also important biological risks. As many as 30,000 people die every day due to water-related diseases, including a child every 8 seconds (UNDP 2006). World farmers rely in between 2,000 and 3,000 Km^3 of water to produce our food (Postel et al. 1996), most of which comes from arid regions. These and other alarming numbers are a wake-up call.

Civil society, academia and policy-makers have been for eyars trying to find a path towards an integrated management of the mismatch between water availability and use –frequently called water scarcity. The lack of water in enough quantity and quality in the place and time where it is needed is an important issue, implicitly –or explicitly– prioritized in the political agenda. The integration is nevertheless proving challenging because scarcity is just the tip of the iceberg, the visible consequence of a bigger issue: our lack of means to deal with the complexity of water.

Facing this challenge is difficult for two reasons.

On the first hand, this complexity is not always acknowledged. And mostly it is not acknowledged because it is not easy to perceive. As Mario Giampietro would put it, the reality –the TAO– is actually seen by no one. What we do see are perceptions of reality –the NAMED– that we mistake for the complete reality. Each of these partial observations generates a *narrative* that guides our relation with the TAO. In the end, the only signal we have of the complexity of water is the number of narratives that are related to the element, which result in the painful observation that our strategies are not fixing the water problems.

On the second hand, when complexity is acknowledged, it is not easy to deal with. The main difficulty of the assessment of complexity is that it cannot be treated as a problem. Complexity is the result of the interaction between systems and as such, it cannot be 'solved'. 'Solutions' tend to come in the form of partial patches that deal with a certain issue highlighted by a certain narrative. If the narrative highlights the perception that water is an important productive factor, it is normal to propose measures to increase its availability and make use of the technical advancements of water engineering. If the narrative highlights the importance for human life and lifestyles, measures will be designed to ensure the access to a clean water source and sanitation of the population. A narrative that sees water as an essential component of the ecosystems will claim measures that maintain the good ecological status of the water bodies. Different narratives do imply different courses of action and this is relevant because some narratives have more power than others to influence the water discourse.

The interaction of the different narratives forms the dominant water discourse. This interaction is not always easy because each of them has its own 'language'. Natural scientists cannot see and will never see social water processes and vice versa, because their methods do not allow that. Those processes that follow the larger natural spatial-temporal scales –like those determining natural water availability– are analyzed by natural sciences. Those which comply with shorter social spatial-temporal scales –like water use in socio-economic activities– are observed by social sciences. Assuming that we acknowledged the epistemological challenge associated with the complexity of water, 'coping with it' means to find ways of effective communication between different narratives. This might be our only chance to deal with water problems.

Analyzing the relation between humans and water

The global water question can be summarized in the issue of mismatch between water availability and use described above. In fact the mismatch between availability and use is an issue for almost all those resources in which human life relies. It has been broadly explored by Sustainability Science, most notably by those fields like ecological economics, bio-economics or industrial ecology that acknowledge the limits that nature imposes over the human biophysical requirements. These fields also face the challenge of dealing with complexity and the need of communication between human-oriented and natural-oriented narratives. It can be argued that the complexity of water is a consequence of the complex organization of the relations between humans and nature. The field of Social Metabolism is a common ground of these scientific areas. It employs the similitudes between the biological process of anabolism and catabolism and the social production and consumption activities. The most visual part of the metabolism is without any doubt the biophysical flow exchange between societies and their embedding ecosystem.

However, water can be considered the Achilles' heel of metabolism studies both conceptually and methodologically. Material balances have for a long time avoided it (Matthews et al. 2000; Eurostat 2001, 2013) or have recommended its analysis in a separate account (Schandl et al. 1999). The reasons cited include excessive volumes, shaky flow taxonomy and data unavailability. Due to the difficulties in its analysis, the OECD (2008, 31) treats water in a special material category named "the borderline cases".

Water science has also acknowledged the importance of connecting human and natural systems. The field of hydrology, which has traditionally focused in the 'natural' functioning of the water cycle, has now included *coupled human-water systems* (Savenije et al. 2013) within its scope. Modern hydrologists argue that *integrated water resources management* (IWRM) is the strategy to follow for their study. However, the field has struggled to find appropriated analytical frameworks for IWRM and a route for implementation for more than 40 years (Biswas 2008).

The impredicativity and interdisciplinarity of the research line

Research lines dealing with complex processes tend to be as impredicative as the very complex processes they study. In complex self-organizing systems, the identity of the parts is defined by the identity of the whole and, at the same time, the identity of the whole is defined by the interaction of the identities of the parts. People born within a European society will develop a different identity that people born within the Maasai Mara. The former will probably not learn to survive on hunted animals while the latter will not learn much about financial debts. Because the Maasai community is formed by Maasai hunters, it will be a hunter's society, creating new hunters. Because the European society is formed by those who know how to apply for a mortgage, it will result in a highly financially indebted society, creating new indebted individuals.

A research that focusses on impredicative elements can never be developed in a linear way. On the contrary, it is the result of a number of iterative discussions, tests and reflections. Once the theory seems to be settled, the practice will show some contradictory results that will force the researcher to go back and question again the theories and designing new practical approaches. Then, once the object of study seems to be characterized, the parts will show extra dimensions that were not included, and which will force a new definition of the whole.

The metabolism of coupled water-human systems, or the water metabolism of coupled nature-human systems, is impredicative. Its assessment does not only consist of the analysis of the sum of the water use of the system components, but also on the characterization of the system itself, including characteristics that emerge from the relation between the components. Since, as previously mentioned, this requires an effort to integrate narratives; the claim is that the impredicativity of the water metabolism has to be tackled using trans- and inter-disciplinary approaches and with a combination of epistemological and methodological reflections tested with applications.

Research objectives and questions

The lack of a methodology able to cope with the complexity of coupled water-human systems and to provide results that are useful for IWRM is not due to the lack of analytical efforts. On the contrary, a number of efforts exist, which only miss a language for their communication.

> *The objective of this research is to develop a language for the accounting and assessment of the water involved in the metabolism of socio-ecosystems that can contribute towards an IWRM.*

In order to reach this goal, the following questions are raised:

1) *What are the issues faced by the current water discourse and IWRM?*
2) *How to integrate hydrology and metabolism studies?*
3) *How MuSIASEM has to be modified to include water?*
4) *How to formalize the MuSIASEM framework in its application for water?*
5) *Why the water metabolism and its analysis with MuSIASEM contribute to IWRM*

What to expect from this research

As commented above, any research activity is limited by our own incomplete vision of reality. Therefore this work has to be interpreted as one contribution towards the creation of a bridge between hydrology and metabolism studies. As such it also has its limitations.

This dissertation contributes:

- An overview of the current issues of the dominant water discourse in Europe
- A critical exploration of the epistemology of Social Metabolism
- A conceptual framework for the integration of hydrology and metabolism narratives
- A methodological framework rooted in the Multi-Scale Analysis of Societal and Ecosystem Metabolism (MuSIASEM)
- The first adaptation of MuSIASEM for water
- Indications on how to do the formalization of the water grammar integrating the water footprint analyses
- Applications of MuSIASEM of water for the assessment of the sustainability of the metabolic patterns.

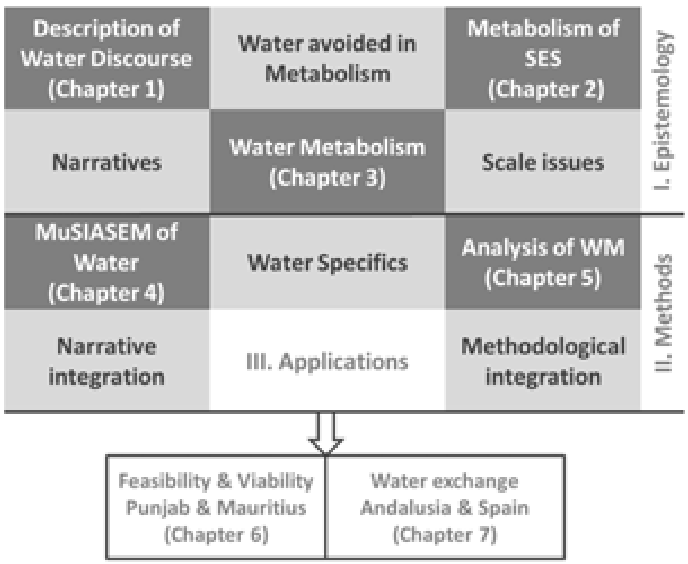
The main limitations of this work are:

- The epistemological discussion about the study of water is rooted in socio-ecohydrology, however, for the methodological framework and applications only virtual water theory and water footprint assessments have been chosen. I am aware they are not the only approaches in the fields, but they are at the moment the most popular and acknowledged analytical sources within socio-ecohydrology and IWRM.
- In Part I there is a definition of three levels of the water metabolism: societal, ecosystem and Earth. However, the applications and the sustainability check have a stronger focus on the societal side, using some indicators for the ecosystem and Earth level, as it is the first time that a MuSIASEM grammar includes dynamics at these levels.
- The numeric results generated in this thesis cannot yet been used for decision making, they have to be better calibrated and validated.
- A complete description of the desirability check could have complemented the dissertation, but this is also a pending issue in MuSIASEM. A short overview is included in Annex .

Reading guide

This research line has been developed in a loop of theoretical, methodological and application developments. For this reason choosing a chronological structure for its presentation would generate redundancy in the material. In order to avoid repetitions as much as possible, the body of the dissertation has been structured in three parts corresponding to the epistemology, methods and application issues. The dissertation mind map is shown in Figure 0.1.

Figure 0.1. Organization of the dissertation body (WM= water metabolism)



Part I *focusses on the epistemological challenges and the design of a conceptual framework that describes the relation between the water systems and the human systems.*

Chapter 1 describes the formation of the water discourse as the asymmetric interaction of different (social, scientific, politic, etc.) narratives. The current paradigm in the 'northern' water discourse is the *reflexive modernity*, which has stimulated the evolution of the water paradigm towards a *new water culture* which in turn aims at reaching an *integrated water resources management (IWRM)*. The multidimensionality of water is made explicit with an exploration of the different narratives involved in the paradigm of the reflexive modernity.

Chapter 2 analyzes the epistemological developments of Social Metabolism studies. As a field of Sustainability Science able to deal with the interaction of socio– and eco-systems, Social Metabolism is –a priori– a suitable conceptual framework for the purpose of reaching an IWRM. However, the field presents important epistemological gaps in this respect as a result of the rapid proliferation of works that deal with the process of the material and energy exchange between humans and nature. A conceptual framework is presented for the study of the metabolism of socio-ecosystems that meets the challenge of dealing with some scale issues like system definition and multiple identities, which otherwise hinder the development of analytical methods.

Chapter 3 challenges the explanation that 'lack of data and high volumes' are the true reasons of the exclusion of water from Social Metabolism studies. Social Metabolism is a useful epistemological ground when adopting a hierarchical definition of the coupled water-human systems as socio-ecosystems but its epistemology is not suitable for water analyses. However, conceptual tools of the current hydrology developments can contribute to the epistemological discussion about the water metabolism. A proposal for the conceptualization of the water metabolism of SES integrates the watershed –ecosystem– and problemshed –social– perspectives within the Social Metabolism framework.

Part II *develops the conceptual water metabolism into a methodological framework useful to make analyses in line with IWRM.*

Chapter 4 presents the MuSIASEM as a heuristic methodological framework specifically developed to deal with analytical scale issues of the metabolism of socio-ecosystems. Its adaptation for the assessment of water presents some challenges since the framework has been mostly used for energy analysis. Using the flow/fund model of Georgescu Roegen for the quantification of the relation between the biophysical exchange –flows- and the system structures –funds, MuSIASEM can help with the framing of the multidimensional definition of water and the delimitation of the system under analysis. The water grammar and taxonomy are presented here.

Chapter 5 explains why MuSIASEM –a tool for the assessment of metabolism- and the water footprint assessment – a tool for the analysis of water flows- can be combined for the analysis of the sustainability of the water metabolic patterns. MuSIASEM has some weaknesses in the stage of flow accounting, particularly in the transformation of direct use into end use of water. This can be solved using the accounting principles of the water footprint, including the volumetric –process-oriented– method and input output analysis. In turn, the water footprint is an indicator of pressure and presents limitations for the assessment of impacts. As a result the integration of the water footprint within the MuSIASEM framework can result beneficial for both.

Part III *presents applications of the analysis of the water metabolism.*

Chapter 6 focusses on the difficulties of formalizing a MuSIASEM water grammar and in the construction of multi-level matrixes of accounting. To that end, it illustrates the development of a feasibility and a viability assessment in Mauritius Island and Indian Punjab. The quantitative assessment with the multi-level matrix allows combining the watershed and the problemshed descriptive domains, and the water services and dimensions in each of them. In both cases, extra regional markets drive the (un)feasibility and (un)viability of the metabolic patterns.

Chapter 7 analyzes the two main methods of the water footprint accounting and their integration within MuSIASEM. The water footprint community frequently seeks the homogenization of the methods for the volumetric estimation of water flows, what hinders its analytical usefulness. MuSIASEM provides a broader taxonomy that can frame different methods and make them commensurable. Regarding IO, its potential for the analysis of flows avoiding truncation errors is connected with a further exploration of the meaning of the direct and indirect use. In both cases tthe ability of MuSIASEM of contextualizing the flows contributes a solution for a pending issue in water footprint analysis.

Dissertation-related published material

The dissertation follows the structure of a monograph. Consequently, the publications related to it cannot be linked to specific chapters, except for the case studies. Also, some contents have not yet been published. A full publication list is covered in the CV in Annex II. The contents of the dissertation are related to the following publications:

Articles

Cristina Madrid-López and Mario Giampietro (in press). The water metabolism of socioecosystems: key issues and a proposal. Journal of Industrial Ecology.

Cristina Madrid, Violeta Cabello and Mario Giampietro (2013). Water-use Sustainability in Socio-Ecological Systems: a Multi-scale Integrated Approach. Bioscience. 63(1):14-24.

Esther Velázquez, Cristina Madrid and María Jesús Beltrán (2011). Rethinking the Concepts of Virtual Water and Water Footprint in Relation to the Production-Consumption Binomial and the Water-Energy Nexus. Water Resources Management, 25(2): 743-761.

Cristina Madrid and Esther Velázquez (2008). El metabolismo hídrico y los flujos de agua virtual. Una aplicación al sector hortofrutícola de Andalucía (España). *Revista Iberoamericana de Economía Ecológica* Vol. 8: 29-47.

Book Chapters

Cristina Madrid-López and Mario Giampietro, (2014). *The water grammar.* Pp 116-134. In Giampietro M, Aspinall RJ, Ramos-Martin J, Bukkens SGF. Resource Accounting for Sustainability Assessment. The Nexus between Energy, Food, Water and Land Use. Routledge.

Cristina Madrid-López, Juan José Cadillo-Benalcazar, François Diaz-Maurin, Zora Kovacic, Tarik Serrano-Tovar, Tiziano Gomiero, Mario Giampietro, Richard J. Aspinall, Jesus Ramos-Martin and Sandra G.F. Bukkens (2014). *Punjab state, India*. Pp 181-193 In Giampietro M, Aspinall RJ, Ramos-Martin J, Bukkens SGF. Resource Accounting for Sustainability Assessment. The Nexus between Energy, Food, Water and Land Use. Routledge

Conference Presentations

Lights and shadows of the red gold. An integrated assessment of Spanish strawberry production and its impacts. **Oral Presentation** at EGU General Assembly. 27 April – 02 May 2014

The incoherence between agriculture and water policies in Andalusia. A societal metabolism perspective. **Oral Presentation** at IV EUGEO Congress: Europe, what's next? Changing geographies and geographies of change. Rome. Sep 2013.

Analyzing water metabolism in Socio-Ecological Systems: A Multi-Scale Integrated Approach. **Oral Presentation** at EGU Leonardo Topical Conference Series on the hydrological cycle. Hydrology and Society: Connections between Hydrology and Population dynamics, Policy making and Power generation. Turin. Nov 2012.

Multi Scale Integrated assessment of Socio-ecological metabolism of water. **Oral Presentation** at ESEE 2011: Advancing ecological economics: theory and practice. Istanbul, Turkey. Jun 2011.

Virtual Water, Water footprint and other indicators of water sustainability. A necessary conceptual and methodological revision. **Oral Presentation** at ESEE 2009: Transformation, innovation and adaptation for sustainability. Ljubljana, Slovenia. Jul 2009.

The water metabolism of the society: Global forces with local consequences. **Oral Presentation** at ISEE 2008: Applying ecological economics for social and environmental sustainability. Nairobi, Kenya. Aug 2008.

Virtual Water in the Economy. The Case of Fruit and Vegetable Production in Andalusia, Spain. **Oral Presentation** at ISEE 2006: Ecological sustainability and human well being". New Delhi, India. Dec 2006.

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Part I Epistemology

Chapter 1
The water discourse

“The present dilemma is that the experts tend to see only a minor part of the overall water-related issue”

(Falkenmark and Rockström 2004, xx)

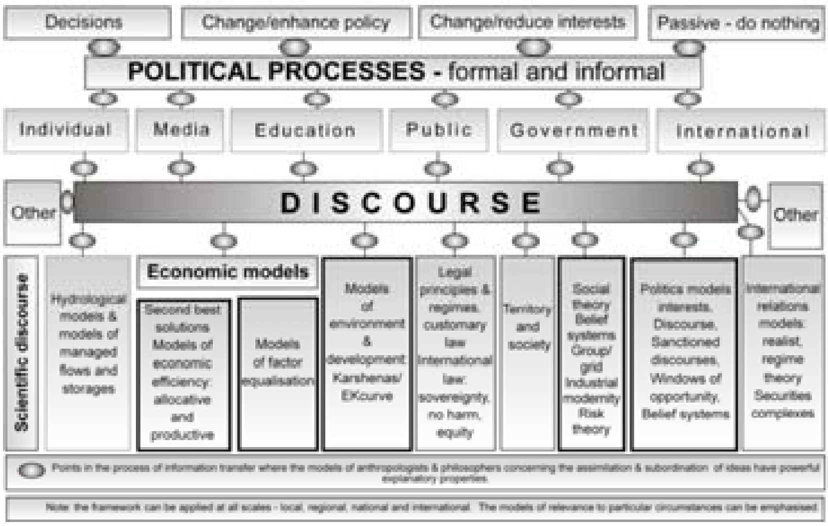
1.1 The importance of the water discourse

All social events are guided by a *social discourse*. A discourse –as defined by Foucault– is an explicit and implicit language, a set of formal and informal rules which we, humans, use to locate ourselves within the broader context of a society. In this way, a *discourse* influences and is influenced by scientific, societal and political processes (Allan 2001) led by coexisting *non-equivalent narratives* (Giampietro et al. 2006). The dominant discourse results from the asymmetric power relations between the narratives.

The existence of a common discourse does not necessarily bring effective communication between the narratives for two reasons. On the one hand, each narrative sees the world through different glasses. In other words, since the congruence relations between what happens in the external world and its formalization is susceptible of variation (Rosen 1991); each narrative formalizes reality in a different way. On the second hand, –as a result– each has its own ‘language’ and *descriptive domain* (Kampis 1991).

Accepting that i) the current social discourse influences research narratives and ii) narratives are partial views of the reality; it can be argued that it is quite important to frame the developments of any piece of science in the discourse under which it is developed. Being such a complex element, this is particularly true for the case of water. The dominant water discourse is formed by a conglomerate of social, politic and scientific narratives (Figure 1.1) that have quickly evolved in the last 50 years following different paradigms. As a result, different definitions of water co-exist.

Figure 1.1. Different narratives that form the water discourse (Allan 2001)

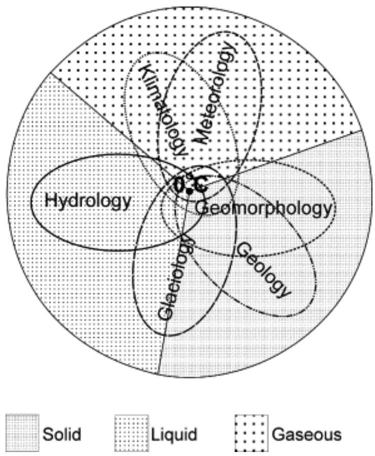


1.2 The narratives of water science

Water science is an interdisciplinary field that assesses the dynamics guiding the water cycle, during which the element suffers a number of changes in its physical state: liquid, solid or gaseous. There is no scientific field that can deal with all the water cycle processes and usually they focus on water is one of the physical states or in the transition between two of them (Dobinski 2006), as shown in Figure 1.2.

Hydrology is the field that focuses on the assessment of *freshwater*, the liquid part of water, which is potentially useful and accessible for humans. Other scientific fields such as Geology or Climatology approach other processes in which the physical state varies. For many years, fields represented in Figure 1.2 have followed a strong earth-science narrative. The connection of water science –particularly hydrology– with social and biological disciplines has been recognized only very recently, acknowledging the influence of human and biological systems over the performance of the water cycle. As a counterpart, the importance of water for the maintenance of the social and biological systems is since long recognized in social and biological science. Influenced by a swift of paradigm, hydrology has experienced an evolution towards the inclusion of social aspects as part of the parameters that influence the water cycle (Savenije et al. 2013). The influence of this change over water management is slower but strong.

Figure 1.2. Water-related scientific fields (Dobinski 2006).



1.2.1 Evolution of water paradigms

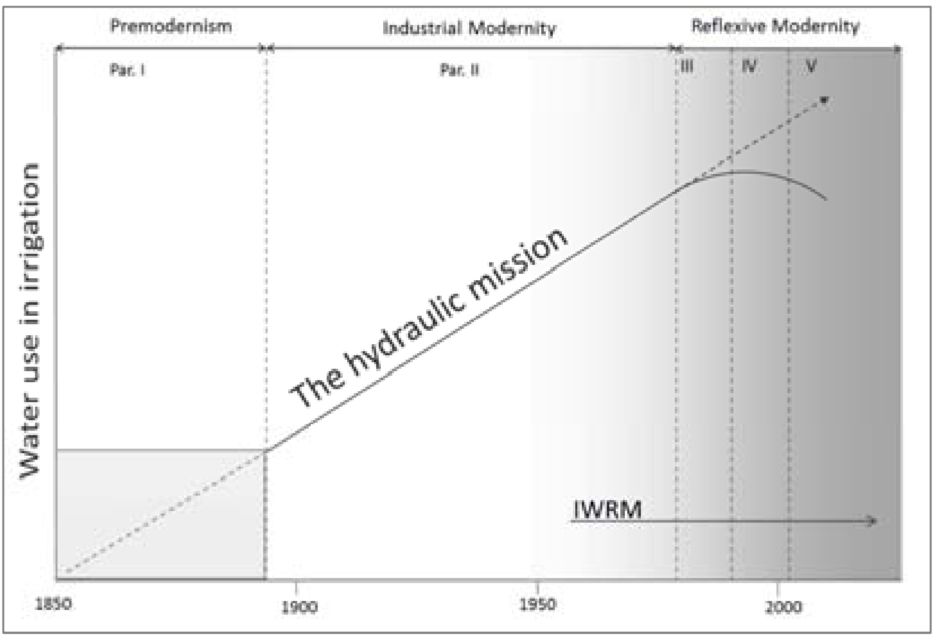
According to Allan (2001) the main water discourse in semi-arid countries has followed five different paradigms since the nineteenth century (Figure 1.3). The access to technical capacities marks the transition from the i) *Pre-modern* paradigm to the ii) *Technical Modernity*. During this long period of about hundred years, the dominant water discourse focuses on what Swyngedouw (1999) calls the *hydraulic mission*. The hydraulic mission is characterized by the resolution of water shortages with an increase of water supply provided by pharaonic hydraulic works. With the green movement, the discourse changed towards the iii) *raise of environmental awareness* and the integration of ecosystems as water users. The fourth paradigm includes iv) *economic concerns* about the productivity of water, resulting from the evidence that suggested a connection between water scarcity and a decrease on economic productivity. The last two paradigms coexist with a last paradigm that highlights the importance of v) *social involvement* in water management.

These five paradigms can be summarized into three broad phases (upper part of Figure 1.3) according to the use of water in irrigation. In the *Pre-modernism* the lack of technological development and centralized state organization conditions water management towards the survival of the household. During this period irrigation water is difficult to separate from other water supply, as marked by the dashed line in the lower left corner of Figure 1.3.

Industrial modernity began with the Enlightenment when capitalism, state organization and the belief that nature could be controlled led the mission of increasing water availability. This brought increasing water use, especially in irrigation. Water becomes one input more in an agricultural sector slowly alienated from nature (Naredo 2003). This is a long period in which science was associated with certainty and seen as the only source of information relevant for water management. Technical knowledge served as a bridge to connect in practical terms water use and availability, ignoring the drivers behind them.

The period of *reflexive modernity* is characterized by a detachment from scientific certainty. Its main pillars –environmental awareness, economic concerns and social involvement– have shaped the current definitions of water and its associated management strategies, and strongly influenced the current water culture.

Figure 1.3. Evolution of the water management paradigm using irrigation water as a proxy. Adapted from Allan (2001) and Biswas (2004).



1.2.2 How 'reflexive modernity' affected the water culture

The term *water culture* has become a synonym of the water discourse. The former highlights the civil society-scientists-policy makers interactions that form the latter. Many authors (see, for example, Aguilera Klink 2008, 2001, 1991; Arrojo Agudo et al. 2005; Martínez Gil 2004) have also acknowledged the evolution of paradigms described above by highlighting the conceptual differences between an 'old' and a 'new' water culture. In summary, the *new water culture* is driven by three factors which mirror the paradigms within the reflexive modernity:

- the multidimensional character of water,
- the acknowledgement of the influence that the relation between natural and human systems have over the water cycle, and
- the claim for a more participative water policy-making.

In this way, the *water culture* and the *water discourse* follow similar paradigms. The old water culture corresponds with paradigm II described by Allan in Figure 1.3, while the new water culture can be equated to the third phase including paradigms III, IV and V. The main differences between the old and the new water culture are summarized in Table 1.1.

The old water culture is rooted in the expansion of the hydraulic works, in order to increase the supply of water for human uses. Water extraction is limited by the technical possibilities of transferring water and not by the characteristics of the territory and the water bodies. Water use is a matter of national security, an excuse (Arrojo Agudo 2005) that serves to justify i) the exclusion of interested parts from decision making and ii) any damage to the environment. Since hydraulic policies are conceived as the remedy for any issue of lack of water, its use is not monitored and rationality is not promoted. Science is seen as a tool that offers certain results which constitute the main foundations for decision making.

Aguilera Klink (2001) includes a transitional paradigm between the old and the new water culture. He argues that this transition period is the closest description to the actual situation in Europe. While there is an aim of including stakeholders in decision making, public participation is not yet well informed and cannot be effective. The lack of reliable statistical data sources and robust analysis happens for two reasons. On the one hand, the methodologies for the assessment of water use and availability cannot deal with the high degree of uncertainty. So they are limited to controlling or avoiding risks, which results in information simply not being produced. On the other hand, specific political and economic interests tend to make it difficult to access to information when this is available (see footnote 19 in Chapter 7, page 186).

Table 1.1. Transition of the water culture. Inputs from Aguilera Klink (2001) and Allan (2006).

	Old water culture	Transitional water culture	New water culture
Paradigm	Hydraulic mission (P. II)	Transition (P. III, IV)	Maturity (P. V)
Dominant Force in Water Policy	Technical	Environmental, economic	Social, economic territorial (River basin)
Water Management	Supply	Demand	Integrated water resource management
Science	Certainty	Risk Control	Uncertainty management
Use Priorities	First irrigation (80-90%), urban supply (10%)	Priorities questioned	Uses compatible with availability
Definition of water	National security issue	Water is a productive and environmental asset	Water as Ecosocial Asset
Public participation	Nonexistent. Social conflicts very rare	Underdeveloped. Social conflicts increase	Key factor in conflict resolution
Efficiency in use and distribution	Not relevant. Lack of incentives	Increasing concern. Some incentives	Essential. Incentives and saving campaigns
Data availability	No statistical data on SE-hydrology	Underdeveloped statistics	Reliable statistics

Nevertheless a raising social awareness about the environmental and economic importance of water exists, which impulses the further change towards the *new water culture*. The New Water Culture Foundation recognizes the “patrimony of memory and the rich symbolism that water has had for human beings from time immemorial” (FNCA 2005, 12). Environmental and cultural concerns are no longer isolated from the social and economic dynamics. Stakeholders are no longer obviated in the decision making but consulted as a key factor for conflict resolution and granted true access to information. Reliable information is available since Water Science has developed methods of analysis which can deal with the high level of uncertainty associated to the drivers and scales of water use and availability. Priority uses are not normative and depend on the compatibility with the territory.

The new water culture pursues the integrated management of water. This task is not easy for two reasons mainly. Firstly, the term *integration* has a really broad meaning, difficult to delimit. And secondly, water science needs to adapt to this view. The next two sections build further on these issues.

1.2.3 The interdisciplinarity of water science

The evolution of the water discourse can also be observed in the developments of hydrology. The tendency for the last 40 years is towards the integration of ecological and social dynamics in the analysis of the water cycle. Terms like Sociohydrology (Sivapalan et al. 2012) and Ecohydrology (Zalewski et al. 1997) are frequent in the literature.

Ecohydrology is defined as the interdisciplinary field that investigates the interaction of the hydrological processes and the biota dynamics (D'Odorico et al. 2010) and has been set as an important field to "advance the integration of social, ecological and hydrological research" in order to improve policy making (UNESCO 2013). It was born at the end of the 1990's to confront the need of connecting the larger scale, long term hydrological processes with the shorter scales of ecosystem degradation and economic processes. In its origins, Ecohydrology is defined as a "factor accelerating the transition (…) to a creative management and conservation of fresh waters" (Zalewski et al. 1997, 13). Nevertheless the work of ecohydrologists has mainly focused on the connections between the physical water systems, the ecosystem and the consequences of the anthropogenic activity, without paying much attention to social drivers (Jackson et al. 2009; Wang et al. 2012).

The relation between the water and social systems –including institutional and economic factors– is studied by those who define themselves as Sociohydrologists. For them "humans and their actions are considered part and parcel of water cycle dynamics" (Sivapalan et al. 2012, 1271). They advise the analysis of *coupled human-water systems* (Braden et al. 2009) and warn that their neglect supposes a perennial hindrance to water management (Bakker 2012; Milly et al. 2008).

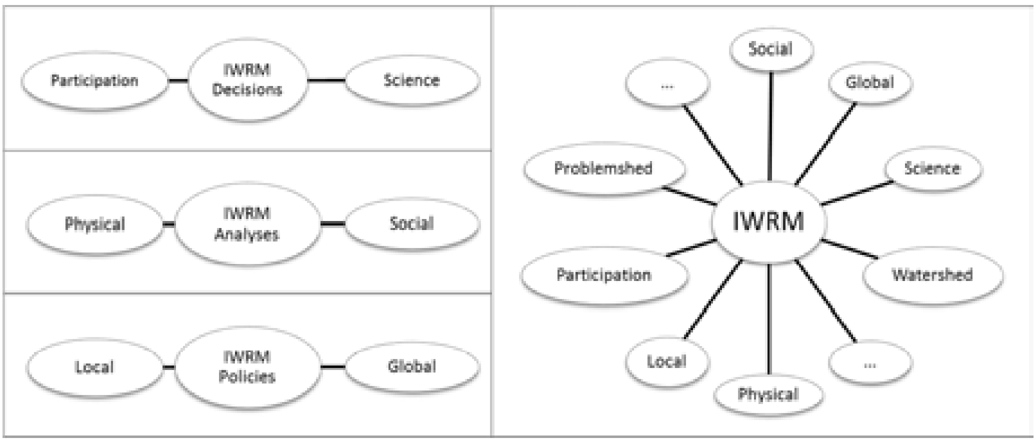
These tendencies tend to merge in what has been called *socio-eco-hydrology (SEH)* (Pataki et al. 2011). Savenije et al (2013) call this development of water science the "water science in the Anthropocene" to show that a number of discussions have arisen around the way the relations between social, ecosystem and water systems must be conceptualized.

1.2.4 The issues of integrated water resource management

Integrated Water Resource Management (IWRM) has been appointed as one of the key concepts of reflexive modernity (Allan 2006), a 'nirvana concept' that embodies an ideal image of integrated management (Molle 2008) of water which aims at combining social, economic and environmental concerns. Its aim is to reach the three E's[1] –social Equity, economic Efficiency and Environmental sustainability.

IWRM has also been related to the new water culture (International Union for Conservation of Nature and Natural Resources 2009) even if its fundamentals were born much earlier, around 1950 (Biswas 2004). Whether IWRM is a successful instrument to support sustainable water management or not is still under debate. Some authors and international agencies defend its role as a process that promotes coordinated water management (Agarwal 2000; Hassing et al. 2009; Jønch-Clausen 2004), whereas some others see issues that prevent it from reaching that objective (Biswas 2008, 2004; Molle 2008; Rahaman and Varis 2005; Rahaman et al. 2004).

Figure 1.4. Meaning of 'Integration' in the implementation of IWRM: conceptual idea (right) and partial integration reached in practice (left)



Criticism about IWRM comes mainly in three lines. Firstly, there is a lack of conceptual understanding about the meaning of 'integrated' due to the multiple interpretations this concept allows. This fuzziness results in an application of IWRM in which integrations are bilateral (Figure 1.4). This is the case of the integration of ground and surface water accounting; physical and social assessments; science-guided and participatory decisions, local and global policies etc. (Biswas 2008).

[1] It can be discussed if these objectives are susceptible of improvement or not, but are the ones given by almost every definition of IWRM.

Secondly, IWRM has been frequently used to maintain standard practices in water management hidden behind its novelty (Allan 2006; Biswas 2004), even if this has posed an opportunity for some orthodox practitioners to become closer to the integrative approach (Molle 2008).

Last, having the concept ‘discovered’ has not automatically brought effective implementation (Biswas 2008, 2004) and recent policies, such as the EU Water Framework Directive[2] (WFD), do not always conform with the aims of IWRM (Rahaman et al. 2004).

The number of levels of integration required for implementation are easy to identify in theory but difficult to put into practice (Biswas 2008) due to its connections with scale issues (more in Chapter 2 and Chapter 3). In IWRM the integration of the poles of a dichotomy axis should be complemented by the integration of the axes (Figure 1.4, right). However practice has proven this task difficult and more efforts are still needed in order to reach it (Rahaman and Varis 2005). IWRM is a paradigm with relevant intentions which has not yet become strong within the main water discourse, mainly due to the many levels of complexity that are to be integrated (Bower 1963).

One of the main challenges of IWRM is the integration of narratives in what Good (2000) calls a ‘*framework of consensus*’. Allan has the conviction that for water issues “explanation cannot be found in a single discipline and (...) that analysis based on a single disciplinary approach is unsafe” (2001, 21). This integration implies not only the integration of views and methods, but the search for better conceptualizations of water that can hold its multidimensionality.

1.3 Why water definitions in the reflexive modernity are important

The definition given to water is key in the formation of a water discourse. The discourse influences how water is perceived and what value it is given, determining the ways in which it should be analyzed and managed. Most of the works that speak about the change in the water paradigm have implicit the idea of change in the definition of water. See for example the works of Castro (2013), Swingedouw (1999, 2006), Naredo (1997), Arrojo (2006), Aguilera Klink (1995, 2008), Falkenmark (2011; Falkenmark and Rockström 2004) and Allan (1998a, 2001, 2006).

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

Each water definition highlights a water dimension. Which dimension is highlighted depends on the narrative that is making the definition. In this sense, water definitions are *semantically closed* and useful for the relevant narrative only. Current water definitions reflect the advancement of the three pillars of reflexive modernity –environmental awareness, economic concerns and social involvement– in a partial way. That is, some definitions stress environmental aspects, whereas some others focus on social or economic concerns. The current trend in management strategies is to emphasize the certain water dimension included on a certain water definition, neglecting the rest. IWRM implicitly involves the challenge of finding a way of relating these definitions.

1.3.1 Pillar 1: Economic Concerns

The relevance of including water in the analyses of the maintenance of the economic systems was pointed out already in the 18th century by the physiocrats (Naredo 2003) and in the 19th century when Alfred Marshall (1879) highlighted that water should be included in the monetary inventories because "the drinking water, the water power and the water highways of a country have great an influence on her destiny" (page 141). In his work, Marshall described water as an element that not only gave the English society its character, but also was irrevocably used during the production processes. In spite of this warning, not only has water been kept aside of these inventories, but its significance for economic growth has been de-emphasized in economic analyses until the second half of the 20th century (Ciriacy-Wantrup 1969). Cases of ever increasing mismatch between water availability and use (Worster 1986) led a group of scholars to question the principles of water management and the very same definition of water. This wave –including the "West-American school" (Turney and Ellis 1962; Holmes et al. 1972)– has been fruitful in studies.

Part of these authors speaks of water as a *limiting productive asset* and considers that the problem of water scarcity has nothing to do with physical aridity but with social management. They questioned the hydraulic policy which is very much based in a governmental, public, and universal supply management (Hirshleifer et al. 1960; Kelso et al. 1973). Following Coase's ideas (1960), their proposal is the creation of well-defined systems of property rights that will allow the development of water markets. These markets would provide the efficiency needed in the allocation of water between competing uses (Anderson and Hill 1997; Erlenkotter et al. 1979; Griffin and Boadu 1992; Griffin 2005, 2008; Howe et al. 1986).

1.3.2 Pillar 2: Social concerns

The economic concerns influence the management of water as a private or a public good. With the growing need of the societies for distant sources of water, the tendency is to provide water supply and sanitation access in a centralized way, with a progressive abandonment of local sources (Bakker 2003), treating water as a *public good*[3].This definition entails the risk of using the *general interest* of the citizens to justify management practices that may not be acceptable for all the population (Aguilera Klink 2008, chap. 3; Swyngedouw 1999). Dellapena (2000) argues that water is not a public good, but treated as such because the costs of excluding others from its use are too high or the cultural values require that all receive a "fair" share of it. As a *private good,* its management tends to be close to *water commodification* (Swyngedouw 2005).

As either public or private good, a most extended strategy is the *privatization of (the provision of) water services*, which is a recurrent topic in the assessments of water law (See for example, Bakker 2004; McDonald and Ruiters 2005).

The UN General Assembly established access to water as a millennium development goal (2000) and later on recognized "the right to safe and clean drinking water and sanitation as a *human right* that is essential for the full enjoyment of life and all human rights" (2010, 2). In the declaration, it is recognized the role of water in enforcing other human rights such as i) the right to life and human dignity ii) the highest attainable standard of physical and mental health and iii) an adequate standard of living (UN Human Rights Council 2011, 2). Access to water services beyond the minimum requirement is considered a *citizenship right* (Arrojo Agudo et al. 2005; Arrojo Agudo 2006).

The human right to water services is related to the definition of water as a *social asset* (Aguilera Klink 1991). Kelso (1967) called this idea the "water is different syndrome" and argued that it is founded in false beliefs about the social needs of water which are, in fact, (economic) preferences for the use of water. However this definition of water did not have its origin in economic preferences but in the special physical and social characteristics of water (Bower 1963); which are not dealt with when defining it as a mere productive factor (Ciriacy-Wantrup 1967) and which make institutional settings beyond the market an essential item for its management (Bauer 1998, 1997; Ciriacy-Wantrup 1969).

[3] A good is considered public when its use by one individual does not reduce its availability for others. A typical example of a public good is the knowledge.

When water is defined as a social asset, two main discussions arise, which show the need of involving social actors in water management.

On the one hand, criticism rises about how market contributes to water management. As a social asset, water cannot be priced. As a result, water property rights, chrematistic values, and markets can never be properly defined and some other factors beyond efficiency should be taken into account in the matter of water management, such as fairness and equity. Another example is posed by those which defend that water is better managed by the 'economics of collective action' (Bromley 1982; Brown and Ingram 1987), an idea worthy of the Nobel Memorial Prize in Economics to Elinor Ostrom. She proved that scarce common pool resources such as water can be better managed with cooperation rather than with competition at local level (Ostrom 1990).

On the other hand, its definition as social asset clashes with commodification and privatization practices. Commodification and privatization are two very much criticized strategies that use market rationality (Castro 2013) for the valuation of water and the control of water-related human relations respectively. These strategies are frequently seen as ways of creating and maintaining certain power relations (Bakker 2003, 2004; Castro 2007, 2008; Swyngedouw et al. 2002; Swyngedouw 1999, 2004, 2005).

1.3.3 Pillar 3: Raise of environmental awareness

The provision of proper water supply and sanitation services is restricted by the limits of the ecosystems, which grant access to and *water resources* or *freshwater*. Water resources are defined as both those water bodies which are accessible for humans (FAO 2012a) or as the amount water that they hold (Shiklomanov 2000). The voice *water renewable resources* refers to quantitative terms only, as it describes those resources that can "return to their previous stock levels by natural processes" (FAO 2012b).

In this discussion, water is mostly defined as an *ecosystem service (ES)*. With the aim of raising the awareness about the dependence of human well-being on the ecosystem functions, the Millennium Ecosystem Assessment (MA) defines water as a part of "the benefits people obtain from the ecosystems", (Millennium Ecosystem Assessment 2005, vii). In the MA, water is considered an ecosystem as well as a group of ecosystem services (Vörösmarty et al. 2005), as shown in Table 1.2.

Table 1.2. Main water ES identified in the MA (Summary from Aylward et al. (2005a))

Provisioning	Regulatory	Cultural	Supporting
-Water Supply -Aquatic organisms for food and medicines	-Maintenance of water quality -Mitigation of damage -Buffering of flood flows -Erosion control	-Recreation -Tourism -Existence values	Maintenance of : -Nutrient cycling -Primary production -Ecosystem resilience

When water is defined as an ecosystem service or as a limited resource, management strategies are conditioned by the natural limits to water use and the need of maintaining a good state of the water bodies. Example of these strategies are the recommendations of using management units which recognize the systemic interactions of different water bodies –like the river basins (FAO 1995)– or the mandates of legal frameworks to promote the good ecological status of the water bodies (see for example the WFD).

1.4 Conclusions

Water analyses and management strategies are deeply influenced by the main water discourse, which is in turn formed by the interaction of different (social, scientific, politic, etc.) narratives. Each of these narratives perceives water in a certain manner, resulting in the definition of the element from many different perspectives. The reflexive modernity guides the water discourse –to a certain extent, globally- towards the evolution of the water culture and the adoption of integrative approaches like IWRM. It seems that hydrology, highly influenced by the social, economic and environmental concerns of IWRM and the reflexive modernity is experiencing (has been already) a change in its focus. This change is pushing the field from the conventional analysis of water process to include ecosystems and societies as important parts of the water cycle dynamics and defining new waves like socio- and eco- hydrology. One of the signals that indicate such a movement is the inclusion of social scientists in the hydrology sections of the American and European Geological unions.

However the integrative waves are easier to pursue in theory than in practice, resulting in the criticism that IWRM has received since its origins. Besides the commentaries about the effective implementation, still some voices consider that IWRM is an oxymoron, because the isolation of water from the rest of the resources already hinders its option for success. Concepts like the nexus which is a derivation of integrated management of resources seem to come to push away already the concepts that are not yet even established. Naturally, in a dissertation it is impossible to solve all the challenges that the new water culture, the socio-ecohydrology and the IWRM face. Beyond the obvious restrictions of time and space, an effective implementation of IWRM requires political will which in many occasions clash with the established one-dimensional approaches to water analyses and management.

Since a single PhD research line can do little about the asymmetries of power among the narratives that form the water discourse, the best this dissertation can contribute is an analytical framework where the narratives mentioned find an intellectual and methodological space for its integration.

Chapter 2
The metabolism of socio-ecosystems

"A human being is a part of the whole, called by us 'Universe',
a part limited in time and space"

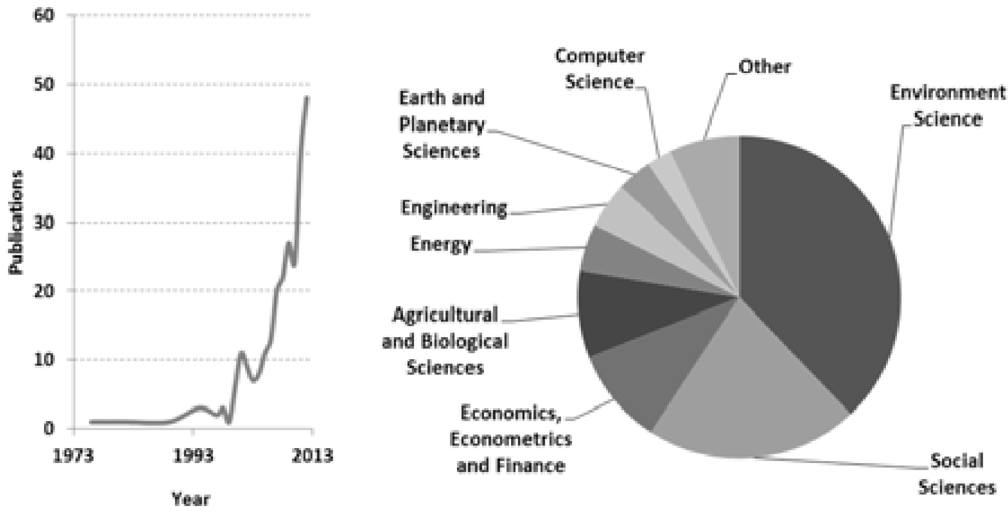
(Einstein 1950. Letter to Robert S. Marcus)

2.1 The boom of metabolic studies in Sustainability Science

The relations between man and nature were clearly included in the conceptualization of the world until more or less the Enlightenment. With the arrival of the logic of Mechanics and the raise of Neoclassical Economics, the study of social relations was driven apart from the relations of nature (Martínez Alier 1987). Consequently, natural and social sciences have generally tended to develop apart from each other. During the last three centuries the works that relate humans and nature have been rare and generally related to the broad fields of Energetics, Ecology and Anthropology (Naredo 2003). However, in the last thirty years this tendency has changed, mainly due to the recent ecological and resource crises. One concept stands out over the rest in these studies: the concept of (social) *metabolism.*

A search in Scopus for the terms "Social Metabolism", "societal metabolism", "society's metabolism", "urban metabolism", or "rural metabolism" in the title, abstract and keywords of works published until 2012 shows how the scientific literature that uses this concept to assess the relation between man and nature grow every year (Figure 2.1). As a result of the rapid proliferation in the number of these studies, the metabolism analogy "has been left largely unexamined" (Lifset 2004, 1). As a scientific field, metabolism studies has not included an epistemological debate about the meaning of metabolism.

Figure 2.1. Evolution of the number of published works on Social Metabolism and their subject area (Scopus)



2.1.1 A note on terminology

The use of the term metabolism is consistent within medical sciences, in which it was originated. Physician Ibn Al Nafis in the 13th century described the reproduction of individuals as a series of internal processes (anabolism and catabolism[4]) in which "*the body and its parts are in a continuous state of dissolution and nourishment, so they are inevitably undergoing permanent change*" (Al-Roubi 1982).

However, as referring to the relation between humans and nature, different conceptualizations of 'metabolism' coexist. 'Metabolism' is interpreted as:

i) a metaphor useful to study the biophysical exchange between society and ecosystem (Matthews et al. 2000; Haberl et al. 2007);
ii) an analogy providing similarities between society and ecosystem dynamics (Ayres 2004; Ho and Ulanowicz 2005),
iii) the biophysical impacts of power relations (Martínez Alier 2004; Naredo 2006; Muradian and Martínez Alier 2001), or

[4] Anabolism and catabolism are the two phases (productive and consumptive) of metabolism.

iv) the property of systems using biophysical flows to organize themselves (Georgescu-Roegen 1971; Giampietro et al. 2011; Ramos-Martin et al. 2007).

Also different terms coexist, such as 'Social Metabolism', 'societal metabolism' or 'socio-economic metabolism', which are indistinctively used to refer to any one of the above conceptualizations. This confusion hinders the development of a *theory of Social Metabolism*. See for example the discussion about how to tackle energy metabolism of H. Haberl and M. Giampietro in the Journal of Industrial Ecology (Haberl et al. 2006; Giampietro 2006; Haberl 2006).

One thing is to talk about 'metabolism' as an interdisciplinary scientific field acknowledging the existence of a relation between humans and nature. In this sense, Social Metabolism is synonym with social or *industrial ecology* and in line with ecological economics (Proops 1989; Christensen 1989; Costanza 1989; Ehrlich 1989; Røpke 2005; Ayres and Ayres 2002). Another thing is to use the term to refer to the characteristics of specific systems (Zipf 1941; Cottrell 1955; Odum 1971a, 1971b; Fischer-Kowalski 1998; Swyngedouw 2006a; Ramos-Martin et al. 2007; Giampietro et al. 2011). In this case, the metabolic pattern is the object under study. In this last sense, not only the metabolic pattern of societies, but that of any self-reproducing system (e.g., cities, households and, also, ecosystems) can be conceptualized and studied (Giampietro et al. 2011; 2014).

To avoid further confusion, in the rest of this dissertation, *Social Metabolism* will be used when referring in general terms to the scientific field. When the term 'metabolism' is used to refer to expected characteristics of specific systems, labels such as *societal* metabolism or *ecosystem* metabolism will be added. With this assumption Social Metabolism is the field that has as object of study the relations between societal metabolism and ecosystem metabolism.

2.2 Social Metabolism as a field of study in Sustainability Science

The use of the concept of metabolism to study the relations between man and nature dates from the end of the 19th century and the beginning of the 20th. During the 1960's the concept was 'rediscovered' and has been used until today (Ayres and Kneese 1969; Daly 2003). However as a field, it has advanced in waves in response to resource crises, without a proper epistemological debate.

Metabolism has been used in parallel but not in an integrated manner to describe both the societal and the ecosystem's biophysical requirements and the processes that use them. However, it seems that the study of the metabolism of ecosystem has not reached such a prominent role as the metabolism of societies has. As a result, the field of Social Metabolism is still too focused on social dynamics, with a conceptualization that stresses the irreversible character of the biophysical exchange.

2.2.1 Roots in social energetics and sociology

Current and early sociologists focus their work in the assessment of the internal dynamics that guide the organization of societies. Some of them studied the biophysical needs of these dynamics, including energy and materials. Authors who studied social energetics are frequently referenced to as the first who studied the metabolism of societies (a more detailed explanaition can be found in Giampietro and Mayumi 2009; Cleveland 1987; Martínez Alier 1995). They tend to focus on the importance that the control over energy sources and processing has for the maintenance of the social dynamics.

Physician and socialist Podolinsky (1995) studied the critical contribution of energy surplus to the maintenance of the societies. Chemist Soddy (1995) argued that wealth is actually generated by the energy used in the transformation of materials in goods and services. Mathematician Lotka (1925) made an important distinction between the endosomatic (individual) and the exosomatic (societal) energy metabolism, setting the foundations of biophysical economics. Sociologist Geddes (1995) proposed the substitution of monetary flows for energy flows in the study of the political economy. In line with this, Chemist Ostwald (1907) approached societal and cultural progress by measuring the efficiency in energy use. He recognized the limits imposed by fossil fuel scarcity and promoted the efficient use –versus the waste– of energy as a key factor for the cultural development of societies.

Anthropologist White (1943) added a qualitative factor to the discussion. He argued that societies developed certain forms of technology to deal with daily tasks and that each of them required different sources of energy. With these ideas, Sociologist Cottrell (1955) highlighted that the identity of an energy converter defines the identity of the energy input required. He studied how socio-economic changes affect the use of certain types of energy and how this affects the societal structures and functions. Philologist Zipf (1941) proposed the description of societies as biosocial organisms that perform a number and type of coordinated processes. These activities rely not only on the use of energy, but also on the availability of human activity. Humans are in this way described as a functional part of the society.

The study of the material metabolism has followed that of the energetic metabolism of societies. With the materialists' ideas of Moleschott and Liebig, Marx

(1859) highlighted the material basis of the maintenance of life, as indicated by the German term used by the author: *Stoffwechsel* (literally, stuff exchange). There is no consensus about how deeply engaged was nature in this relation. One group of authors argue that he used the term just to refer to the exchanges that took place within societies (money and labour included) without establishing a connection between the societies and the ecosystems (Martínez Alier 1987; Martínez Alier and Naredo 1982; Benton 1989; Naredo 2003). Some others maintain that his definition implicitly involves the characterization of societies as parts of nature, that coevolve with it (Norgaard 1994; Foster 2000) as he spoke about a rift between the nature and societal metabolisms. In any case, he contributed to the development of the Social Metabolism by defining societal metabolism as the labour-controlled circulation, exchange and transformation of material elements (Swyngedouw 2006; Foster 2000).

Schäffel's (1881) definition included some of the ideas that later on would be used by theoretical ecologists. His usage of metabolism includes a prominent role of the limits ecosystems pose to societies. He shares the worry about efficient use of energy of Ostwald and distinguishes the progressive and regressive parts of the metabolism of societies, which are close to Ulanowicz's idea of productive and dissipative functions of the ecosystem. Padovan (2000) argues that Schäffel recognized the importance of the exchange with nature not only for the maintenance of the biophysical part of the society but also for the maintenance of its structures. He argues that for Schäffel:

> *"the exchange of materials does not only serve as a means of conserving the bio-organic substratum of society, that is conserves biological bodies, it is also indispensable for maintaining the extra-organic parts of the social body: the functions of social life, the spiritual, religious, ideas, culture and symbolic aspects which cannot exist without an exchange of materials" (Padovan 2000, 1).*

In this way, the regulation of the societal metabolism depends on the conscious needs and reasons developed by the society. According to Padovan (2000), Ward (1906) built on the work of Schäffel adding that the transformation of nature by humans was a requisite for the progress, as it was necessary for the society. In this way, the links with the ecosystem are mentioned just as a consequence of the societal dynamics, among which is the need for the control of nature.

2.2.2 Roots in Ecology and thermodynamics

These first works that highlighted the connection between ecosystem and social dynamics and the energy requirements of ecosystems come from the field of Ecology and include principles of Thermodynamics.

Quantum physicist Schrödinger (1967) studied the connection between the maintenance of living systems and their physical exchange, thus focusing in the description and measurement of the energy flows that maintain societies and ecosystems. For Schrödinger, the metabolic processes in living systems are possible because of their ability to feed on "negative entropy"[5], exporting positive entropy to the surroundings and avoiding the consequences of the second law of thermodynamics. Geologist Vernadsky (2002) proposed the concept of biochemical cycle that connected the metabolic processes taking place at different spheres on Earth (also approaching the study the interaction between society and ecosystems).

Theoretical ecology pioneers have studied the organization of the ecosystem, its relation with the human system and how the flows of energy affect both. Margalef (1968a) and Odum (1971b) defined ecosystems as metabolic networks that organize themselves through *informed autocatalytic loops*. These metabolic networks express systemic properties that can be useful to assess its functional and structural organization. Following this idea, Ulanowicz (1995) describes the *ecosystem integrity* as the configuration of the structures and functions that allows them to exist as a whole. This whole is formed of two main functions (Ulanowicz 1986) the productive and the dissipative. The productive part is formed by those structures whose function is to made a surplus of energy available to the dissipative part, which at the same time is responsible to control the integrity of the system. The impact that the societal biophysical requirements exert over the ecosystem (Odum 1996, 1971a) and the complex organization of the ecosystem and the society (Holling 2001; Allen and Starr 1982; O'Neill et al. 1986) have also been assessed by these authors.

2.3 Defining the human-nature relations: socio-ecosystems

The historical lack of conceptual integration between the societal and the ecosystem metabolisms is one of the drivers of the resource crises because it promotes a situation of ignorance in which resource use cannot be adapted to resource availability (Giampietro et al. 2012). The need for a more holistic approach to the analysis of the interface between socio-economic systems and ecological systems is illustrated by the popularity gained in the last years of the term *socio-ecological system (SES)* (Berkes and Folke 1998a; Young et al. 2006; De Aranzabal et al. 2008).

[5] A quite controversial concept in conventional physics

A unique formal conceptualization of the SES is not possible because it would require the integration of different narratives and the simultaneous use of non-equivalent descriptive domains. This implies that even if the strong link between human and ecosystem processes is acknowledged, the way in which this relation is defined in analytical terms will be different depending on the aim of the study. As a result, different tendencies exist for the definition of SES. Some definitions (Berkes and Folke 1998b; Berkes et al. 2002) emphasize the idea that man is inserted in an ecosystem, following the work of theoretical ecologists (Odum 1971b; Margalef 1968b). This approach uses the concept of *resilience* as a tool for the delimitation and assessment of the sustainability of SES (Folke 2006). The other main perspective describes the ecosystem as an entity that is integrated within the social sphere and influenced by its relations and it assesses the SES using the frame of *adaptation* (Janssen et al. 2007; Anderies et al. 2007). Works also exist that connect both approaches and which include the idea of *vulnerability* (Gallopín 2006; Young et al. 2006).

Farhad (2012) argues that the following characteristics are common to the many definitions and interpretations found in the literature:

- human societies are embedded in ecological processes with which they have strong biophysical ties; and
- the socio-economic system and the ecological system in which it is embedded should be considered as one *complex adaptive system* (Holland 1992), which is expected to express non-linear behavior and, therefore, is difficult to model.

2.3.1 Socio-ecological systems as holarchical, open and autopoietic systems

SES have been classified both as networks (Norgaard 1984; Ostrom 1990) and hierarchies (Odum 1971b; Allen and Starr 1982; Kay et al. 1999). This last definition, as we explain in section 2.4, offers a better ground for metabolic analyses. *Hierarchy theory* is the branch of *complexity theory* dealing with the epistemological implications of multiple scales (Grene 1969; Pattee 1973; Salthe 1985; Allen and Starr 1982; O'Neill 1989). According to hierarchy theory, the same system does express different identities depending on the scale at which it is observed. The *identity* of an observed system is each of the researcher's perceptions of the investigated system as an entity (or individuality) distinct from its background and from other systems with which it is interacting (Giampietro 2003). Thus, the identity of a system depends on the set of selected relevant qualities (observable attributes) chosen for both its perception and representation.

In analytical terms, the identity of a system can be characterized by measuring the process rates at each of the levels of observation (O'Neill et al. 1986). The processes at a certain level act as a filter for the processes at lower levels in the hierarchy (Giampietro 1994).

Koestler (1969) stated that *living hierarchical systems* can be perceived and represented only in terms of *holons* Holons represent at the same time a part of a whole at one level –a *black box* interacting with its context– and wholes formed by parts at lower levels. Living hierarchies, can be expressed as the inter– and intra-level relations between holons (Giampietro 1994) and defined as *holarchies* (Koestler 1967). These relations influence each other and form cross scale feedbacks (Giampietro 2003). As a result, holarchies show an aggregate behaviour that does not equal the sum of the relations between the parts, but that emerges from them (Holland 1992).

In order to adapt, living systems' holons communicate a set of biophysical and/or information flows to the higher level, which has the capacity of restructuring the lower levels (Holling 2001; Simon 1962a). The information exchanges at one level operate at a pace that is fed from the pace of the higher levels and the pace of the lower levels. Maturana and Varela (1980) called this type of organization *autopoiesis.* The autopoietic organization refers to a network of processes of production, transformation and destruction of components that (re)produces the very network and its own components plus its boundaries (Giampietro et al. 2009b; Varela et al. 1974). In summary, autopoiesis refers to the property that defines complex living systems (Mingers 2006, chap. 3).

Prigogine (1978) defined *dissipative systems*, as those systems which survive thanks to the reduction of the internal disorder at the expense of the dissipation of energy sources –the concept of negative entropy suggested by Schroedinger–. In this way, the autopoiesis is responsible of the stabilization of the thermodynamic openness associated with living systems far from thermodynamic equilibrium (Ulanowicz 1986; Brooks et al. 1989; Weber et al. 1989). The complex adaptive character of SES has been proved empirically (Liu et al. 2007). Kay at el (1999) implicitly defined SES as *self-organizing hierarchical open* (SOHO) *systems* whose behaviors and structures must be interpreted with reference to non-equilibrium thermodynamics. Structurally SES are *nested holarchies* (Allen and Starr 1982; Giampietro 1994) in which the social holon(s) form a part of the ecosystem holon(s). They express non-linear emergent properties and autopoietic and dissipative behaviour. These characteristics result in scale issues that might hinder the development of SES research and management.

2.3.2 Scale issues in socio-ecological systems

The scale issues might be overwhelming for scientists that aim at dealing with SES. The main issues faced are related not only to the very definition of scale, but also with the multi-scale character of complex systems in general and SES in particular. These issues include the identification of relevant patterns, the definition of causality, or the generalizability of results and management.

The most important scale issue is related to the *epistemology of scale*. The term is used to refer to a number of concepts including level, extension and resolution, which have frequently brought confusion in its usage, especially in social sciences. This confusion is more frequent with the terms level and scale. In complex system theory, *scale* is usually defined as the relevant dimension used to analyze a phenomenon; *level* is referred to as the units within the scale; *extend* is the size of the dimension measured; and the *grain* or *resolution* is the precision used for the measurement (Gibson et al. 2000).

Another important issue exists about how the relevant scales are defined for an analysis. Manson (2008) argues that, since a theory of scale does not exist, the formation of a scale ranges between the pure realism to the pure constructivism. R*ealistic scales* follow the thesis that nature has scales independently of observers. *Constructed scales* are actively created by the observer and therefore the determination of its levels will be entirely manipulated by them. *Hierarchical scales* reconcile realist and constructivist ideas by recognizing the critical contribution of the observer to the definition of the scales and existence of organizational levels in an analysis. The author concludes that the scale should be considered a complex entity whose realistic or deterministic construction would depend on the analysis.

Apart from these epistemological issues, there are other issues that result from the fact that the relations within and between the holons in a holarchy are nonlinear.

The first issue is related to the difficulties faced for the identification of the object under study. The emergent behavior and the holarchical character of SES results in the appearance of different identities, for each of the levels under observation and each of the narratives that guide it. Each identity has an associated *descriptive domain* defined as “the domain of reality delimited by interactions of interest” (Kampis 1991, 70). The concurrence of multiple levels mentioned before implies the unavoidable coexistence of *non-equivalent descriptive domains* that cannot be reduced to each other using a formal system of inference (Mandelbrot 1967; Rosen 1985). As a result, each identity and descriptive domain is observed within a scale defined by the boundaries of the description (its extent in space and time) and its grain (resolution).

A consequent second issue is the difficulty of establishing causality in SES due to the presence of *impredicative loops* (Rosen 1991). This means that the definition of independent and dependent variables used to explain a process is affected by the choice of focal level of analysis implying a given scale. For example in theoretical ecology has been proved that when adopting a given scale of analysis the number of predators (independent variable) determines the numbers of the preys (dependent variable), but when the scale of analysis is changed the reverse causality is found (Carpenter and Kitchell 1987). For this reason, the choice of researchers of a given scale for observation may be determining a relation of causality (Giampietro and Mayumi 2003).

A last issue is known as *scale mismatch* (Cumming et al. 2006; Cash and Moser 2000) and it is associated to the fact that the levels of the processes, of the analysis and of the management of SES usually do not match. For example, in the definition of boundaries for a studied system, the relevant extent used for its management (economic) might not fit with the extent used for the analysis (ecosystem). The scale mismatch can be produced from the lack of understanding of the functioning of SES or from unrecognized changes in a process (social or ecosystemic). It is generally accepted that the scales mismatches in SES result in deficiency of appropriate analytical frameworks and mismanagement of the SES and their holons (Cumming et al. 2006; Cash and Moser 2000; Lovell et al. 2002; Gibson et al. 2000; Giampietro 2003; Giampietro et al. 2006).

2.4 A conceptual framework of the metabolism of socio-ecosystems

Social Metabolism researchers currently faces the immense challenge of designing comprehensive analyses of the societal-ecosystem dynamics (Golubiewski 2012) but they try to deal with it without having questioned its own theoretical roots. The lack of debate has generated a certain state of fuzziness in which works that assess only some metabolic relations are categorized as full metabolism analyses (Giampietro et al. 2011).

A system's metabolism is a dissipative process in which a biophysical exchange is guided by the structural components of the system. The exchange is possible only because of favorable external boundary conditions. In this way, there is a clear differentiation between the system's internal dynamics and the dynamics of its surroundings (the context). As the activity of ecosystems defines the boundary conditions for the metabolism of any society, comprehensive analyses in Social Metabolism should include not only the processes characterizing societal metabolism but also those processes characterizing the ecosystem metabolism, or in other words, the whole complex of metabolic patterns of the SES.

According to its two main properties of SES, a comprehensive analysis of the metabolism of SES should include:

- the process of internal *self-organization (for components of both ecosystems and societies)*, and
- the process of *biophysical exchange* with the surroundings *(for components of both ecosystems and societies)*.

The biophysical exchange with the surroundings is essential for the survival of any metabolic system. Such an exchange is possible only if favorable external boundary conditions exist. In conceptual terms, the existence of boundary conditions entails a clear differentiation between the internal processes of a metabolic system and its surroundings (the context). As the activity of ecosystems defines the boundary conditions for the metabolism of any society, comprehensive analyses in Social Metabolism should include not only the processes characterizing societal metabolism but also those characterizing the ecosystem metabolism.

Figure 2.2. Relations that need to be included in the study of the metabolism of SES.

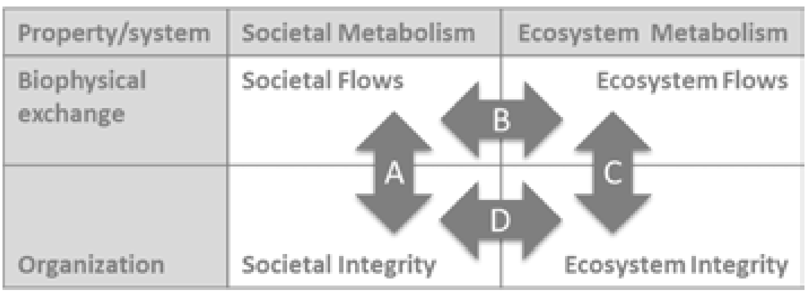


Figure 2.2 –which will be recurrent in the rest of the dissertation– shows the set of four relations relevant to the study of SES metabolism:

- Relation A indicates the dependence of the social organization on material and energy flows for their functioning and reproduction. Examples of the study of this relation include the works in environmental justice (Martínez Alier 2004, 2009; Schneider et al. 2010).

- Relation B encompasses the energy and material exchange (describing only flows) between society and ecosystem. This is the most widely assessed relation in Social Metabolism and has been studied for materials, energy and also water (as, for example, Bringezu and Moriguchi 2002; Haberl et al. 2007; or Kenway et al. 2011). This relation is frequently combined with relation A in input-output analyses that relate economic activity with biophysical flows (Lenzen and Foran 2001; Wiedmann et al. 2007).
- Relation C indicates the dependence of the ecosystem organization on material and energy flows for its own functioning and reproduction. This relation is mainly studied by ecologists (Odum 1983; Margalef 1968a) and has been combined with relation B in, for example, studies on ecosystem services (de Groot et al. 2002).
- Relation D deals with the structural organization of SES (Gallopin et al. 1989; Berkes and Folke 1998b) and the existence of a connection between societal and ecosystem structures and functions. The nature of this relation is one of the objects of study of Complex Systems Theory (Pattee 1973; Salthe 1993; Koestler 1969).

2.4.1 Why a hierarchical organization of SES for metabolism studies?

As previously commented in section 2.3.1 the complex nature of the SES (relation D) can be represented as a network or as a nested holarchy and in this last case, the societal holon(s) (Koestler 1969) would be represented as part of the ecosystem holon(s). As with the case of other hierarchies, the study of a holarchical SES can use the basics of hierarchy theory in order to deal with the scale issues –like *system definition*, *methodology selection*, and *identity changes*– explained in section 2.3.2. This representation is useful for three reasons.

First, the holarchical conceptualization is useful to frame not only the biophysical exchange but also the interaction of the societal and ecosystem organizational structures. It explains why the pace of the social processes is limited by the pace of the ecosystem processes –because the latter are on a higher hierarchical level and therefore it acts as a filter on what the lower level can or cannot do in relation to favourable boundary conditions– and vice versa, why the societal processes can accelerate locally ecosystem processes.

Second, when different hierarchical levels are described, the processes at each of them can be studied using methods able to observe their pace and type, using a more appropriate narrative. For example, the economy of a country *S* can be assessed with macroeconomics methods like *Input-Output* (Leontief 1951), which can observe processes happening within a time-extend of one year. For the observation of the changes in an ecosystem methods able to deal with longer time extends are needed, such as the assessment of an ecological succession in decades or centuries (Odum 1969).

Third, this type of representation explains why SES express different identities and behavior at different levels of observation (Simon 1962b; Pattee 1973; Salthe 1985, 1993; Allen and Hoekstra 1992; Ahl and Allen 1996). The integrated use of suitable narratives for the observation of each of the levels (holons) across different descriptive domains needs the adoption of a new language.

2.4.2 The need of a comprehensive view of SES metabolism

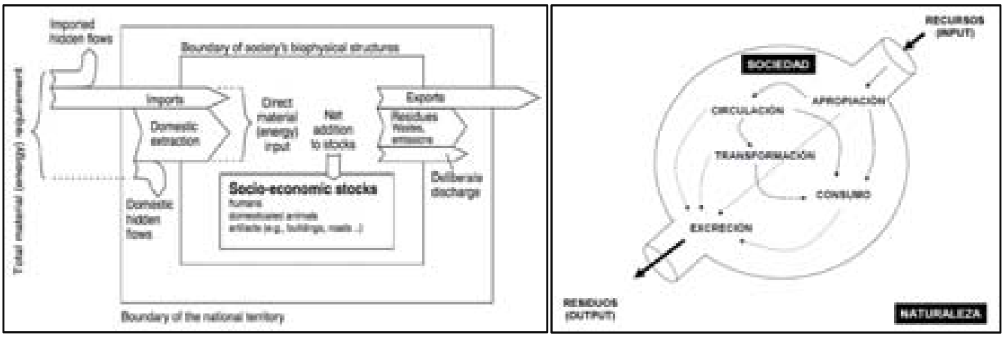
Some authors (Giampietro et al. 2011, 2012) argue that the term metabolism should be described by all A, B, C and D relations of Figure 2.2. However, the historical conceptualization of the metabolism presented in the sections above has hardly covered them. As Table 2.1 shows, almost all relations have been analyzed, but not simultaneously. A comprehensive description is hard to tackle analytically and most of the studies focus on relation B (the extraction of materials from nature). Whereas this extraction is relatively easier to observe, the complex behavior of SES is, by definition, difficult to pattern.

Table 2.1. Relation between the theoretical framework and the intellectual roots presented above

Relation/Flow	Energy	Material
A (Societal dependency)	Podolinsky, Soddy, Lotka, Geddes, Ostwald, White, Cotrell, Zipf,	Marx (Moleschott, Liebig), Schäffel, Ward.
B (Flow exchange)	Schrödinger, Vernadsky	
C (Ecosystem dependency)	Margalef, Odum, Ulanowicz, Prigogine,	Vernadsky
D (Holarchical organization)	Holling, Allen, Koestler, Maturana, Prigogine	

There are two main problems when metabolic analyses are too focused on relation B. On the one hand, the emphasis is given to the flows whereas the really important question –if the are compatible with the structures and functions of both the society and the ecosystems– is neglected. For the society, the relevant aspect is to see how biophysical flows contribute to the maintenance of its internal functional structures. In the same way, the important is not how much (material, energy) flow is appropriated from an ecosystem, but how this appropriation interferes with its organizational processes, affecting the possibility of reproducing its functional structures.

Figure 2.3. Two conceptual representation of Social Metabolism that emphasize biophysical exchange by Haberl et al (2004) (left) and Toledo (2008) (right).



On the second hand, when flows are the focus of the study, the society is perceived as a *black box* that does not allow seeing the components and their interactions. In this case, the only way of evaluating the evolution of the system is to assess the changes in the flows. When this is the case it is difficult to know whether a decrease of energy use in a country is due to the change in consumption patterns, to a decrease of the population, or to the delocalization of the production (externalization through imports).

Figure 2.3 shows two widely extended representations of the Social Metabolism. Both give a high relevance to biophysical flows, while the internal organization of the system is not complex. In the left scheme, the black box scheme is clear, as only the input and output flows plus stocks are represented. The right scheme shows some internal processes, like circulation or transformation but not as functional structures of the system. Also in both cases the society is represented as a whole, not as a holon forming part of an ecosystem. In other words, the ecosystem is not considered beyond the extraction of the flows, thus neglecting relations C and D of the presented framework.

Due to the issues of scale presented above, failing to include all four relations in Social Metabolism studies is quite dangerous. A comprehensive conceptualization must include the social processes and the ecosystem processes together with the biophysical flow. In this way, the field Social Metabolism should not assess the societal metabolism only, but the metabolism of the SES.

2.5 Conclusions

This chapter has been included in the structure of the dissertation with the course of the time. From the beginning the idea was to search for methods that could support the inclusion of water within the current developments of the social metabolism, and not to question its roots. It did not seem estrange that water was excluded from the analysis given the situation of lack of data inherited from the old water culture as presented in Chapter 1. In turn, the fact that the metabolism concept –while so well known- was not used much within hydrology –with the exception of maybe Swyngedouw- switched on a light about the need of questioning how the field of social metabolism was advancing.

A look at the epistemology of the analogy of metabolism shows that the field is also dealing with its own challenges. As Lifset (2004) puts it the analogy of metabolism "has been largely unexamined" and "defined by usage". A definition of the water metabolism could not be solid if it is built on unsolid ground. This is why the approach to the definition of the socio-ecological systems, their complexity and their metabolism has been necessary. The scheme proposed here for the classification of relations is naturally one option, but so far it has proven useful in providing a map where the different metabolism-related works can be located. The idea is that if the purpose is to bring closer certain narratives, it is useful to know where these narratives stand.

Using this conceptual scheme it can be argued that most of the works that use the concept of metabolism are somehow partial. It is not a bad thing, but not acknowledging this fact does hinder the purpose of integration that is pursued in water and sustainability science.

Chapter 3
The water metabolism of SES

"I ask the reader to remember that what is most obvious may be most worth of analysis. Fertile vistas may open out when commonplace facts are examined from a fresh point of view"

(Whyte 1965, 24)

3.1 Water metabolism as a bridge between SE-hydrology and Social Metabolism

Water can be considered the Achilles' heel of metabolism studies. The assessment of material balances have for a long time avoided including water (Matthews et al. 2000; Eurostat 2001, 2013) or have recommended its analysis in a separate account (Schandl et al. 1999). The reasons cited include *excessive volumes* (Wolman 1965; Fischer-Kowalski and Haberl 1998), *shaky flow taxonomy* and *data unavailability* (see for example Matthews et al. 2000; Naredo 2003; Carpintero 2005). Due to the difficulties in its analysis, the OECD (2008, 31) treats water in a special material category: "the borderline cases".

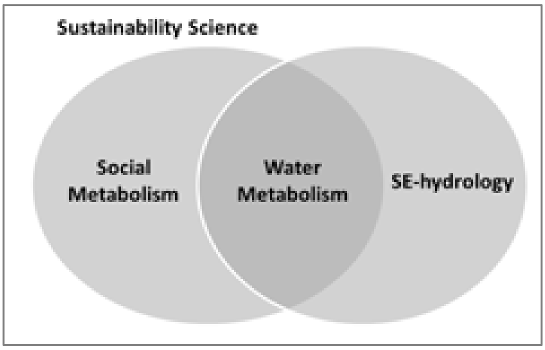
The attempts to represent the interaction between humans and nature in metabolism studies have revealed the epistemological challenges explained in Chapter 2 –too much emphasis in the societal holon and in the biophysical exchange. Within this setting, some explicit efforts have been made towards the inclusion of water in metabolism studies but these have resulted problematic (see, for example, Koehler 2008) in relation to:

i) the classification of water as an exchanged flow and

ii) the delimitation of a *water observation system* (WOS)

In analytical terms, metabolism studies characterize a metabolizing system and a *metabolite*, that is, the biophysical flow that maintains the system alive. The nature of the metabolite determines the taxonomy of its flows, the ways in which the observation system must be delimited and the methods required for its analysis. In other words, metabolism studies –as the field that assess the organization and biophysical exchange of the SES– must be complemented by a field which understands the specifics of the metabolites (nitrogen, energy, etc.), in this case, hydrology.

Figure 3.1. Integration of the fields of Social Metabolism and SE-hydrology



In metabolic jargon, SE-hydrology approaches water as a metabolite, a part of a system and as a system itself. As a metabolite, it is defined as a flow consumed by the society. It is also an essential part of the ecosystem. When the regular patterns of water processes change in the ecosystem, the ecosystem changes its identity. Also, water at the Earth level is a system itself, usually known as the water cycle.

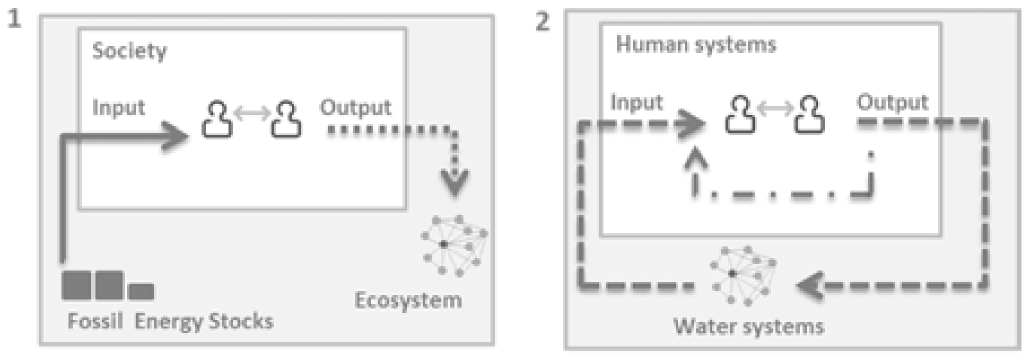
Hydrology has traditionally focused on the 'natural functioning' of the water cycle, studying it as a complete system without including in the observation the activity of ecosystems and humans. As explained in Chapter 1, it has only recently begun to recognize the important role of ecosystem and anthropogenic activity (Savenije et al. 2013) over the higher level of the water cycle, giving rise to the development of a socio-hydrology, an eco-hydrology and their integration, a *socio-eco-hydrology* (SE-hydrology), and integrating social and ecosystem dynamics in traditional hydrology analyses (Falkenmark and Rockström 2004; D'Odorico et al. 2010; Pataki et al. 2011; Sivapalan et al. 2012).

This integration is one of the challenges of IWRM which SE-hydrology has not yet overcome. Epistemologically, SE-hydrology lacks a conceptualization of the coupled human-water systems that facilitates the integration in conceptual terms and serves as foundation for the development of a methodological framework. Metabolic studies can provide this conceptual ground since coupled water-human system can be defined as a specific case of SES. The common space of SE-hydrology and Social Metabolism (Figure 3.1) in what it can be called *water metabolism studies* (WMS).

3.1.1 The challenges of Social Metabolism for the inclusion of water

A reflection about the concept of metabolism like the one developed in Chapter 2 is not only needed for the internal evolution of the Social Metabolism field, but also as a way of identifying potential synergies with other fields which have a better understanding of the metabolites.

Figure 3.2. The linear nature of (fossil) energy metabolism (1) and the cyclic nature of water (2)



As mentioned earlier, Social Metabolism is strongly rooted in the development of (social) energetics (Cleveland 1987; Geddes 1995; Giampietro 2014). In the early works of Podolinsky (1995 [1880]), Geddes (1995 [1885]), Ostwald (2009 [1907]), Soddy (1995 [1922]), Lotka (1925), Zipf (1941), White (1943) and Cottrell (1955) societal metabolism is described as a chain of societal processes that dissipate a set of specific types of energy inputs that are essential for the maintenance, reproduction and functioning of society. These early contributions were heavily conditioned by the industrial revolution and the growing exploitation of fossil energy sources and deeply associated with the social changes of the time. The general perception of fossil energy as a reserve that is depleted when used to generate a flow of energy input to society led to the adoption of a basic narrative of energy metabolism as an irreversible, linear energy flow. This may explain why from the onset the focus of energy metabolism has been mostly on flow exchange and the social biophysical dependency (relations A and B in Figure 2.2).

A first challenge faced in the definition of the water metabolism is the fact that the narrative about Social Metabolism has been predominantly *occupied with linear flows*. Figure 3.2 shows the unidirectional, irreversible flows of fossil energy in the representation of the Social Metabolism (1) and the cyclic flows of water as represented in SE-hydrology (2). The change from filled to dotted line in the graph of energy metabolism shows the change in the composition in the energy form. This differs with scheme (2) where water flows are extracted from water ecosystems. After water use, water output flows go back to the ecosystems and might be available for further use, thus figuratively flowing back. Indeed, a certain mass of water can first be diverted from the water systems to be used in the refrigeration of a thermal station (flow in society), then spilled back to the river (back to ecosystems), then be extracted and used for showering in a household (again in society).

This issue explains the difficulty in finding a proper taxonomy of the water flows since, for example, returns to the environment are difficult to consider, especially in further analytical stages when they have to be considered in quantitative terms.

A second challenge is the strong focus of Social Metabolism in the *social holon* of the SES. In this way, the field delimits its *descriptive domain* using short time extents (usually one year) and compatible space delimitations, such as countries or states. The studies focusing on ecosystem metabolism have a different spatiotemporal scale, usually much longer than one year and geographically delimited by soil types, water catchments or alike. However these are seldom included in Social Metabolism studies, as argued in Chapter 2.

This issue explains why there is often lack and incompatibility of water data: it is usually easier to measure water *availability* within an ecosystem descriptive domain but water *use* is measured within a social descriptive domain. Trying to combine the two in the same quantitative analysis then becomes problematic.

A third challenge is that, since societal metabolism is approached as a black box, there is no conceptual space for the continuity between ecosystem components and social processes. As a result, metabolites are classified as such only when "they cross the border into the socioeconomic system under investigation, that is usually when they are marketed" (OECD 2008, 32).

In the case of water, this issue has two consequences. First, there is no conceptual space that allows the epistemological connection between i) the water flows within the society, ii) the water components of the ecosystems and iii) the water system (the water cycle). Second, there is no space for the definition of different types of water use, most notably direct and indirect.

3.1.2 Integrating Social Metabolism and SE-hydrology

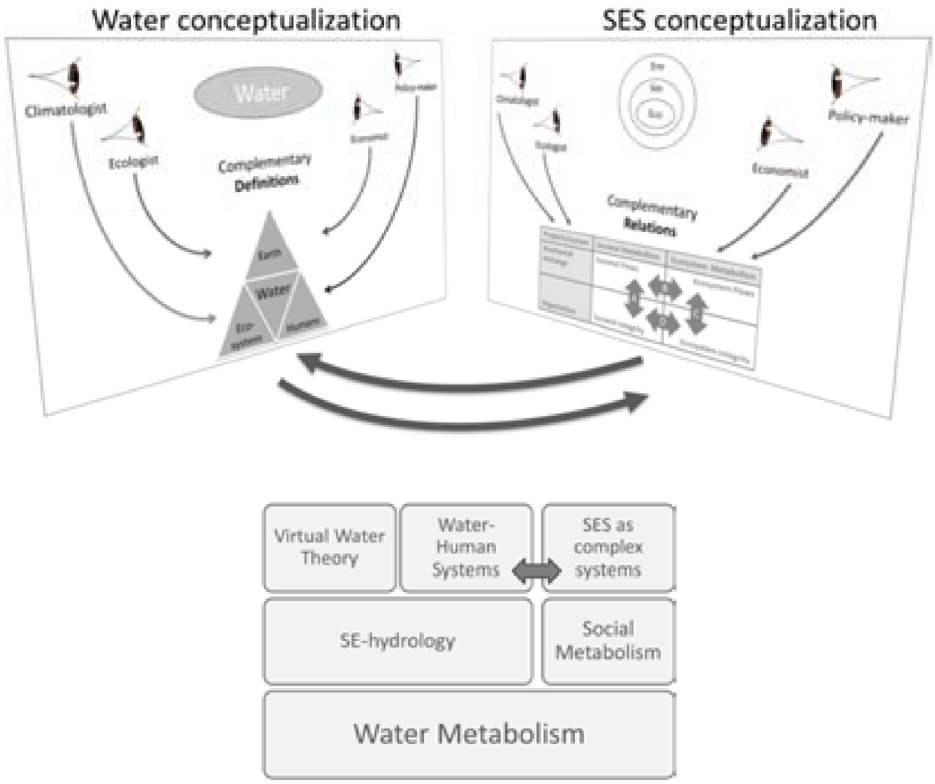
The above issues can be summarized in a lack of a complex characterization of the coupled water-human systems which can be used for the integration of different levels of analysis, and the different descriptive domains and water definitions associated to them. In order to fill this gap, the conceptual framework for the description of the metabolism of SES developed in Chapter 2 is used in combination with:

- SE-hydrology conceptualizations of water as a multidimensional metabolite which allows the consideration of the different dimensions of water presented in Chapter 1: *virtual water theory*, and *eco-hydrology* definitions of the relations between water and the ecosystem
- a SE-hydrology conceptualization of water systems in line with the principles of IWRM and SES: the *coupled water-human systems*

The integration follows the scheme of Figure 3.3.

The conceptual space of the water metabolism contributes to create a bridge between Social Metabolism and SE-hydrology by approaching water-human systems as a specific case of SES. In this way the relations between society and ecosystems and the link between water use and system maintenance find a conceptual space. The theory of virtual water is used as a ground for the description or the multiple roles that water plays in the social and the ecosystem holons of the water-human systems.

Figure 3.3. A conceptual bridge between of SE-hydrology and Social Metabolism.



3.2 A metabolic definition of coupled water-human systems

3.2.1 The global water system

Discussions in the field of SE-hydrology on the link between the water cycle, ecosystems and human activity have resulted in the conceptual definition of the *Global Water System* (GWS (GWSP 2005; Hoff et al. 2010; Vörösmarty et al. 2004). The GWS is characterized as a system in which “the earth (…) behaves as a single, self-regulating system, comprised of physical, chemical, biological, and human components” (GWSP 2005, 15). In this way, the GWS is defined as a hierarchy formed by Earth, ecosystem and social holons (Vörösmarty and Sahagian 2000; Vörösmarty et al. 2004). In this case, not only societal and the ecosystem metabolism can be defined, but also the Earth metabolism of water (see left picture in Figure 3.3).

The ‘*Earth Metabolism of Water*’ is typically known as the Water Cycle. Its continuity is essential for the renewal of water resources for both social and ecosystems. It represents the main energy distributer and temperature regulator of the Earth and determines its geological and biological characteristics. The water cycle requires a huge flow of energy to renew the characteristics and services of water at the level of the whole planet. The flow sums up 44,000 TW –one third of the total solar energy reaching the Earth (Taube 1985)[6].

The '*Ecosystem Metabolism of Water'* is an intermediate level bridging the very large scale of the global water cycle –the study ground of conventional hydrology– to the lower level of the consumption of water by social systems. Water processes at this level allow life by providing essential functions to the ecosystem, thus allowing the provision of services to humans. The higher level is connected to this level because it provides the flows maintaining the ecosystem's 'reservoirs'.

The '*Societal Metabolism of Water* is the lower level of the GWS, in which water processes are related to the maintenance of the societal structures that proved water services to communities and individuals. The pace of the water processes at this level is guided by the pace of the ecosystem metabolism of water, which is guided by the water cycle.

3.2.1.1 The issue of scale in the GWS

Due to its complex character, scientists that deal with the GWS –like those who deal with SES– face the scale issues commented in section 2.3.2. The GWS also expresses different identities depending on the levels considered –Earth, ecosystem or societal metabolism– and their associated *descriptive domains*. This multiple identities are in fact the multiple dimensions of water.

The scale issues are not alien to SE-hydrologists. Hydrology has a natural –or hard– science tradition and natural scientists have been more aware of their importance than social scientists (Gibson et al. 2000), especially with reference to the different extends that are required for a certain assessment.

For the definition of the water metabolism it is particularly important the issue of scale mismatch, which arises when two or more different scales are necessary to reach a good understanding of a phenomenon. Since water can be perceived either as a metabolite (a specific flow), a part of a metabolizing system (ecosystem) and a system that metabolizes energy (the water cycle), it is important that the selection of the scale associated with these different perceptions is compatible with the purpose

[6] This amount represents 4,000 times the total amount of exosomatic energy controlled by humankind in 1999, which was around 11 TW (Giampietro 2003).

of the analysis. As argued below, the Social Metabolism of water operates within scales defined by social processes while ecosystem metabolism of water defines different ones. This mismatch reveals itself frequently when policies are designed with different scale foundations, like agricultural policies and water management policies (Cabello-Villarejo and Madrid-López 2014; Moss and Newig 2010).

The problem of communication between the different narratives that form the water discourse presented in Figure 1.1 is actually at the root of the problem of scale mismatch. The different narratives clash because their descriptive domains, relevant scales and water dimensions (or definitions) are only understood by each of them and irrelevant for the rest.

3.2.2 The descriptive domains of the water metabolism

The GWS is a global expression of the concept of *coupled water-human systems* (WHS) formed by the water-related interactions between the Earth, the ecosystem and the societal metabolism. In order words, WHS are a specific case of SES in which only water-related processes are considered. Due to the issue of scale, WHS do not have natural limits[7] and any *water observation system* is necessarily the result of applying the descriptive domain associated to a certain narrative to the delimitation exercise. In broad lines two main approaches are currently in use in SE-hydrology which are useful for the conceptualization of the water metabolism: the watershed and the problemshed.

In physical terms, a watershed refers to the drainage basin of a river or its borders. In conceptual terms, a *watershed* defines a geographically/physically delimited water system. Due to its strong physical component, some authors have criticized that the isolated use of the watershed for the delimitation of a water observation system neglects other non-physical dimensions (Allan 1998b; Earle 2003) like international trade (Allan and Mirumachi 2012; Zeitoun et al. 2010), or international relations (Daoudy 2012; Turton et al. 2003). Those who follow the watershed approach use the processes within the *Earth* or *ecosystem holons*, usually precipitation patterns or drainage, to geographically delimit water systems. A typical example of a watershed-delimited water system is a river basin, or a particular ecosystem, which is mostly approached by eco-hydrologists.

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[7] The establishment of these limits is a frequent topic of discussion in conventional hydrology –see for example the debates about how to delimit the frontier in *surface-water* and *groundwater* interactions (Sophocleous 2002)

The *problemshed* (Allan 1998b; Earle 2003), on the other hand, defines a domain on the basis of social elements that affect water flows. A strict *problemshed* approach is useful to highlight water issues that are caused by social dynamics, but misses crucial physical links such as the strong link between water and land (del Moral Ituarte 2008; Falkenmark 1995; Rulli et al. 2013). The problemshed approach uses processes within the *social holon*, –such as production and consumption or international trade– to delimit an abstract water system, which is usually difficult to map in geographical terms. A typical example of a problemshed-delimited water system is the water involved in the productions of the goods that maintain certain consumptions patterns, independently of the river basin of origin. Assessments of the problemshed are (implicit of explicitly) conducted by socio-hydrologists.

While the watershed approach is the oldest within SE-hydrology, the problemshed perspective adds very important parameters to the definition of the water metabolism. In hybrid water observation systems there is a space for the connection of ecosystem and social dynamics, even in these last do not inflict any direct pressure over the water bodies. A methodological framework that uses this hybrid conceptualization of the water observation system is flexible enough to combine analyses at each of the holons of the GWS, as argued and presented in Part II of the dissertation.

3.3 Defining the metabolite

The multiple levels of the water metabolism pose a challenge to the definition of water as a metabolite. Water is used by societies and ecosystems in different ways and its conceptualization in each of the holon must be different.

3.3.1 Water within the problemshed: the theory of virtual water

The concept of *virtual water* (VW) can be considered one of the most impacting ideas in the recent development of socio-hydrology (Stockholm International Water Institute 2008). Originally a 'side' idea born from the discussions about water management and agricultural production in the arid Middle East, VW has overcome controversy as a political and economic concept (Ansink 2010; Gawel 2014; Gawel and Bernsen 2013; Kumar and Singh 2005; Merett 2003; Wichelns 2010) and become an important global narrative (Frontier Economics 2008). It is a concept that implicitly defines the societal metabolism of water, particularly relevant in the definition and quantifications of water use –as explained in Chapter 4. However, the theory of VW has contributed much more than just its quantitative indicators. VW is an idea with "conceptual utility" (Allan 2003, 6) which summarizes in a 'catchy phrase' a completely new way of understanding water systems as *problemsheds* and water management as *hydrohegemony* issues (Allan 2001, 1998b).

It is argued that VW discussions are "not based on an underlying conceptual framework" (Wichelns 2010, 2217). However, a complete VW theory has been developed during the last 20 years. It has been implicitly described by the work of many authors that have approached VW as a quantitative indicator of indirect water use (Hoekstra and Hung 2005; Lenzen 2009; Zeitoun et al. 2010), as a parameter to describe international trade resources (Yang and Zehnder 2002; Yang et al. 2003), as a political strategy to maintain power or peace resources (Allan 2001; Nassar 2007) or as a nexus (Earle 2003; Allan 2003; Allan and Mirumachi 2012). In doing so, they have given a description of water in terms of its societal metabolism, that is, in relation to the relevant social functions to be maintained.

V*irtual water* was defined by Professor Tony Allan as the water associated to the production of a good, understood not only as the physical amount contained in it, but as the amount of water that was needed to generate such a product (Allan 2011, 2001, 1998a). It was born from the observations on how international trade served to ameliorate water scarcity in the Middle East and North Africa region. In this way, VW emphasizes the idea of a connection between the biophysical exchange of water and the social processes guiding economic and political decisions from local to international levels.

The quantification of this amount of water has received most of the attention in academy and resulted in the definition of the *water footprint assessment* (Hoekstra and Chapagain 2007a) as a way to improving the methodologies for the assessment of water flows. This point is further discussed in Chapter 5 as it is related to the methods employed for the assessment of the water metabolism.

3.3.1.1 Another way of describing water use

The quantitative aspects of VW are rooted in some conceptual reflections that have been done in more explicit or implicit terms. On the one hand, a discussion has been made about how to define water use. On the other hand, a classification of water has been necessary in order to better approach the water exchange.

The differentiation between *consumptive* and *non-consumptive water use* is of common usage by several international organizations (Food and Agriculture Organization of the United Nations 2014a, 2014b). However, this definition depends on the time extend of the analytical representation (more about this in Chapter 4).

With a differentiation between direct and indirect flows, VW poses on the table a way of defining water use in terms of the problemshed scale. The *direct water use* – either consumptive or not– defines the use of water from a production perspective, that is, the amount of water directly used by an activity. This is the typical parameter given by the water statistics. The *indirect use* defines the use of water from a *consumption perspective*, that is, it defines the amount of water required to maintain a certain consumption pattern with independence of i) who has extracted that water and ii) where this extraction has happened.

The direct and indirect use of resources is acknowledged in the assessment of macroeconomic patterns, particularly in those analysis that use input-output analysis (see, for example, Proops 1988; or the discussion in Serrano and Dietzenbacher 2010a). The implications of this distinction are important for policy-making. It highlights that the responsibility of a certain environmental impact can be attributed either to the social function directly utilizing the resource (for example agriculture) or to the function consuming the product (the households who eat the meat).

The differentiation between direct and indirect use of water is the pillar of the VW theory. VW discussions highlight the important role that direct water use has, particularly in agriculture (Allan 2011; Hoekstra et al. 2011a), but also how political or economic decisions that change consumption patterns somewhere else indirectly affect this water use (Allan and Mirumachi 2012; Zeitoun et al. 2010). This is the quantitative key of VW: the indirect use of water by the inhabitants of a region that imports product from somewhere else.

3.3.1.2 The ‘economically invisible’ and ‘politically silent’ factor

Trade is a key component of the VW theory. In this way, VW not only highlights the important role of the biophysical exchange of water for the processes of production and consumption within a society but also gives the reason why inter-regional social dynamics must be used to delimit the problemshed in water analyses. VW theory has opened the space for the discussion about the role of water availability as a driver for the design of international trade strategies. In this manner, water poor regions can increase their imports of water-demanding products to save domestic resources (Allan 2001; Hoekstra and Hung 2005; Nassar 2007; Yang and Zehnder 2002). This does not mean that water is the only relevant factor guiding international trade (Kumar and Singh 2005; Wichelns 2004, 2001), but that it is indeed an important part of the picture, at least under a certain threshold of water availability (Yang et al. 2003).

Because water is often not valued in economic terms, the price of products does not indicate the opportunity cost or the potential damage inflicted over the water bodies in the producing region. As a result, VW associated to trade is described as *economically invisible* (Allan 2011, 2002). In this way, VW theory provides a ground for the discussion about whether water availability should be considered in trade and production management political strategies.

When the import of VW ameliorates water scarcity decision-makers can avoid its public acknowledgement. In this way, VW is considered *politically silent* because it allow the policy makers of water scarce regions to avoid the burden of water shortages, increasing water prices or other unpopular measures (Allan 2002; Allan and Mirumachi 2012). Also, VW theory creates a space where intra– and inter-regional water conflicts (Turton 2000) can be analyzed in relation to the biophysical flows, complementing the discourse of conflict analysis (Castro 2008; Swyngedouw 2004).

3.3.1.3 The nexus

Virtual water theory highlights the idea that water is a nexus able to link different holons of the GWS. It was born with a nexus vocation (Allan 2003) and VW theory enlarges the understanding and the scope of water analysis by defining water as a nexus among social systems, among natural systems and between natural and social systems, as shown in Table 3.1.

First, VW connects various ecosystem holons. International trade creates a "global hydrological system" (Allan 1999, 73) –a global problemshed– where indirect water use connects different natural water systems –local watersheds. It does not connect the watersheds in a real way via direct water use (Merett 2003), but it transfers its consequences across the globe via indirect use.

Second, VW theory provides a space to define water uses in the interphase between the societal and the ecosystem holons (Zeitoun et al. 2010; Zhao et al. 2010), that is, to define the boundaries of the social system as described in section 2.3. In this way it provides the conceptual ground for the connection between the problemshed and the watershed-defined water observation systems.

Third, in VW theory the relation between various societal functions is clear –via indirect water use. In this way, the direct water use of holon A is the indirect water use of holon B when a relation between them both exist –as explained in section 5.2.1.2. As a consequence, it also connects policies guiding each social function with the water-related policies, like water and agricultural policies (Cabello-Villarejo and Madrid-López 2014; Stefano and Llamas 2012).

Table 3.1. Examples of nexus connections in Virtual Water Theory

1) Basin A → VW trade → Basin B
2) Consumption → Indirect VW→ Production → direct VW → Environmental Impact
3) Social holon A (Clothes use) → Indirect VW → Social Holon B (Cotton Production)
4) Energy→ Indirect VW → Food→ Indirect VW →Water → Direct VW →Land

Fourth, already since its origins, the VW concept was picked it up by the world bank to name the link between water, land and food production in the *water-food-trade nexus* (Allan 1998b). Its extension to the analysis of some other societal functions different from agriculture has resulted in the separation of the concepts. The 'nexus' has evolved to include other parameter like energy or land use in the *water-food-energy nexus* (German federal government 2014a, 2014b) but the central body of VW theory can still be recognized in the consideration of indirect use of energy for water supply (García-Rubio and Guardiola 2012; Meerganz von Medeazza and Moreau 2007) in the indirect use of water for energy production (Galan-del-Castillo and Velázquez 2010; Gerbens-Leenes et al. 2009a; Olmstead et al. 2013) or in the processes of water grabbing via land grabbing (Rulli et al. 2013).

3.3.2 Water within the watershed: re-defining water resources

The main epistemological question around the definition of water within ecosystem metabolism is the differentiation between water the biophysical exchange and the water bodies that are parts of the ecosystems. As previously commented in section 1.3.3, the term *water resources* –or freshwater resources– is used to refer to the water usable by humans (Shiklomanov 2000) as well as for the water ecosystems holding them (FAO 2012a). In the water metabolism the first description can be considered as the biophysical exchange whereas the second refers to those ecosystems that use the water. This second connotation presents the difficulty of defining water as a part of the ecosystem and as a resource at the same time.

Zimmermann (1951, 15) claimed that resources cannot be defined in substantive terms: "resources are not, they become". In this way an amount of water would be considered a resource only when it provides a certain benefit. Even when

Zimmermann – as institutional economist– referred to the elements that provide services to humans, this functional definition of resource can be considered also in reference to other water users like ecosystems. Following this definition, the impact of the water exchange over the water bodies can be conceptualized. When water loses its ability to provide a service, the water resource is no longer available (Bridge 2009), thus "nature sets the limits within which man can develop his arts to satisfy his wants" (Zimmermann 1951, 11).

Falkenmark & Rockstrom (2004) argue that water not only societies but also ecosystems depend on water. They propose a further step in the definition of *indirect water use* as they argue that humans also benefit of the water-maintained ecosystems. In this way, it is the use of water by plants what they consider indirect (human) water use. In general lines, that is to say that all water can be indirectly used: the water cycle maintains the stability of the ecosystem's water, which stabilize the water exchange between societies and ecosystems. Any element that breaks the stability of the Earth or the ecosystem metabolism of water will affect the societal metabolism of water.

The classification of water ecosystem services (Aylward et al. 2005b) explained in section 1.3.3, refers to the 'capacities[8]' of water of providing the services above mentioned. However, that classification presents a conceptual issue: it describes metabolic processes of all three GWS holons as if they were happening within the ecosystem.

In this way, the descriptive domains of other levels (earth and society) and the water attributes relevant for these are omitted. The water cycle functions are included in the classification as services provided by ecosystems when they are in truth part of the metabolism of a different holon. Some of the processes presented as ecosystem services are truly services provided by ecosystem functions to humans, like maintenance of water quality, while others are functions of the water cycle, like *water supply*, which provide a service to humans, like *access to water*, and also to ecosystems, like *supporting systems*.

[8] Capacities here refers to the ability of providing a service, thus it is equivalent to the word resource.

Table 3.2. Metabolic reclassification of water resources

Resource/User	Services to Ecosystem	Services to Society	Services to Individuals
Water Cycle Functions	Supporting Regulatory: -Water quality Provision: -Precipitation	X	X
Ecosystem Functions	X	Provision -Water availability +Diverted +In situ Regulatory: -Environmental lodging Cultural -Recreation	X
Social Functions	X	X	Provision: -(De)Centralized supply Regulatory: -(De)Centralized collection
Water mass attributes	Nutrition -Maintenance of Life	Nutrition -Maintenance of social functions Cultural -Religion, Folklore values	Nutrition -Maintenance of Life -Maintenance of well-being

Brauman et al (2007) partly deal with this issue when they implicitly argue that the services are provided to humans by a water mass, which is made available to the societal metabolism by the ecosystem metabolism. This differentiation is relevant because it highlights that all water services rely on a certain volume of water of defined characteristics that is delivered by processes happening at a different level of the GWS in a certain time and place.

When water cycle functions, ecosystem hydrological functions and water services are differentiated, it is easier to recognize the multiple scales at which they operate (Brauman et al. 2007; de Groot et al. 2002) and follow the multi-scale setting for their management recommended by the Millennium Ecosystem Assessment group (Reid et al. 2006). This way, the water cycle functions provide supporting services to ecosystems (either if they are used by humans or not). As ecosystems are maintained, the ecosystem functions can give services to societies, and then societal functions (centralized water sector or individual decentralized water activity) give to individuals the services of water supply and sanitation, and make possible for water to give services to individuals (nutrition) due to its attributes.

Table 3.2 shows a re-classification of the water services of Table 1.2, following this metabolic logic. This classification gives a definition of water resources within the watershed scale and allows the multi-scale definition of water resources missing in the Millennium Ecosystem Assessment. The table shows how some scales are unconnected, like the water cycle and the individuals, since individuals do not receive water from the climate, but from the water processes happening at the level of the ecosystems –like rivers or the rain.

Ecological and social water services –resources– are therefore impossible to disconnect. The social function that provides supply and sanitation relies on the water provision by the ecosystem hydrological functions, which relies on the water cycle functions, like precipitation. This connection is difficult to find in literature.

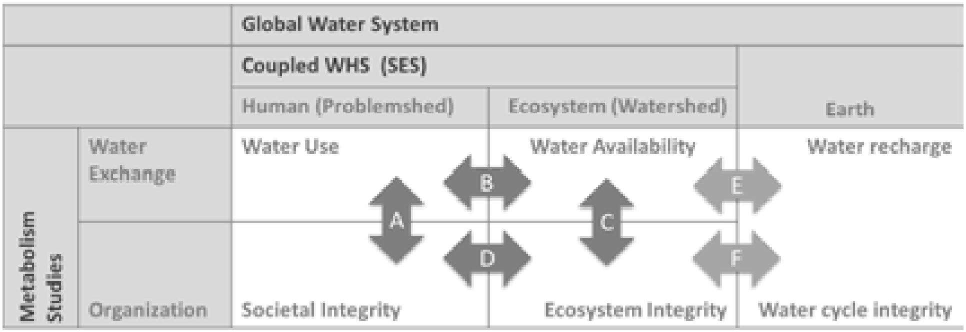
3.4 A conceptual framework of the water metabolism

The problem of including water in metabolism studies can be solved if the different narratives are integrated using a metabolic view of the human-water coupled systems. In this way, the specifics of water can be considered, including its multidimensional and cyclic nature. Using the conceptual scheme given in Figure 2.2, Figure 3.4 presents a framework for the conceptualization of the water metabolism of SES.

The scheme shows a characterization of the GWS and how the WHS is put on a level with the SES. The water metabolism of SES is the equivalent of the metabolism of the coupled water-human systems. A third holon has to be included which stabilizes the water processes of ecosystems: the water cycle. In this way, the ecosystem is not only included as a context of the society but also as a proper system, whose context is defined by the processes of the water cycle. The relevant relations for the study of the water metabolism are:

- Relation A indicates the dependence of the social organization on water flows for its own functioning and reproduction. In conceptual terms it is equivalent to the indirect water use described by the VW theory.
- Relation B encompasses the water exchange between societies and ecosystems, which is conceptually equivalent to the direct water use in quantitative and qualitative terms.

Figure 3.4. Conceptual definition of the water metabolism using a hybrid water observation system



- Relation C indicates the dependence of the ecosystem organization on water for its own functioning and reproduction. In conceptual terms it corresponds to the water resources that maintain the ecosystem.
- Relation D deals with the structural organization of WHS as hierarchical systems
- Relation E Indicates the water recharge of the ecosystem as a result, for example, of the precipitation or condensation processes of the water cycle.
- Relation F deals with the structural organization of the GWS that combines the processes of the water cycle with the social and ecosystem processes, via the ecosystem holon.

It must be noted that the row separation between the system and the biophysical exchange does not exist for the case of the water cycle. In this holon water *is* the system and what maintains this system is the energy from the sun plus a set of physical constraints determining the distribution of the overall amount of water over different typologies of funds and flows elements. The analysis of the water metabolism requires the integration of the three levels, their associated descriptive domains and relevant water dimensions. In Part II, a methodological framework called Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism is used for the framing of the societal, ecosystem and Earth water metabolism.

3.5 Conclusions

The critical review of the concept of metabolism presented in Chapter 2 has been useful to highlight the potential connections between the metabolism of SES and the description of the GWS as an entity that includes human dynamics. The definition of the GWS is a visible fact of the changes happening within the field of hydrology, but not the only one. Virtual Water theory has been chosen to describe water in metabolic terms because, implicitly, virtual water is a metabolic description of water. Naturally to follow this syllogism, the metabolism has to be described in the complex manner as a property of the SES. In this way VW theory provides a conceptual ground to frame water within the relation A of the metabolism scheme of Figure 2.2, as it describes water for the abilities it presents, including its role in the maintenance of the politic power.

The metabolic relation C –which connects the ecosystem with the biophysical exchange- does not have a direct translation within hydrology, to the best of my knowledge. Part of this issue is the consideration of water as a resource for humans, a consideration that those in line with Falkenmark's work have fortunately re-considered. Her type of work –which highlights the ecosystem dynamics as parts of the water cycle, ad the humans as those that interfere with them- has influenced the consideration of the water (ecosystem, climate, social) services as a way of describing the metabolic role of water within the ecosystem. The multi-scale setting defined in Table 3.2 is the result putting this definition within the holarchical setting of the SES, which I this case is translated to the GWS or the its concrete expressions as coupled water-human systems.

Reaching the relations E and F in an analysis where relation A is explored is impossible. Due to the holarchical character of the GWS, the three levels of the water metabolism do not connect in a cyclic manner but as if they were the wheels of a clock. Again, these relations are included so the narratives that can observe these levels find their space in the discussion. These narratives refer to Climatology, Paleontology, Geology and in general those approaches that deal with processes whose metabolic changes can only be observed in the log or very long run.

In colloquial language, now this explanation is at the point where the actors involved in a discussion arrive to the table and find their names in the side of a chair. That is, the narratives can be located within the frame of metabolism and rules have to be defined about how to integrate their views. These rules are the methodological framework, which is described in part II.

Part II Methods

Chapter 4
MuSIASEM of water

"If names are not correct, then language is not in accord with the truth of things.
If language is not in accord with the truth of things,
then affairs cannot be carried out successfully"

Confucius, Analects 1 (ca. 450 BCE)

4.1 A language for the assessment of the water metabolism

As explained in Chapter 3, the water metabolism is the result of a number of processes that take place at different paces in which different dimensions of water are highlighted. Some of these processes are determined by the broad-scale dynamics of the Earth and ecosystem metabolism –the watershed perspective-, while some others are determined by societal metabolism dynamics operating at a much narrower scale –the problemshed perspective. Governance of water resources also takes place and has consequences at various different scales (Laborte et al. 2007). As a result, quantitative analyses based on the consideration of only one scale and perspective at the time are unlikely to provide an adequate input for the management of water resources that is sound for both natural and social systems.

As explained in Chapter 1 and in Chapter 3, the effective implementation of IWRM requires an analytical framework that explicitly addresses the issues of scale. These issues of scale cause the partial integrations in water analysis and managements shown in Figure 1.4. In sum, this framework should be able to provide a space where the analyses of the different levels of organization of the couple water human systems can be connected.

Table 4.1. The different dimensions, issues, and disciplines that need to be addressed in a holistic quantitative analysis of the water metabolism of SES and the related role of MuSIASEM (Madrid et al. 2013)

Perspectives	Biophysical		Socioeconomic	Policy
Issues	– Water Resources	– Extraction of Water	– Water used in social processes	– Selection of Goals – Definition of Priorities – Evaluation of Results
Disciplines	– Ecology – Earth sciences	– Engineering – Agronomy – Industrial Ecology	– Economics – Sociology	– Political Ecology – Policy Studies – Science for Governance
Frameworks	– MuSIASEM			– Social Multi-criteria Evaluation
Output	– Ecological Constraints	– Biophysical Constraints	– Social Constraints	– Conflict & Institutional Analysis

Here, the *multi-scale integrated assessment of societal and ecosystem metabolism* (MuSIASEM) is chosen as a common ‘language’ that can be used to join the representation of biophysical, ecological, social, and economic water aspects. It has been chosen because it provides a space for the integration of the various dimensions, disciplines, and issues involved in holistic quantitative analysis of SES metabolism of water, as shown in Table 4.1

4.1.1 The Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM)

The *multi-scale integrated assessment of societal and ecosystem metabolism* (MuSIASEM) (Giampietro 2003; Giampietro et al. 2011, 2009b; Giampietro and Mayumi 2000a, 2000b) is a heuristic methodological framework specifically developed to deal with analytical issues of the metabolism of the SES like the definition of the metabolite and the delimitation of the system.

Acknowledging that the study of societal and ecosystem metabolism dictates the use of different scales does not mean that the resulting analyses must be necessarily disconnected. MuSIASEM establishes a bridge between the hierarchical levels –holons– of the SES and their associated non-equivalent quantitative analyses (Giampietro et al. 2013b, 2006; Giampietro and Mayumi 2000a). It joins the quantitative analysis of the societal metabolism energy and material flows represented across social functions –like food production or health services– with the quantitative analysis of the ecosystem processes. In this way, MuSIASEM lays the foundations for a thorough study of the terms of the inevitable social-ecosystem competition resulting from the use of the same pool of resources.

MuSIASEM was first developed for the analysis of agroecosystems (Giampietro 2003) and has been mostly used for the analysis of the metabolism of energy (Diaz-Maurin and Giampietro 2013; Giampietro et al. 2012; Ramos-Martin et al. 2007; Velasco-Fernández et al. 2015) and the the specifics of endo– and exo-somatic energy (Cadillo-Benalcazar et al. 2014). However it has also been successfully applied to the study of food systems (Arizpe et al. 2011; Aspinall and Serrano-Tovar 2014) and land use (Aspinall and Serrano-Tovar 2014; Serrano-Tovar et al. 2014). It is rooted in the definition of SES as holarchical, open and dissipative systems and the definition of metabolism that includes all four metabolic relations explained in Figure 2.2.

The different descriptive domains associated to the multiple identities expressed by complex systems -described in section 2.3- are connected using *grammars.* The quantification of the relations between the natural and the social perspectives is performed using the *flow/fund model*. In this way, MuSIASEM uses *semantically open* definitions of the metabolites that, for the case of water, are useful to show their multidimensionality.

Due to its origins as a method for the assessment of the societal metabolism of energy (Giampietro and Mayumi 2000a, 2000b; Giampietro 2003; Ramos-Martin and Giampietro 2005; Ramos-Martin et al. 2007; Giampietro et al. 2011) MuSIASEM has a strong focus on the social scales of analysis. Its novelty is associated to the use of an open scheme of the society that contrasts with the black box approach frequently used within metabolism studies. This open box scheme can embrace the holarchical definition of SES, including the interactions between the society and the ecosystem. Nevertheless the definition of the relations for the study of the interface society-ecosystem is still under development (Giampietro and Lomas 2014).

4.1.2 The challenge of analyzing the water metabolism with MuSIASEM

Due to its semantic flexibility, MuSIASEM can be used for the analysis of any biophysical requirement –metabolite– that contributes to the self-reproduction of any system. However the framework needs to be adapted to the specifics of the metabolite. This adaptation means that a definition of the system limits has to be found, which is significant for the relevant metabolite under study. Recently, the specifics of the elements of the *water-food-energy nexus* have been integrated in a single protocol of analysis (Giampietro et al. 2013a; Serrano-Tovar et al. 2014; Madrid-López et al. 2014; Diaz-Maurin et al. 2014). This integration does not mean homogenization. That is, while keeping a common root, the framework is adapted to the peculiarities of each element.

The most relevant adaptations for the use of MuSIASEM in water analyses are related to:

i) how to merge the cultural, economic, natural, etc. dimensions of water –sections 1.3 and 3.3– in a single analysis and
ii) how to design a grammar that includes the three levels and the two main descriptive domains of the water metabolism– sections 3.2.1 and 3.2.2.

The adaptation of MuSIASEM for the assessment of water presented here has been developed with the aim of meeting two challenges:

i) how to define a volume of water between different narratives (e.g., how to define the taxonomy of water), and
ii) how to include the external limit represented by the ecosystem integrity in the assessment of the maximum flow of water that can be used by society (eg. Including the environmental impact)

4.2 A multidimensional definition of water

As explained in section 1.3, the literature on water studies abounds with definitions of *water* that highlight a certain dimension of water, depending on the narrative used to define it. The perception of water as a multidimensional resource results from the fact that the element keeps its chemical composition during all stages of its cycle. The continuity of water is highlighted, for example, by its description as 'the blood of the Earth' (Falkenmark and Rockström 2004; Lankford 2002; Stikker 2007). Water keeps being H_2O within climate processes, in a riparian ecosystem, as soil moisture, as baptism water or as freshwater. It is because of this continuity in its composition that the 'same' element can be perceived as 'different' at different levels, thus associating different perceptions –dimensions– to the same reality –H_2O.

This multidimensionality can be included in the framework of the Social Metabolism when water is defined as a metabolite. As such, water is described within the problemshed as an element that maintains the societies in different ways. Within the watershed, water is described as a resource at different levels: ecosystems, societies and individuals.

The conventional definitions of *water resources* as the amount of water which is potentially usable by humans (FAO 2012a) or as water bodies (Shiklomanov 2000) are too narrow for its use within MuSIASEM. These definitions, highlight only the role of water for societies or ecosystem, but do not integrate them. Aguilera Klink (1995) proposed to avoid the economic term 'resource' and use *Ecosocial Asset* to highlight that water plays important roles for the societal and the ecosystem metabolisms (as covered in Table 3.2). The idea of the ecosocial asset fits better in MuSIASEM because it includes the relation of water dependency of the societies and the ecosystems. However, it is challenging to implement this complex concept in a quantitative assessment. To that end, a semantically open definition of water is needed. In MuSIASEM this definition is given using Georgescu Roegen's flow-fund model.

4.2.1 Semantically open definitions of water

The definitions of water presented in section 1.3 are *semantically closed* and its meaningful use is restricted to the corresponding narrative and associated analytical level. For this reason it is useful to outline a *semantically open* definition of water that is able to adapt to different levels of analysis, and to connect water narratives and descriptive domains. A *semantically open* definition of water is not substantive and can be adapted to the analysis.

Table 4.2. Examples of the use of semantically open definitions of water resources in MuSIASEM

	Water Attribute	Water resource (service)	Holon (User)
Water from body 1	High heat capacity	cooling	Thermal power station in Europe
Water from body 1	Meets the safety standards	bathing	Households in Europe
Water from Ganga River	Does not meet safety standards	---	Households in Europe
Water from Ganga River	Meet cultural standards	bathing	Households in Varanasi

The use of semantically open definitions for the classification of water is exemplified in Table 4.2. The relatively high heat capacity of water (the attribute) and the need for efficient cooling processes (end-use) on a region located in Europe define a given water flow as a resource for that thermal power station (a societal function, holon, or end-user). The same water mass could be used by the population of a close town if it meets the safety standards for qualifying as bathing water. However, this population would not consider a water resource for bathing the waters of the Ganga River, which would be considered a bathing resource in Varanasi because of cultural reasons.

Semantically open definitions can be seen as 'unscientific' due to the subjectivity that belongs with them. Semantically open definitions need a reference against which they can be formalized. In MuSIASEM the 'closing' of the definitions of water is done using as a reference the end use given to water, following Zimmermann's (1951) functional theory of resources, presented in –section 3.3.2. This theory stated that the resources are the services given by natural elements, not the elements themselves. Implicitly this theory highlights that the definition of water as a resource depends on the end use given to it and that resources can be used, but not the natural elements.

4.2.2 The roles of water as flow and as a fund.

Within the multi-scale setting of MuSIASEM water fulfills a maintenance function for the societal level but a structural function within the ecosystem. In this type of representation, the water ecosocial assets are consumed within the society in order to maintain their internal structure while they remain part of the ecosystems.

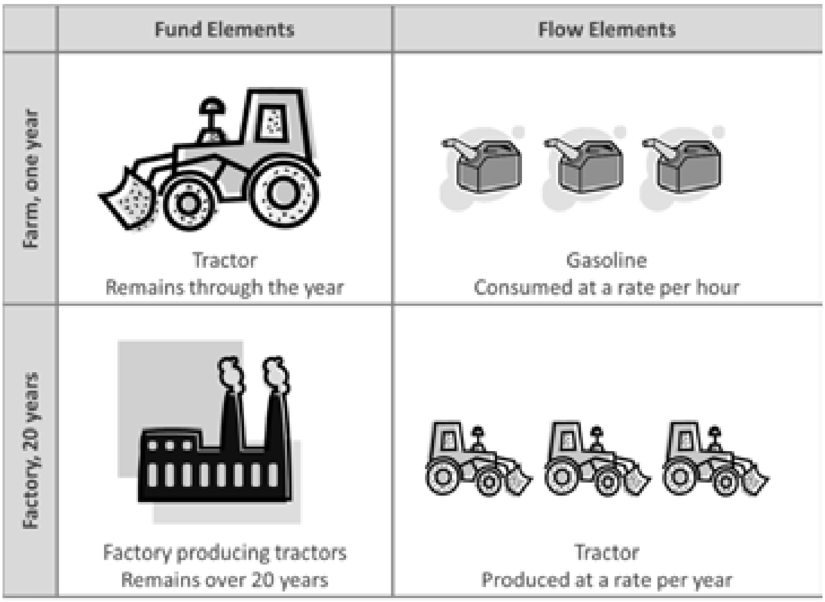
4.2.2.1 <u>The flow/fund model</u>

As mentioned above, in MuSIASEM, the relation between a water volume and the user of water –either within the societal or the ecosystem metabolism- is needed to build a taxonomy of water. This issue is solved using the *flow-fund model* proposed by Georgescu-Roegen (1971). The model was created for the quantitative analysis of the biophysical processes underlying the functioning of a modern economy. According to the author, the true objective of the economic system is the reproduction of the society, which is done at the expense of a biophysical exchange. The model distinguishes between:

- *flows*: elements appearing or disappearing over the duration of the analysis; and
- *funds:* elements preserving their identity over the duration of the analysis.

The definition of an element as a flow or a fund depends on the time extend of the representation. For example in Figure 4.1, if the metabolism of a farm is analyzed, taking into account all the processes that happen in the farm in one year, then a tractor is a fund that needs a flow of fossil energy to perform its activity. If a tractor factory is analyzed for a period of 20 years the buildings and the machinery of the factories are the funds, whereas the tractors produced are output flows resulting from the transformation of metals and other input flows.

Figure 4.1. Semantically open definition of a tractor as a flow and a fund (after presentations of Giampietro)



As explained in section 2.4 and Figure 2.2, a comprehensive analysis of the SES metabolism includes the process of internal *self-organization*, and the process of *biophysical exchange* with the surroundings. MuSIASEM uses the flow-fund model as (i) a semantic criterion to define the processes of self-organization of the holons of the SES across scales, and (ii) a formal criterion to represent the biophysical exchange among them (Giampietro et al. 2011).

As a result, *fund elements* are used to describe 'what the system is'. The idea of sustainability implies that these elements are reproduced in the metabolic process, as described by the process of *autopoiesis* in section 2.3.1. *Flow elements* are used to describe 'what the system does' with regard to the interaction with the context (at the large scale) and that among its internal components (at the local scale) (Giampietro et al. 2011). In this way, the internal organization of a system is defined by the quantitative and qualitative characteristics of the fund elements consuming or generating flows at a given rate. This organization regulates the exchange and use of flows.

The assessment of the metabolism is done by characterizing the metabolic patterns in terms of unit of flow used by unit of fund. In this way, once the relevant funds are identified it is easy to establish the system boundaries and the higher and lower levels than must be included in the analysis. For each of the analytical levels, the relevant categories of flows (energy, biomass, water) must be defined, following the 'converter specificity' of the metabolism described in section 2.2.1. Since the definitions of the relevant funds vary with the aim of the study, so do the categories of flows that have to be considered at each of the analytical levels.

4.2.2.2 Application to water

A very particular characteristic of water is that it can be represented as both, a flow and a fund element in MuSIASEM. The selection will depend on the spatial-temporal scale associated to each of the analytical levels. This is to say that the adoption of a substantive fix classification of water as either flow or fund is not useful for the purpose of analyzing metabolic patterns. However, due to the fact that social processes have much shorter temporal scales than natural processes, in most of the cases water has the role of a flow in the societies and a fund in the ecosystems.

Within the societies, each time a mass of water provides a service, its attributes are modified. The services that a given mass of water can provide are reduced by its use in order maintain and reproduce the social funds. For example, after falling on a turbine, a certain volume of water has reduced its potential energy, part of which is now transformed into electricity. Later on, the same water can be used for cooling a thermal station gaining temperature and losing its ability of cooling it again. Downstream, the same mass of water will be used in a shower only this once and maybe later will be used for toilet flushing if the household technology allows it. In each of the steps water has lost its ability of providing that particular service again. Naturally, since the total amount of water is more or less constant in Earth, this mass will at a certain point in time and space will eventually be able to provide services again, but not during the social time extent of the representation. Another indication of its role as flow is that the mass of water is required at a certain rate, and not all at once.

Within ecosystems, water is an element that forms part of the ecosystem itself. It certainly provides some structural services to ecosystems as well, that are essential for its maintenance. However in doing so, the mass of water is not degraded by the ecosystem. Also, usually in order to provide the service to the ecosystem, the mass defined as water fund is needed all at once. This is the case of a lake, for example, whose water volume is needed all at the same time in order to provide the environment for aquatic life. Is also the case of a river, whose predictable flow pattern is constantly required to maintain the riparian ecosystem.

The fund definition of water contrasts with its definition as a stock. It should be noted that not all flows of water are related to the increase or decrease of a stock. The flow of water cooling a thermal power station which comes back to a lake does not change the stock of the lake, but it changes its temperature, changing the capacity of that water fund to provide a service to the ecosystem and or other social functions. Therefore, humans can generate a reduction in the size and quality of ecosystem water funds not only by over drafting flows out but in general lines by inflicting any change in its characteristics.

The use of the fund-flow model to define analytically the role of water has an important strength for the assessment of the water metabolism. With the introduction of the concept of fund, it provides a ground for the accounting of qualitative-related water services –mostly those known as 'non-consumptive water uses' and 'water pollution'– which are still a challenge for IWRM. The evaluation of the trade-offs of the water exchange between the society and the ecosystem requires the ability of linking the roles of water as a flow and as a fund.

4.3 The delimitation of the system

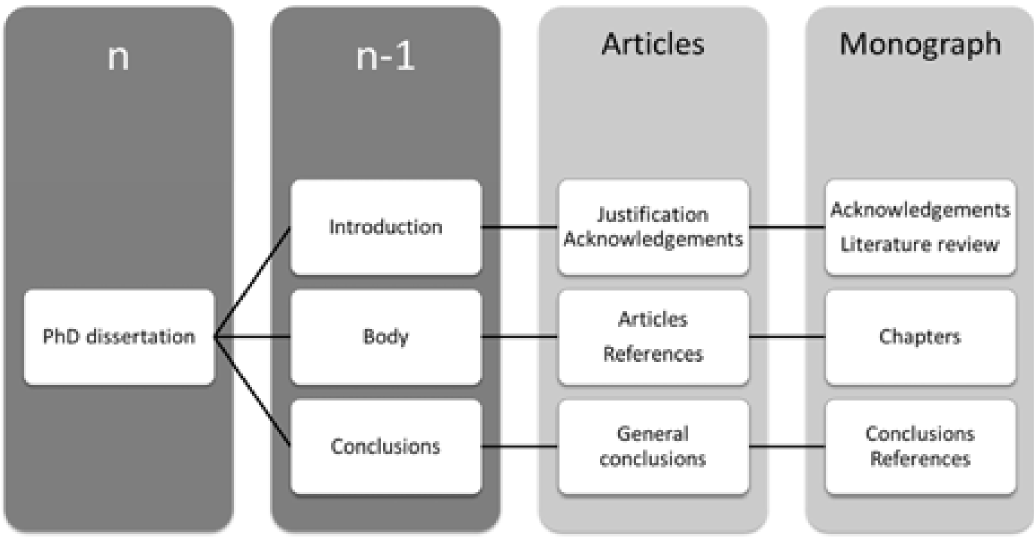
In MuSIASEM, the analytical delimitation of the SES implies the definition of relevant hierarchical levels, its components and the relation between them.

4.3.1 The use of grammars in MuSIASEM

The organization of the information in MuSIASEM does not follow the structure of a model, but that of a grammar. A *grammar* is a set of rules that formalizes logical relations of a language (Chomsky 2006), like word function within a sentence –subject, object, etc.– and classification of sentences –subordinates coordinates, etc. In MuSIASEM, grammars are used following the proposal of Kauffman (1993). The goal is to structure the representation of the process of *autopoiesis* (Giampietro et al. 2011) in a hierarchical system.

Figure 4.2 shows an application of the concept of grammar for the structuring of a PhD dissertation. The two left columns show the semantic categories while the two right columns show the specific formalization for the case of a compendium of articles and the traditional monograph formats. The whole at level n is the complete PhD dissertation, which is formed by three parts: introduction, the dissertation body and the conclusions. How these three parts are formalized –that is, transformed into concrete identities– varies depending on the type of dissertation. At the same time, the type of dissertation has been chosen by a researcher –and probably the PhD research supervisor(s)– according to different personal and professional parameters like the aims of the researcher after PhD studies, access to research funds, or previous collaborative works.

Figure 4.2. A grammar for the structuring of a PhD dissertation



There are some contents that tend to belong with one semantic category, while other contents might be included in several different ones. In the example, the acknowledgements are in both cases represented as part of the introduction of the dissertation while the references might be a part of the body or the conclusions, depending on the type of dissertation chosen. In the compendium of articles, each of the articles includes the references used for that work. In the monograph, references used in all chapters tend to be included at the end. In any case, the semantic categories remain the same and it is their formal meaning what changes.

Grammars are preferred to models as they use semantically open categories, which can be later on formalized by the analyst depending on the aim of the analysis. Models are much less flexible structuring tools because the categories are formalizations themselves. In a model, level n-1 of Figure 4.2 would be semantically closed and referred to fixed contents.

In MuSIASEM, SES are organized as sets of hierarchically arranged semantic categories describing i) systems functions –used to categorize funds-, ii) biophysical exchange –used to categorize flows- and iii) flow/fund relations –used to define qualitative characteristics. In this way, a SES can be characterized using sets of funds structured at different hierarchical levels which use flows in a specific way. The formalization of the fund and flow semantic categories can be given using different methods coming from different scientific fields or narratives. In this way, MuSIASEM deals with the unavoidable coexistence of non-equivalent narratives in the analysis of the metabolism of SES.

Figure 4.3. Example of the representation of energy grammars. Adapted from Giampietro and Diaz-Maurin (2014)

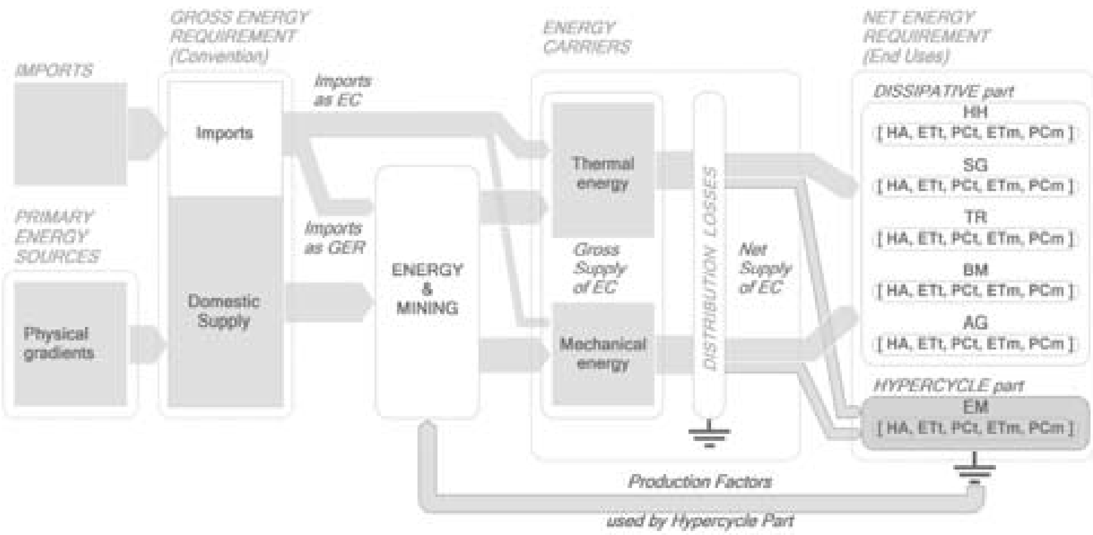


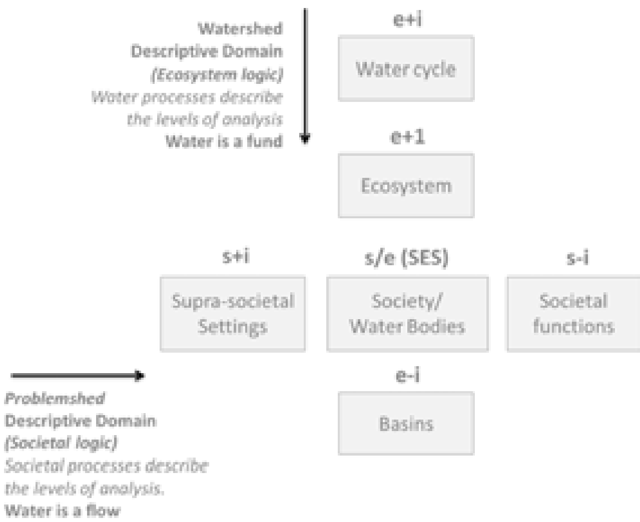
Figure 4.3 shows an example of an energy grammar in MuSIASEM. In the scheme, the equivalent to the PhD dissertation of Figure 4.2 is a society, and the parts are: (i) the dissipative part – represented by the end users of energy; and (ii) the hypercycle part - represented by the Energy and Mining sector. The levels above the society level there are represented by the processes which make available the energy sources, divided in those coming from another society (imports) and those coming from the local ecosystem (domestic). The different types of energy flows are

represented as arrows that connect the processes happening at these levels. These flows are defined in three different semantic categories: the gross energy requirements, the energy carriers and the end use of energy. The semantic categories are relevant only for the level at which they can be observed. A taxonomy of energy flows is defined for each semantic category. The gross energy requirement can be imported or domestic. The energy carrier can be thermal or mechanical. And the net energy requirement is classified according to end uses.

4.3.2 Defining analytical levels for water

As explained in section 3.2.1, the concept of GWS can be assimilated to that of SES. This simile is very powerful to combine the descriptive domains of the watershed and the problemshed perspectives, meeting the challenge faced by IWRM of integrating them both. Since the problemshed domains is associated with the Social Metabolism and the watershed with the ecosystem metabolism, the roles of water as flow and fund in each of the domains is established in general lines. Figure 4.4 shows the way these two domains are interrelated.

Figure 4.4. Definition of the analytical levels involved in the water metabolism of SES combining the watershed and the problemshed descriptive domains. Adapted from Madrid-López and Giampietro (2014).



The *watershed descriptive domain* is used to define the levels for the analysis of the ecosystem metabolism. In this domain, water is considered as a fund, a structural component of the ecosystem that contributes to the expression of its identity and which must be conserved. The levels defined in this domain take into account the different times at which fund water-processes take place.

The *problemshed descriptive domain* defines the levels for the analysis of the societal metabolism. In this domain, the levels of analysis are described taking into account the societal functions. In this domain, water is considered a flow that contributes to the stability of society.

The holarchical organization of SES into societies and ecosystems is not discrete. As a result, the levels of analysis are necessarily arbitrary and given by the analyst. In each domain (watershed and problem shed) one of these levels has to be chosen as *focal level* (s/e in Figure 4.4 – *s* stands for societal, *e* stands for ecosystem). The focal level thus has a component from each one of the descriptive domains. The metabolic processes within these levels interact with each other and with the processes that happen at contiguous levels in the hierarchy, which stabilize them from above (*s+i, e+i*) and from below (*s-i, e-i*).

Box 4.1. Analytical levels in the watershed descriptive domain

The water cycle (e+i) is 'the' fund of the Earth. The water-related processes happening at this level stabilize the processes at the lower levels at the expense of dissipating energy from the sun.

The ecosystem level (e+1) includes those process of the ecosystem that affect the water cycle, like biomass decomposition or biomass growth.

The water bodies level (e) forms the interface between the ecosystem and the societal logics. It goes beyond the usual definition of water bodies to include all the processes that make water 'appropriable' by humans. Examples include not only processes like rivers or aquifers, but also the soil moisture.

The basins level (e-i) is include as a lower level that allows the disaggregation of water bodies attending to more local processes. It is the level in which the link between land and water is covered.

Box 4.2. Analytical levels in the problemshed descriptive domain

<u>*The supra-societal settings (s+i)*</u> refer to the level in which institutions that guide global social processes can be perceived. Examples of processes at this level are the international trade, transnational regulatory schemes, or transboundary agreements that affect the next level of organization.

<u>*The society (s)*</u> is the level where the set of institutions that emerge from the lower levels of organization is perceived[9]. This in this level the relevant processes are related to the appropriation of water by the society, like the provision of water –either centralized of decentralized– or the treatment of polluted water.

<u>*The societal functions (and sub-functions)(s-i)*</u> level refers to the internal organization of societies. Examples of processes included in this category are food production (agriculture), provision of education and health, governmental management, mining, etc.

The geographical extent of the focal level can correspond either to the water bodies appropriated by a certain society or to the social activity influencing certain water bodies. During the pre-analytical stage, it can be chosen which of the domains sets the limits of the focal level. This is done implicitly in all water analyses, as in some cases studies are performed within river basins (eg. Cabello and Madrid 2014; Zeng et al. 2012a), while in other cases the level chosen is set within the social scale, with political (eg. van Oel et al. 2009) or economical limits (eg. Chen and Chen 2013).

4.3.2.1 The two triadic readings

MuSIASEM grammars are formed using a one axis logic in which the levels are distinguished above (n+i) or below (n-i) the society (n). It is frequent that the upper levels mix social upper levels and upper ecosystem levels. For example, Figure 4.3 pictures at the same level (n+i) the imports of energy sources –coming from the international trade with a social logic– and the domestic extraction of primary energy sources –coming from the ecosystem. The same scheme is followed by the food grammars (Cadillo-Benalcazar et al. 2014).

The water grammar can also be represented in a single axis, where the upper levels (n+i) are defined by ecosystem upper levels (e+i) and the lower levels (n-i) are defined by the social lower levels (s-i), as pictured in Figure 4.5. The analytical connection between the lower societal levels and the upper ecosystem levels is

[9] That is, following its characterization as a holarchical system described in Chapter 2, a society is defined as more than the sum of the processes that take place at lower levels.

established to bridge the metabolic patterns of both holons. In this way the viability check –performed following a social logic– can be connected to the feasibility check –driven by the ecosystem logic.

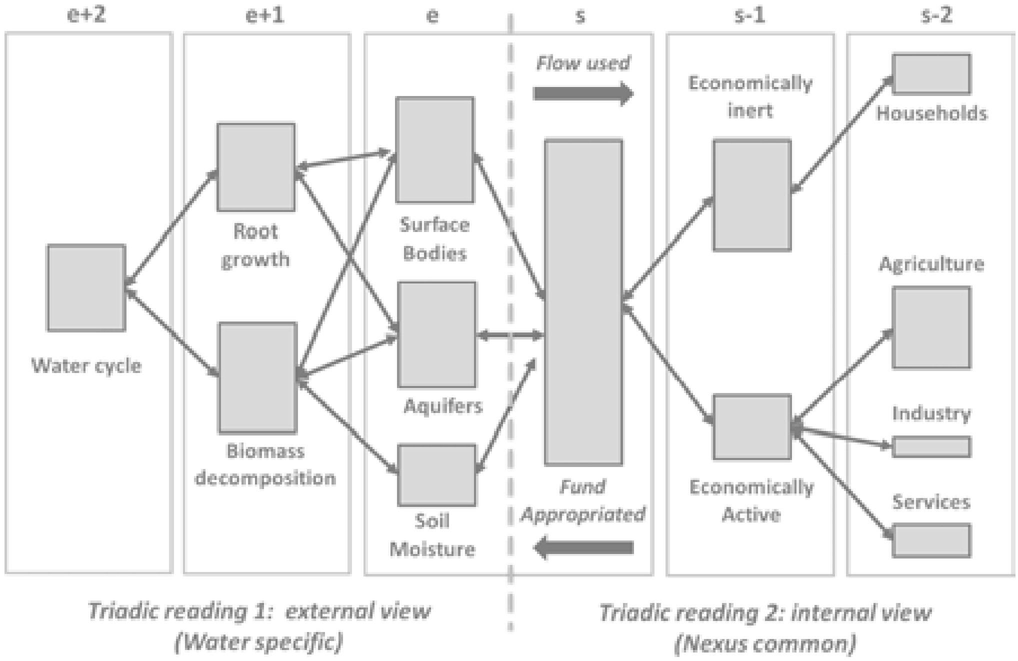
When a two-axes grammar is represented in one axis, two *triadic readings* are distinguished. The social levels form the *internal view* of the societal metabolism (processes inside the black box) whereas the ecosystem levels form the *external view* (processes outside the black box). For the case of the water metabolism of SES, the external view focusses on the processes that make water available for the social system. In turn, the internal view focusses on the social processes that use water. However, in section 3.4 it was argued that the water metabolism of SES must include the ecosystem metabolism, whose 'external view' is formed by the metabolism of the water cycle. In order to include this connection, the external view of the water metabolism also includes the water cycle, as the context of the ecosystem water-related processes.

The triadic readings are used to describe the same processes under the two perspectives of the problemshed and the watershed, especially those processes observed at the focal level, which combines both of them. The external view interprets water flows as appropriation of the water bodies and, by extension, of the ecosystem processes related to water and the processes of the water cycle. As describe in the taxonomy later on, these processes are the roles of water as a fund. The internal view interprets water flows as the use of water done for the maintenance of the societies, and its components –as a flow.

This representation implements the conceptual framework of the water metabolism described in Figure 3.4. The external view is used to define the water flows exchanged between the society and the ecosystem levels (relation B) in reference to the way in which they impact the water dependency of the ecosystem (relation C). The internal view is used to define the water flows (relation B) in reference to the water dependency of the society (relation A?). The exchange between the water cycle and the ecosystems (relation E) is included in the external view as the external constraint to all the previous ones.

A single-axis representation is very useful for the assessment of water within the nexus. The connection with other elements is possible due to the common structuring of the internal view following the patterns of the social processes, which are the societal funds. Therefore the lower levels of the water grammar are the same than for energy or land assessments. The levels of the external view are defined by the water processes, such as rivers, aquifers or lakes, and the processes that feed them, such as rain or water inflows, which are water funds.

Figure 4.5. Dendrogram that combines social (s, s-x) and ecosystem (e, e+x) logics in the division of levels. Adapted from Madrid et al. (2013).



4.3.2.2 The 'shadow levels'

The focus on the two triadic readings seems to leave aside the upper social levels and the lower ecosystem levels of the analysis. However, they are still included in the definition of the system, simply not drawn in the representation of the grammar. They can be called 'shadow levels' because they do influence the levels represented in the grammar. For example, the indirect use of water promoted by imports associated to the social fund 'cereal consumption' in a country is related to the consumer's decisions (at level s-1) on what product to buy. This decision is influenced by the country's decision about the productive structure of the economy (at level s), that focusses in the production of vegetables. This decision is in turn influenced by the situation of the international markets (at level s+1) that price better vegetables than cereals.

The shadow levels must be taken into account in the analysis of the water metabolism because they complement the information of the triadic readings in the integration of the roles of water as a flow and as a fund. For example, using the shadow levels the environmental impacts of the indirect use of water can be better analysed. As explained in the next chapter, this is one of the weaknesses of the analysis of the water footprint. These levels also provide a semantic ground to describe the influence over VW trade of water scarcity or social –or suprasocial- arrangements.

4.4 A taxonomy of water

An important strength of the MuSIASEM grammars is their structuring of the flows and funds following analytical levels. In this way, the grammars embrace the hierarchical organization of SES described in section 2.3.1, which clashes with the representations of a metabolic system as a *black box* (see Figure 2.3). In black-box representations the organization of the funds are difficult to picture. Since the definition of flow types depends on the specificity of the funds, also the classification of flows is hindered. This explains why in metabolism studies it is so difficult to define a taxonomy of water, because it has to complement the two visions of what is going on both “outside the black box” and “inside the black box”.

4.4.1 Designing a taxonomy

In order to make explicit the relation between and among fund and flow elements, MuSIASEM uses dendrograms to represent metabolic processes (Giampietro and Bukkens 2014). A *dendrogram* is a tree-diagram that shows taxonomical relations. One of the usual examples of a dendrogram is the tree-diagram showing the classification of a living organism using the taxonomic ranks (domain, kingdom, phylum, class, order, family, genus, and species). Note that these ranks are the semantic categories of the taxonomy, while the formal categories are given by the concrete instance (for humans: *eukaryiota, animalia, chordata, mammalia, primates, hominidae, homo, sapiens*).

Figure 4.6. A dendrogram of the hierarchical structure of functional societal holons. Adapted from Giampietro and Bukkens (2014).

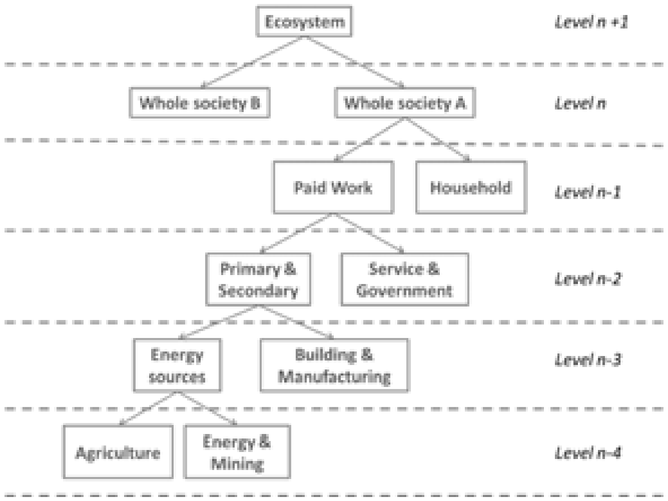


Figure 4.6 pictures the dendrogram of a typical classification of a society in MuSIASEM. It shows a taxonomy of the functional roles of social funds. The society expresses its identity as a whole at level n and can be 'open' in different holons, depending on the purpose of the analysis. In the example, a classification attending to the economic productivity is used to distinguish in level n-1 the economically productive paid work from the households. The differentiation in level n-2 is done in relation to the direct material involvement in primary and secondary productive activities versus the tertiary sector. Level n-3 distinguishes production and consumption of energy and level n-4 between endosomatic –agriculture– and exosomatic –energy and mining-energy production. A MuSIASEM dendrogram can be extended to include the ecosystem as context of the society, as previously described and as indicated by level n+1 in Figure 4.6. This ecosystem might be the context to one of more societies, depending on the definition of society used.

In MuSIASEM dendrograms serve to structure the functional perception of funds, to classify relevant flows and to establish typologies of holons. In this way, not only a dendrogram of funds can be drawn, but also one that represents the flow taxonomy, where each of the flows is relevant for the related fund only. It is worth to put some effort into the definition of a taxonomy of funds and flows. As explained in Chapter 5, the [relevant flow]/[fund] relation is used to establish typologies and types of holons across different scales, an essential step in the analysis of the sustainability of the metabolic patterns.

Table 4.3. Taxonomy of water combining multiple dimensions of water. Adapted from Madrid-López and Giampietro (2014)

<table>
<tr><th></th><th>Role</th><th>Levels</th><th colspan="2">Services</th><th>Dimensions</th></tr>
<tr><td rowspan="10">Ecosocial Asset</td><td>System</td><td>Water cycle (e+i)</td><td rowspan="3">Supply
→</td><td></td><td></td></tr>
<tr><td rowspan="5">Fund</td><td rowspan="2">Ecosystem functions (e+1)</td><td rowspan="5">Recharge
←</td><td>Precipitation (climate element)</td></tr>
<tr><td>External Inflow (global requirement)</td></tr>
<tr><td rowspan="3">Water Bodies (e)</td><td rowspan="3">(Availability)
Appropriation</td><td>Surface (Natural element)</td></tr>
<tr><td>Ground (Natural element)</td></tr>
<tr><td>Soil (Natural element)</td></tr>
<tr><td rowspan="5">Flow</td><td rowspan="2">Society (s)</td><td rowspan="2">Extraction
→</td><td rowspan="5">Direct Use
←</td><td>Distributed (social service)</td></tr>
<tr><td>Non-Distributed (social service)</td></tr>
<tr><td rowspan="3">Societal Functions (s-i)</td><td rowspan="3">Indirect (end) Use</td><td>Life (right)</td></tr>
<tr><td>Citizenship (right)</td></tr>
<tr><td>Economy (productive asset)</td></tr>
</table>

4.4.2 A classification of water

Up to date, taxonomies in MuSIASEM do not mix flows -money, energy or food- and funds -human activity, power capacity or land. However, in the case of water a taxonomy that combines systems, funds and flows is necessary to reflect its multidimensionality. This supposes the challenge of identifying the processes taking place at the Earth level, the ecosystem levels and the societal levels. Table 4.3 shows the taxonomy for water within the MuSIASEM framework. Water is considered a multidimensional ecosocial asset that fulfils the roles of a system, a fund, and a flow at each of the three holons of the GWS –Earth, ecosystems and societies.

4.4.2.1 The services

As covered in section 3.3.2, the chain of service provision –what can be considered the water resources- begins with the process at the highest level of the water cycle and continues to the lower levels of the hierarchy. The amount of the water available for a specific social system relies on the recharge of the water bodies (focal level e/s). The recharge of the water bodies is regulated by the ecosystem functions (e+1), that channel the supply of water provided by the water cycle (e+i). Also, the appropriation of water bodies by the society is the result of the extraction function of the society (e/s), which makes possible the direct use of water by the societal functions. In turn, the direct use of water by a social function A is translated into de indirect use of water by another certain function B (at levels s-i).

These categories can be interpreted using an internal and an external reading. Their definition is covered in Box 4.3, Box 4.4, and

Box 4.5.

Box 4.3. Categories of services in the external view

The supply refers to the service of producing the ecosocial asset by the water cycle. This process connects the water cycle with the ecosystem funds.

The recharge is the equivalent of the service known as ‘water provision’ understood from the point of view of the ecosystems. It is related to the ability of the ecosystem processes of allowing the replenishment of the water bodies, including the soil moisture (preservation of water funds).

Box 4.4. Categories of services in the interface

The availability is the service of making water reachable by societies. This is an interface process that connects the water bodies –external view- with the society fund –internal view. As such, it depends not only on the recharge (at a higher level) but also on the social possibilities of accessing the water (at lower levels).

The appropriation is the ability of the social processes of forcing a quantitative or qualitative change over the water funds (the water bodies). The external view interprets the appropriation as the infliction of a damage that breaks the normal functioning of the water bodies and that might damage the ecosystem processes. The internal view interprets it as the effective use of the attributes of the water mass contained in a water body.

The extraction is the process of withdrawing a certain mass of water from the water bodies. This process, usually done by the social function water handling –centralized or not- might be complemented by treatment and distribution of water or not.

Box 4.5. Semantic categories of services in the internal view

<u>*The direct use*</u> refers to the action of a social function of degrading the attributes of a certain mass of water with the purpose of maintaining its integrity.

<u>*The indirect use*</u> denotes the action of a social function A of inducing direct use by another social function B. The B function might be located within the same ecosystem or not.

<u>*The end use*</u> *is the water volume that provides a service to a certain user and can provide from direct or from indirect water use.*

4.4.2.2 The dimensions and the top-down and bottom-up readings

Section 1.3 highlighted that a different definition of water results from each of the pillars of the paradigm followed by the current water discourse –the reflexive modernity. In section 4.2 above it was argued that each of the definitions of water comes from a different narrative and highlights a perception of the dimensions of water. The taxonomy presented here integrates these dimensions –and definitions- of water, solving one of the key issues of IWRM –the lack of operationalization of the integration of water dimensions- and at the same time contributing to deal with one of the issues of the assessment of water in metabolism studies –the lack of a taxonomy that can be used in assessments of water in SES.

The taxonomy in Table 4.3 has semantically open categories of services in the same way that the energy and food grammars have semantically open categories of processes that determined the end use of energy. For each service provided –except for the supply- a bottom up and a top down reading is possible. In this way, the recharge can be formalized using a disaggregation of the source of the recharge (precipitation or external inflow) or using the end user of the recharge (a type of water body). Similarly, the appropriation and extraction services can be formalize with a disaggregation by source of water (bodies) or by the end type of extraction (distributed or not, or centralized or not). Also, the direct use of water can be described from the point of view of the source (a central water system or not) or by the direct end use given to water- to maintain the societal functions. Finally, the indirect water use categories that are relevant are also related to the maintenance of social functions.

The dimensions of water related to its role as a fund cover important water and ecosystem functions; whereas those related to its role as a flow cover the end use by societal structures in order to maintain some societal functions. It is possible to choose a disaggregation of used water depending on the societal structures using it (agriculture, mining, households, etc) or the societal function it maintains. In Table 4.3 the option chosen is the last one, following the classification given by Arrojo (2005), described in Box 4.6.

Also, the definition of the water dimensions relevant for extraction using the debate centralized versus decentralized water supply systems is quite relevant in political terms, since not all societies have the possibility of cleaning and distributing the water to users (see for example this debate in Domènech et al. 2012; Domènech 2011).

Box 4.6. Dimensions of water relevant for water end use (Arrojo Agudo 2005)

The life dimension is the one related to the description of water as a human right. The lack of water for this use is described by the author as a 'humanitarian disaster'. At this level the relevant services provided by water to individuals are those related to biological survival, as for example, body nutrition and self-cleaning.

The citizenship dimension refers to the description of water as a social service like cleaning or recreation. The lack of water for this use is described as a 'political failure'.

The economy dimension makes reference to the description of water as a productive asset. Economy water use has the purpose of producing economic benefits. It includes the water needs of the economic sectors and reaches between 50 and 80 % of a society's total water use. The lack of water for this use endangers the economic settings of the society.

4.5 The water grammar

The water grammar combines the semantic discussion –water as a flow or fund- the syntactic discussion -definition of levels- and the taxonomy of water under a same umbrella. They are used to provide the 'rules of the game' of the quantitative analyses of the metabolic patterns in MuSIASEM. As explained in the previous sections, the MuSIASEM of water has some differences with regards to the analysis of energy and food. This includes the use of two descriptive domains to define analytical levels and a taxonomy of water that integrates its role as a flow and fund –and as a system. The design of this water grammar sets a further step in meeting the challenges of integrating water within metabolic studies, as explained in section 3.1.1.

4.5.1 *A flow-fund supply grammar*

As Georgescu-Roegen (1971) defines it, fossil energy sources are a *stock-flow supply*. They are extracted from a stock, transformed, and dissipated by society, thus resulting into stock depletion. As such, the societal metabolism of fossil energy is *unidirectional* and *irreversible*. This may explain why from the onset the focus of energy metabolism has been only on flow exchange (relation B in Figure 2.2). Changes in the internal organization of these stocks do not affect structural funds of the ecosystem. The stock-flow scheme also applies to the mining of metals and other materials. As a consequence, the narrative about Social Metabolism has been predominantly occupied with linear flows.

However, as explained in section 3.1.1, this narrative does not suit the case of water, which is in general defined as a *fund-flow supply*. That is, water flows are extracted from structural ecosystem funds –water bodies– that need to be maintained within a defined range of qualitative and qualitative characteristics. If the equilibrium of the water bodies is disturbed, the ecosystems embedding society may crash. The term fund-flow supply is the MuSIASEM name for the geochemical material cycles. Like water, other elements like carbon or Zinc are guided by this flow-fund logic and as a result, the water grammar could be used as an example of some other elements of this type.

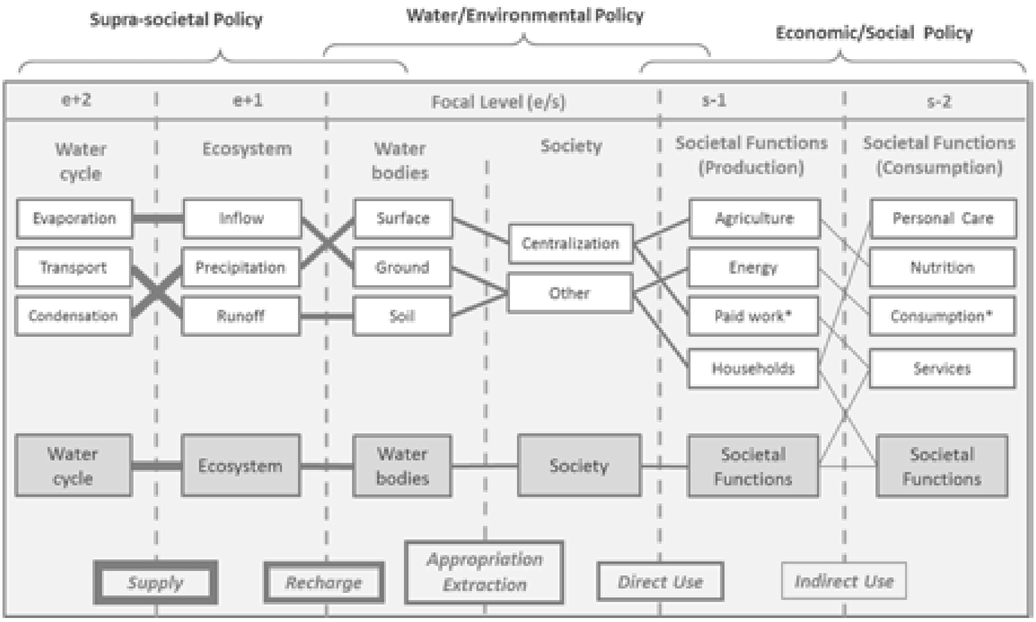
4.5.2 *The representation of the water grammar*

In order to cover this cyclic character, the water grammar does not organize the water processes using a temporal line, as described in the next chapter –see section 5.3.1. In turn, it represents the processes of the GWS in analytical levels following relation D –the holarchical organization- of Figure 2.2. The graphic representation of the water grammar using semantic categories is shown in Figure 4.7.

The scheme shows the two triadic readings in a dendrogram. The names of the levels are in the upper part of the figure and go from the water cycle to the societal functions. For each of the levels, some examples of relevant processes are represented as *compartments* like evaporation, precipitation, surface water bodies, centralized water handling or agriculture. These processes correspond to the dimensions of water presented in the taxonomy of Table 4.3 for the focal level and upper levels. This representation of the grammar is not showing the water dimensions of the lower level –life, citizen and economy- as described in the taxonomy, but the compartments that will use them, the *end user*.

In the grammar, two sets of dendrograms are represented. The upper one is showing the processes happening in the domestic ecosystem. The lower diagram shows the processes happening in other ecosystems which are connected to the domestic society via international trade –indirect water use, or VW. In this way, the shadow levels corresponding to supra-societal settings are also considered in the grammar.

Figure 4.7. Semantic representation of the water grammar



At the bottom of the figure, the services of water are represented in the interface of the levels to show the two interpretations –bottom-up and top-down- with which these categories can be read. The connection provided by the services is marked with the lines connecting the compartments. For the sake of clarity not all the possible connections between compartments are drawn. The decreasing thickness of the connectors shows the degradation of the water ecosocial asset after providing each of the services.

The upper part shows and example of how the water grammar can be used to identify the levels of action of a certain policy. Supra-societal policies like agreements of extraction on transboundary basins can influence the inflow of water reaching a certain basin (inflow). Environmental policies affecting the focal level can tax the qualitative appropriation of the water bodies (pollution) or the over extraction of water. Water policies affect the extraction from the view of the society by changing the price of water of by investing in infrastructure. Finally social policies might secure the access to water of all the population and economic policies might change the productive structure, thus changing the relations that guide the indirect use of water. Beyond identification, a water grammar can be used for the development of more effective policies that have the aim of affecting the water metabolism, as shown by the example in Box 4.7.

Box 4.7. How a water grammar can contribute to the development of policies

The literature on VW and WF is divided about the relevance of the local water scarcity as a driver for the VW flows. As explained in section 3.3.1, some authors argue for the idea and some against. It is possible that aridity and other issues play as equally important role in the issue and surely it depends on the case, which one has the higher influence over the VW trade.

Let us use the example of a SES with political delimitation –a state- in which the inflow of water to the surface water bodies is limited by an agreement with a neighbor country. The state is a part of a country with a centralized water and food policies and the state must send all its agricultural production to a central pool. The water is scarce and the services of recharge of the water bodies cannot provide enough water to satisfy the extraction activities.

With a water grammar like the presented here, the key issues described above can be explicitly located within a level and linked to the policy that has influence at that level. Once this step is done, it is easier to identify an action strategy and prioritize the policies that will be more effective to change the most important processes. In the example, changes over the international agreement can be costly and since they operate over processes out of human control, not very effective. In a situation of changes in the precipitation patterns, that investment of efforts can result in a waste. A policy that promote changes on the productive structure of the state seems a more effective effort, because it affects to processes that are under human control

4.6 Methodological contributions of MuSIASEM for IWRM

As commented in Chapter 1, the issue of IWRM tackled here is related to the lack of a methodological framework that integrates the different definitions and dimensions of water. The framework should provide a space where the different narratives can communicate. MuSIASEM can provide such a space because it is specifically designed to deal with the complexity of SES, which –as described in the Chapter 3- is analogous to the coupled water-human systems regarding different narratives that highlight different water dimensions.

This criticism about IWRM comes mostly in three lines. First, due to the lack of a clear definition of what is to be integrated. This problem is solved using a multi-scale definition of metabolism that serves as a map for the location of the narratives and MuSIASEM can be used as the language to orchestrate them..

Second, it has been argued that IWRM has been used in an opaque manner to maintain current unsustainable practices and reductionist approaches. Since MuSIASEM identifies the choices made prior to the analysis, the results obtained are transparent and do not allow for misinterpretation. The semantic flexibility of MuSIASEM allows the definition of the integration terms for each case study while maintaining the semantic categories, thus making the analyses comparable but respecting the conceptual needs of the case.

Third, IWRM has a strong dependence of policy-making. MuSIASEM cannot solve the issue of asymmetric power, however, as a governance tool, it reaches its full potential in the identification of current metabolic bottlenecks and in the building of scenarios that can make easier the development of policies.

4.7 Conclusions

Once the narratives can be located in the space of the social metabolism, MuSIASEM grammars are the language needed for their integration. Narratives closer to relation –the dependence of the ecosystems from water- will be more comfortable in intellectual terms within the descriptive domain of the watershed. Those narratives closer to the relation A –the social dependency on water- will be more comfortable within the problemshed. The joint structuring of the problemshed and watershed in the MuSIASEM grammar sets the space for their communication.

On the one hand, the two axis for the determination of analytical levels of Figure 4.4 are movable. This means that the focal level can be adapted to the interest of the relevant narratives to combine. This means that a focal level can be set to study from the effect of less precipitation over the production of cereal (levels e+i and s-i) to the effect of international markets over certain water funds, as it will be the case in the case studies presented in Chapter 6.

The flow/fund model is used to determine which narrative belongs to each of the analytical levels. In the same way that the tractor could be an output flow in a factory or a power capacity fund in a farm, water processes are defined as funds when their changes (of the process) cannot be seen during the representation. As a result, those narratives assessing the fast water processes of the society as irrigation, or bottled water consumption, will perceive the predictable flow of the river as a fund. While the narratives that focus in geological processes of sedimentation will be able to see the changes in the water bed thus assessing the river as a flow that erodes the soil.

With the definition of a taxonomy, the analytical relation between these definitions of water is made explicit. The taxonomy presented here has not used the shadow levels and it focuses on the relations between the dimensions of water that are presented in MuSIASEM dendrograms. However, as it will be shown in the case studies of Chapters 6 and 7, this only means that for each of the no considered levels –like international markets- the same dendrogram with the representation of the water roles, levels and dimensions can be drawn (see Figure 6.1).

The contributions of MuSIASEM to the establishment of IWRM do not go beyond the analytical part. However, the structuration of the analysis in a multi-scale setting is also useful to determine targets for decision making, thus letting a space on the table for this narrative as well.

Chapter 5
The analysis of the water metabolism

“Essentially, all models are wrong, but some are useful.”

(Box and Draper 1987, 424)

5.1 MuSIASEM tools

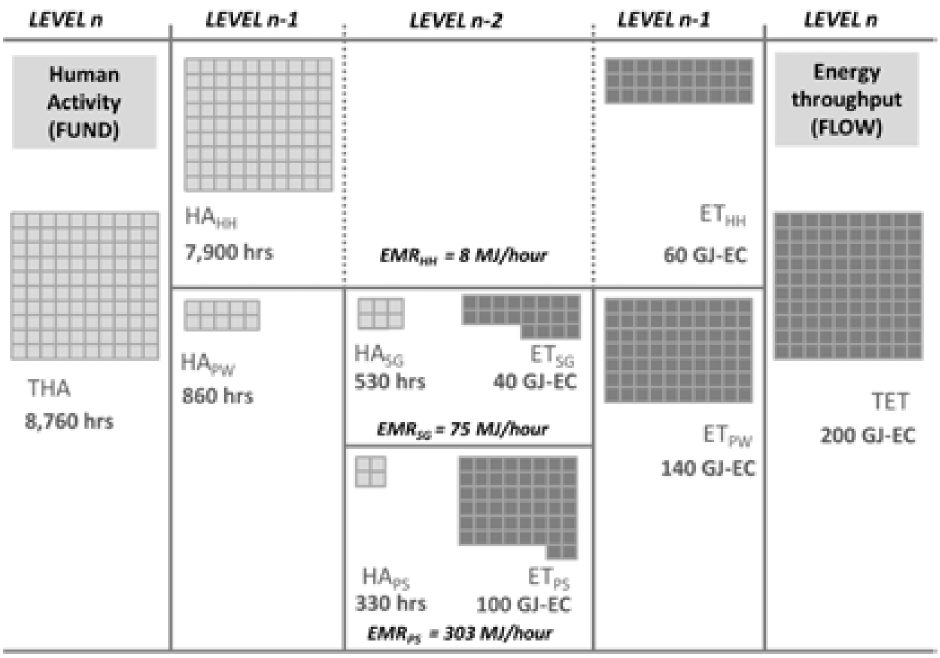
As explained in Chapter 1, IWRM was born with the purpose of promoting *sustainable water management* (Biswas 2004) and has not yet reached the objective mostly due to the lack of integrative frameworks. This lack can be solved by framing different water analyses within metabolism studies and using MuSIASEM for their integration -as described in Chapter 3 and Chapter 4. As social metabolism is used as a parent conceptual framework, it is necessary to give a metabolic definition of sustainability which can be applied to the assessment of water.

In its origins *sustainable development* was defined as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brutland 1987, chap. 2). Ever since, the semantics of the concept and how to operationalize it have been under discussion (Holmberg 1992; Harris 2001, 2003). Norgaard (1994, 22) argues that “it is impossible to define sustainable development in an operational manner in the detail and with the level of control presumed in the logic of modernity”. That is to say, giving a normative definition of sustainability is impossible. Classifying a certain process as sustainable or unsustainable within the SES cannot be done without examining the internal organization of the society and its relation with the context -the environment- which is precisely what MuSIASEM is designed for.

5.1.1 A 'quanLitative' assessment

MuSIASEM is used as a frame to perform both quantitative and qualitative analyses of the metabolism of SES. The quantitative side is rooted in the biophysical exchange, which is necessarily associated to a quantity. The qualitative side is related to the way in which the structure of the system is designed, that is, to the way in which the grammar is formed.

Figure 5.1. Quantification of flow/fund relations for energy. Adapted from Giampietro et al. (2013a)



For the quantitative assessment, MuSIASEM uses quantitative *proxies* of each flow and fund semantic categories. Within the societal system (level s, s-I in Figure 4.5), the proxy used as social fund is the *human activity* (HA), typically formalized using an *indicator* of hours devoted to a certain social function. In this way, following the explanation of Georgescu Roegen (1971), in MuSIASEM the social system is seen in terms of HA reproducing more HA (Kovacic and Ramos-Martin 2014; Giampietro and Bukkens 2014; Giampietro et al. 2011).

In the study of the ecosystem, the relevant fund is no longer the human activity. Ecosystems are also pictured as ecosystem structures reproducing ecosystem structures. The quantitative proxy used is frequently the *mass* involved in each of the ecosystem structures, usually formalized with an indicator of stable *biomass* for each components of the trophic chain (Giampietro and Lomas 2014).

The functions to which HA and biomass are devoted determine the unit of funds which use or produce the flows. Figure 5.1 shows an example of the quantitative estimation of the flow/fund relations for energy following the energy grammar presented in Figure 4.3. The left side shows how human activity has been structured in the HA of the Households (HH) and the Paid Work (PW) functions at level n-1. Next the HA of the Services and Government (SG) and the Productive Sectors (PS) has been disaggregated at level n-2.

The right side mirrors this disaggregation for the *energy throughout* –a flow-, using as indicator Gigajoules of *energy carriers* (EC) (Giampietro et al. 2012; Diaz-Maurin and Giampietro 2013). 'Energy carriers' is a semantic category in MuSIASEM, together with the 'primary energy sources' and the 'end use of energy', equivalent to the categories 'recharge' or 'appropriation' in the water grammar. Also, like in water, the disaggregation of energy types is defined for each category. As a result, the proxies used to define energy types changes with the semantic category. For example, for the analysis of energy carriers the proxy is thermal (e.g. fuels) and mechanical (e.g. electricity) energy available for end use. In the case of Figure 5.1, both have been aggregated.

The coefficient between the size of flows accounted in a given category for a given element and the size of societal funds accounted in a given category for the same element is the *metabolic rate* of that element. In the case of the example, the energy metabolic rate (EMR) is measured for the HH at level n-1 and for the SG and PS at level n-2 in Megajoules of ET per hour of HA devoted to each of the functions.

The qualitative aspects of the metabolism are included in the definition of the relevant analytical levels, flows and funds. This is done during the *preanalytical steps* (Giampietro 2003; Giampietro et al. 2011) in the definition of the grammar. The choices made during the preanalysis are influenced by the narrative of the analyst and also by the main scientific and social discourse. These choices can determine the results of the analysis (Kovacic 2014). One of the most important achievements of the MuSIASEM framework is that it makes explicit the qualitative choices that determine the results of the analyses, that is particularly relevant when the scientific results are used for governance purposes.

The characterization of the funds, the flows and the relation between flows and funds contributes to the definition of metabolic types. A *metabolic type* is established by an expected set of flow/fund relations. For example the agriculture compartment in Figure 4.6 could use more exogenous energy (e.g. more tractors) than endogenous energy per unit of fund – hectare or hour of labor- or less (e.g. more farmers working). These would be two different types of agricultural systems. Types are not to be mixed up with *instances,* which are the specific cases of types observed. The Canadian agriculture, US agriculture and Dutch agriculture are three instances of the type of agricultural holon using more exosomatic than endosomatic energy per unit of fund.

The 'quanlitative' analysis in MuSIASEM can integrate all relations A, B, C and D in Figure 2.2 and Figure 5.2 because it helps to establish a relation of congruence that has to be maintained. This congruence is not only quantitative –the amount of energy-, but also qualitative –the type of energy. If relation A changes quantitatively or qualitatively –for example, more energy per hour of HA is needed– while relation D is constant –the same human activity devoted to each function– necessarily relation B –the energy exchange– has to increase, what will affect relation C. This relation of congruence is used in MuSIASEM to check if certain metabolic patterns –current or foreseen– are feasible (in relation to external constraints) and viable (in relation to internal constraints), as explained in the next section.

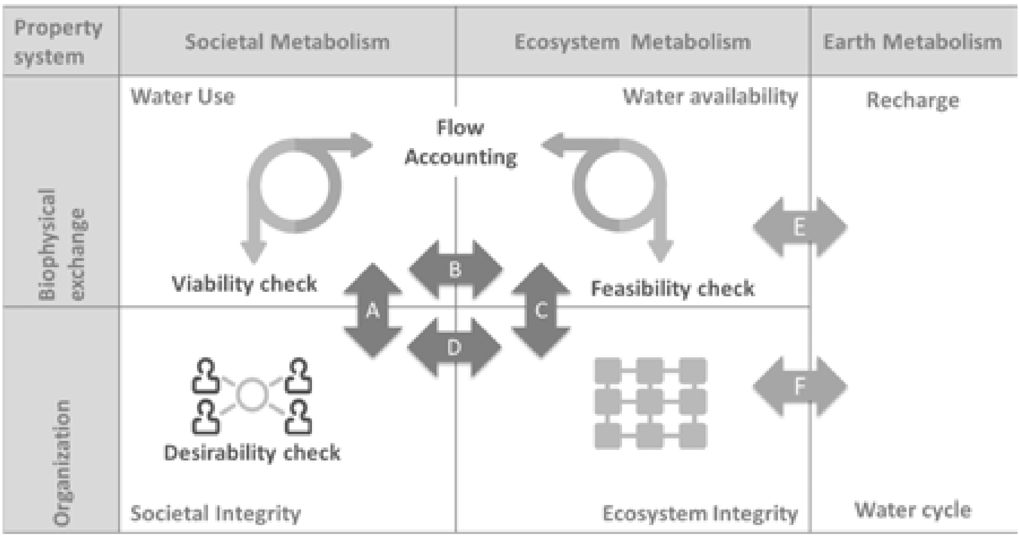
5.1.2 A metabolic description of sustainability

In metabolic terms, *sustainability* is related to the ability of maintaining a set of A, B, C and D relations making it possible to stabilize the reproduction of the metabolic pattern as described in Figure 5.2. In MuSIASEM the sustainability of the metabolic patterns is analyzed with a desirability, viability and feasibility check.

The *desirability* of a metabolic pattern is its ability to meet the expectations of the members of the society (Giampietro et al. 2011). Metabolic patterns are not always desirable and many people live in undesirable conditions –compared to their own expectations– as a result either of a lack of decision power or a trade-off choice. The desirability check is related to the perception and power of different of social groups and as such its analysis is rooted in public participation. Desirability is an important factor because it determines the robustness of the social fabric keeping together the institutions of a given society.

The *viability* of the metabolic patterns is the ability of the biophysical exchange of maintaining certain social dynamics (Ramos-Martin et al. 2007). Viability refers to processes that are under human control (Giampietro et al. 2011). As such, it has to do with the material foundations of the societal organization, giving an idea of the ability of the social system to reproduce itself with the existing institutional settings and state of material dependency –relation A. Metabolic patterns are viable if the societal flow/fund metabolic rates can maintain and reproduce the social funds inside the black box.

Figure 5.2. Assessment of sustainability in MuSIASEM of water.



The desirability and viability checks study what Giampietro et al. (2012, 2011, 2009a) call the *internal constraints* of the societal metabolism. Strictly speaking, not only the biophysical requirements, but also the social desires must be considered as internal constraints. When the total biophysical requirements which make the system *viable* and *desirable* are met, still the social metabolic patterns need to be consistent with the ecosystem metabolic patterns, which pose the *external constraints* to the metabolism of societies. Internal and external constraints differ in an important point. While the internal constrains can be controlled by the social system, the external constraints depend on the ecosystem dynamics which –as explained in section 2.3– belong with a higher hierarchical level that is beyond human control.

The *feasibility* of the metabolic patterns is the ability of the biophysical exchange of not damaging the ecosystem functions, given by relation C. Feasibility refers to processes that are outside human control (Giampietro et al. 2011). Therefore, it requires a good coordination between the external and internal constraints of a metabolic pattern, that is, it requires coherence between biophysical relations A, B, and C, and also structural relation D. The feasibility check explores also the changes in the structure of the ecosystem funds that result from the biophysical exchange determined by human activities.

A sustainable pattern is given by a desirable and viable social biophysical dependence –relation A– which also permits a feasible environmental biophysical dependence –relation C– via the exchange –relation B. In MuSIASEM the *sustainability domain* is defined as the space of options that are at the same time desirable, viable and feasible. The concepts of desirability, viability and desirability are also semantically open as they mean something different depending on the social and the ecosystem funds.

For example, a certain amount of timber use per hour of human activity –which maintains the society within the viability domain– might be desirable for society A and B, while not for Society C. Then, for the ecosystem surrounding society A, the extraction needed for this use might be feasible, while for the ecosystem surrounding society B, it might not. Being another semantically open set, the combination of desirability, viability and feasibility checks provides a solid foundation for policy making. These analyses can be adapted to the specific cases under study while keeping the comparability of the results, which is essential for scenario building when different alternatives have to be compared.

5.1.3 MuSIASEM tools for the assessment of the sustainability

As mentioned in Chapter 2 complex, hierarchical systems express different identities at each of the observations levels. Also, as Figure 5.1 shows, the 'quanlitative' characterization of the flow/fund relations can be done for any level of analysis. In this way each flow/fund relation characterizes the identity of the SES at each of the levels, that is, it characterizes the pace of the processes for each of the SES holons.

5.1.3.1 Multi-level multi-dimensional matrix

In MuSIASEM, this characterization is represented in multi-level matrices. Figure 5.3 shows the basic functioning of a multi-level matrix for the assessment of the viability of a metabolic pattern. In the summary matrix of the upper left corner, the levels relevant for the analysis are listed in rows, also with the indication of the relevant compartments. The whole society (level n) is divided in households (HH) and paid work (PW). Also, the PW is disaggregated into other paid work (PW*), agriculture production (AG) and the energy and mining societal functions (EM).

Figure 5.3. Set of multi-level matrixes for viability assessments.

	Level	Flow		Fund	Flow elements		Fund elements	
		Food	Water	HA	Economy	Life	Men	Women
Whole	n							
HH	n-1							
PW	n-1							
PW*	n-2							
AG	n-2							
EM	n-2							

AG Vectors	Level	Flow		Fund
		Food	Water	HA
Cereal	n-3			
Vegetable	n-3			
Fruits	n-3			

Figure 5.4. Set of multi-level matrixes for feasibility assessments

Problemshed	Level	Flow		Fund	Flow elements	
		Food	Water	HA	Surface	Soil
Whole	s					
HH	s-1					
PW	s-1					
PW*	s-2					
AG	s-2					
EM	s-2					

Watershed	Level	Flow		Fund
		Food	Water	LU
Whole	e			
Basin 1	e-1			
Basin 1.1	e-2			
Basin 2	e-1			

This tool is called *multi-level matrix* because it is possible to open the matrix as much as needed. In the example, the vector –row- AG at level n-2, can be opened at level n-3 in the production of relevant crops, as pictured by the matrix below in Figure 5.3.

Also, the tool is a *multi-dimensional matrix*, because the flows and funds can be aggregated or disaggregated as required by the analysis. In the example, the matrixes on the right show a disaggregation for the flow of water into its economy and life dimensions and a disaggregation for the fund HA into men and women. The parameters used for the disaggregation are also chosen by the analyst and depend on the objective of the study. In this way, the fund distinction could also be done with a separation between children and adults, o between children, teenagers and adults per gender.

The multi-level matrixes can not only be used for the assessment of the viability of the societal metabolic patterns –as it is the case of the example– but also for the analysis of the feasibility , as illustrated in Chapter 6.

5.1.3.2 Sudoku effect and the impredicative loop analysis

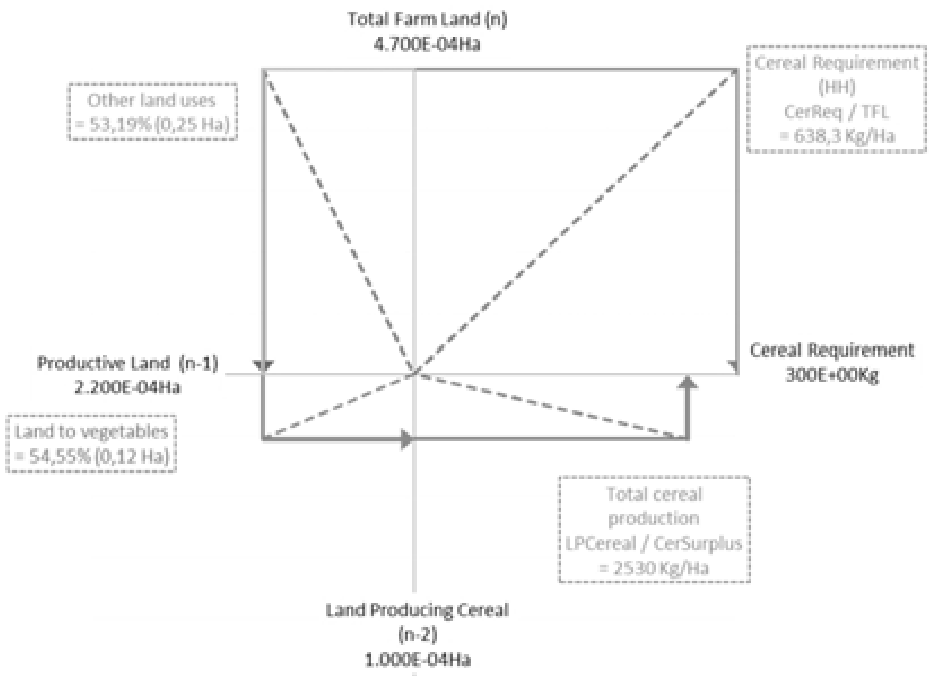
The pace –flow/fund rate– of the processes at each system (level n) is influenced by the pace of the functions that form it (levels n-i) and the pace of the processes forming its context (levels n+i). This congruence is used within MuSIASEM to perform the viability and feasibility checks. In a multilevel matrix, the sum of the quantities of each class of flows and funds at levels n-i must be equal to the level n (vertical coherence). Also, the relation flow/fund (horizontal coherence) is checked. When a flow component changes in quantitative or qualitative terms, either the fund or the flow/fund relation must also adapt to the new situation.

For example, in the scheme presented in Figure 5.3 reducing the use of thermal energy in agriculture –by reducing the amount of diesel available for pumping water– necessarily means an adjustment of the metabolic pattern. This change can be

i) a qualitative change to other forms of energy –for example, changing to electric pumps-,
ii) the reduction of exosomatic energy used per hour of HA must be compensated by an increase in endosomatic energy –using more labor in a manual pump-, or
iii) a change in the structure of the agricultural system in terms of fund –leaving the piece of field affected by the energy reduction fallow, thus reducing the amount of HA required in the sector.

The viable and feasible option space is given by the vertical and horizontal congruence relations, which are guided by the internal rules of the holons. For example, in a social holon, the institutions[10] will guide the decision about which option of adaptation is more desirable. The constraints put by the feasibility, viability and desirability option spaces are similar to the horizontal, vertical and internal constraints of a game of Sudoku. This is why in MuSIASEM this congruence check is called the *Sudoku effect* (Giampietro et al. 2014b; Giampietro and Bukkens).

Figure 5.5. ILA representing the area of colonized land (fund) vs. food production (flow)



The Sudoku effect is used to show in quantitative terms the impredicative loops of the SES. An *impredicative loop* is a 'chicken-egg' situation typical of hierarchical systems in which the identity of the parts is determined by the identity of the whole;

[10] Institutions in this dissertation are understood as social formal and informal rules (Vatn 2005), and not as organizations, which are actors that contribute to the institutional settings

and the identity of the whole is determined by the identity of the parts. In metabolic language, this refers to the above explained situation in which the type and pace of the flow/fund rate at one level determines and is determined by the type and pace of the flow/fund rate at lower levels.

The analysis of congruence between the metabolic rates of the holons at different levels is called *impredicative loop analysis* (ILA) in MuSIASEM (Giampietro et al. 2013b). The ILA is a graphic representation of a relevant flow and fund relation at two different levels where the congruence between them is highlighted. It is particularly relevant to assess the viability and the feasibility of the metabolic patterns once the main bottlenecks have been identified using multi-level matrixes.

Figure 5.5 pictures an example of an ILA of the food production in a farm. The land is treated as a fund while the food production is treated as a flow. The figure shows that from the total land of the farm (level n) most of it is devoted to other non-productive land uses (53.19%). About 45 % of the productive land is devoted to cereals with a very low yield, 2,530 Kg/ha, which results in a cereal production lower than the total cereal required to maintain the farm land in good conditions (300 Kg per year). In the case of the example, the system is not viable, because the biophysical flow of food is not enough to maintain the ways of life of the household.

5.1.4 Analytical contributions and limitations of MuSIASEM for IWRM

The analytical tools used in MuSIASEM are used to identify current metabolic bottlenecks and to build scenarios. Opposite to the metabolism methods that focus on the assessment of flows, MuSIASEM can embrace the changes in the structure of societies and ecosystems at a macro-, meso– and micro-scale. Models considering only flows cannot show the structural qualitative changes because they do not approach funds. In other words, results coming from analysis of flows cannot tell why the water is useful for ecosystems and societies or how the water is being used.

However, the characterization of previous metabolic patterns and the build of scenarios tend to face data issues regarding the funds. The problem is that the flow/fund ratios do not remain constant and the changes in the funds are not always known. The changes in the flow/fund rates determine the transitions –see the discussion between Haberl et al. (2006), Giampietro (2006), and Haberl (2006). This has been one of the main arguments against using Input-Output analysis within MuSIASEM

The Sudoku effect is used in MuSIASEM not only to check the coherence of the metabolic patterns, but also to fill data gaps and identify mistaken records. In the example posed in Figure 5.3, if the total water use at all levels and the economy water used were known, it would be possible to fill the column of the life water. Also, it is easy to see when some records are not correct, as using this information would lead to unviable metabolic patterns. For example, if the metabolic rate of life water is less than 0.04 l/h this would mean that a person has less than a liter per day, what it would be inviable.

The analysis of metabolic patterns with MuSIASEM cover the relation expressed in Figure 2.2 –also covered in Figure 5.2. Relation D is the definition of metabolism rooted in complex theory, where the metabolic systems are considered holarchical, open and dissipative systems. Relations A and C show the dependency of societies and ecosystems on a biophysical flow and in MuSIASEM are quantified by flow/fund relations and qualified by the selection of the relevant levels of analysis, funds and flows. However, in the definition of water flows associated to relation B, MuSIASEM still has some difficulties in the analysis of the indirect use of water.

5.2 Water footprint assessment

The *water footprint assessment* (WFA) is defined as a protocol for the study of the sustainability of water use along the supply chain (Hoekstra et al. 2011b). It is rooted in the estimation and contextualization of the indicator of the *water footprint* (WF); and described as three activities:

i) Water footprint accounting
ii) Assessment of the sustainability of the WF
iii) Formulation of a response strategy

WF accounting has gained recognition not only among scholars –that have classified as a research tool of Ecohydrology (Zeng et al. 2012b)-, but also among decision-makers and practitioners (Hastings and Pegram 2012). Part of its success, is due to the user-friendliness of the WF indicator, which in turn owns much to the indicator of *virtual water* (VW), and to the fact that this indicator was close ties with methods like life cycle assessments or material flow accounting. As a result of this close ties, for example, it is difficult to classify works dealing with water use as part – or not- of the WFA literature.

Since WFA is a relatively new protocol, it is still under development, particularly regarding the sustainability assessment and response strategy formulation. The accounting part is better developed, mainly regarding the link between direct and indirect water use. As a result, it has been chosen as a method of analysis of water use for a number of cases and scopes.

The WFA has a number of analytical limitations, mostly related to the narrow taxonomy of water included in the WF (Hoekstra et al. 2011b); the need of better contextualizing the WF indicator (Vanham and Bidoglio 2013); or even the (questionable) need of standardizing the WF methodology of accounting (Thaler et al. 2012). These issues can be solved when WFA is inserted in a methodological framework like MuSIASEM.

5.2.1 The indicators of virtual water and water footprint

The *water footprint* (Hoekstra and Chapagain 2007a) belongs to a group of sustainability-indicators called the *footprint family* (Galli et al. 2012; Čuček et al. 2012). The family was born with the *ecological footprint* (EF) (Wackernagel and Rees 1996) which has been defined as an indicator of the productive land required to maintain certain consumption patterns in terms of extraction of inputs and of absorption of waste. The EF originated as a "life cycle analysis of the land implications of consumption" (Wackernagel and Rees 1996, 77) and the family uses the 'cradle-to-grave' approach in order to "translate human consumption into natural resource use" (Hoekstra 2009, 1964).

Footprint indicators are estimated by balancing the direct use of resources in the production (DU_p) with the indirect use in imports (IU_i) and exports (IU_e) following Eq. 5.1.

$$Footprint = DU_p + IU_i - IU_e \qquad \text{Eq. 5.2}$$

For the case of water, the indirect use corresponds to the indicator of *virtual water*, defined as the volume of water associated to the production process of a certain traded good (Allan 2011). As explained in Chapter 3, in this way, the WF follows a problemshed perspective, where the use of water in one place can be connected to production processes all around the world via virtual water (Allan 1998a, 1998b, 2001).

5.2.1.1 <u>Definition of water use in the WFA</u>

The WF is defined as an indicator of water appropriation, where appropriation is defined from the perspective of the social use of water and not from the perspective that affect the natural side, which is the water withdrawal (Hoekstra et al.

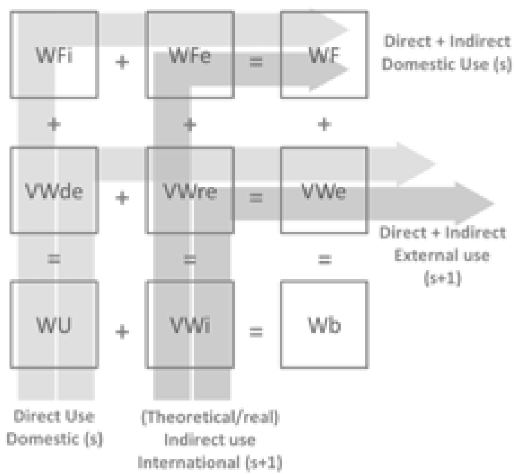
2011b; Hoekstra 2009; Hoekstra and Chapagain 2007a). It has two main components, the quantitative use of water and the qualitative use of water.

The quantitative side of the WF includes consumptive-use only, understood as the part of the water withdrawal which does not return to the same catchment from which it was taken. Water flows like the water needed for hydropower are not considered in the analysis, unless this is evaporated (Mekonnen and Hoekstra 2012). The qualitative water use is defined as the appropriation of the lodging capacity of the water masses.

5.2.1.2 The direct/indirect water use link

The indicators of the VW and the WF are deeply related, since the VW is a component of the WF. As Figure 5.6 shows, the WF accounting distinguishes between internal WF (WFi) and external WF (WFe) and between direct water use (WU) and indirect WU (VWx) (Hoekstra and Chapagain 2007a). The internal WF is the part of the WF originated from domestic direct water use, while the external WF is the indirect use of water originated somewhere else. The total domestic water use (WU) minus the part of it dedicated to the production of exported goods –the domestic exported virtual water (VWde)- results in the internal WF (WFi).

Figure 5.6. The flow accounting scheme of the WF and relation with MuSIASEM taxonomy of services. Adapted from Cazcarro et al. (2014)



From the total indirect use of water coming from international sources –the imported virtual water (VWi)- the fraction re-exported (VWre) is substracted to estimate the external WF (WFe). The total of VW exported (VWe) has also a domestic component (VWde) and an international component (VWre). The water budget (Wb) is defined as the total amount of water that is available for use, which originates from the domestic water use (WU) and the internationally promoted indirect use (VWi) and that has as destination the maintenance of the domestic consumption patterns (WF) or the consumption patterns of others (VWe).

This accounting scheme is useful within the MuSIASEM water grammar of Figure 4.7 because it provides a method to transform direct use into indirect use. In Figure 5.6 the domestic direct water use in one society is 'converted' into the indirect water use in other societies. In Figure 4.7, the level s-1 shows the point of view of the production, covered by the direct inputs of water –WU in Figure 5.6. The level s-2 of the water grammar covers the point of view of the consumption, or the WF.

But this method for the translation of direct water use in indirect water use is not only applicable to complete societies. It is also applicable to processes, or sectors. If the agricultural sector is considered the domestic system, the WU then will be the water directly used by the sector in, for example, irrigation. Then the indirect use of water coming from other systems might be the VWi that was used in the production of tractors, allocated in another sector. The water involved in the production of the agricultural sector can be attributed to the final demand of agricultural products or form a new input in other process, depending on if the agricultural products reach the final consumer (VW) or are used as intermediate input of other processes (VWe).

However, the WU in location A which resulted in a VW import to location B is not always easy to map. As a result, there are two ways of understanding the indirect water use associated to the imports of VW. The real *VW* indicates the actual water extraction involved in the production process whereas the *theoretical VW* –or saved VW- is the amount of water that would have been extracted from the water bodies, should the production would have taken place in the place of consumption. This distinction is very useful and exchangeable depending on the purpose of the analysis. Using the theoretical VW it can be argued that VW is a tool to save water in arid regions (Allan 2002; Yang and Zehnder 2002). However, the WF analyses use the real VW imports in order to establish a bridge with the local water use in the origin and its environmental impacts (Hoekstra and Chapagain 2008).

5.2.1.3 Applications

The origins of the VW concept as a driver to justify the imports of water-demanding crops in water-arid regions influenced the first quantifications of the VW indicator. This early contributions focused on the assessment of the water embedded in the trade of agricultural products (Hoekstra and Hung 2002; Chapagain and Hoekstra 2003; Hoekstra and Hung 2005; Chapagain et al. 2006a). With the course of the time, the analyses of the WF have become a major topic in water-related journals to the point that quantifications of the VW have been absorbed by WF analyses.

Estimations of the VW and WF have been done for the global (Hoekstra and Hung 2005; Chapagain et al. 2006a; Chapagain and Hoekstra 2008; Mekonnen and Hoekstra 2010) and regional levels including[11]

- countries (Guan and Hubacek 2007; Zhao et al. 2010; Hoekstra and Chapagain 2007b; van Oel et al. 2009; Novo et al. 2009),
- states (Verma et al. 2009; Bulsink et al. 2010; Ma et al. 2006),
- river basins (Aldaya et al. 2009; Zeitoun et al. 2010; Zeng et al. 2012a; Mekonnen et al. 2012; Vanham 2013),
- products (Gerbens-Leenes et al. 2009a, 2013; Chapagain and Hoekstra 2007; Dabrowski et al. 2008; Mekonnen et al. 2012; Chapagain et al. 2006b; Galloway et al.; Aldaya and Hoekstra 2010; Chapagain and Hoekstra 2011; Mekonnen and Hoekstra 2010), and
- companies (Hewlett-Packard 2014; Franke and Mathews 2010; The Coca-Cola Company 2010; Chapagain and Orr 2010), as a tool to advise *water stewardship*.

5.2.1.4 Colors of the WF

The conceptual origins of VW have also influenced the taxonomy of water flows included in the WF. While the VW imports (WFi in Figure 5.6) are a “politically silent and economically invisible” way of increasing the water budget of a society (Wb in Figure 5.6), these VWi were once in time a direct use of water -as sketched in Figure 5.8-, coming from a certain water source. That is to say, all the virtual water –quantitative and qualitative- use originates from the environment at a certain point.

[11] For a more complete list of applications, see Hoekstra et al. (2011b)

WFA uses the differentiation between green and blue water proposed by Falkenmark (1995) and Falkenmark and Rockstrom (2004) to deal with quantitative use of water (Aldaya et al. 2010; Chapagain and Hoekstra 2011; Hoff et al. 2010). As explain in the section 3.3.2, the authors flagged out the quantitative relevance of the water needs of plants in a certain ecosystem, independently if these where suitable for human use or not. In VW theory, *green water* is the part of soil moisture which is usable only by plants and whose use has a low *opportunity cost*[12]. *Blue water* is the water that comes from the surface or groundwater accumulations (rivers, aquifers, etc.) and that can be used to satisfy any (human) need, thus having a high opportunity cost.

While blue water is relatively easy to control by humans, green water is out of human control whereas it supposes about 65% of water use. As Allan (2011, 43) poses it "we can't really do much with green water, except sit back and admire nature at work". Indeed, it is the blue water the one that can be easily manipulated. As a result most of the analyses of water use –and the indicators of water withdrawal- only focus in blue flows, ignoring the fact that green water is the most important source of water for the maintenance of human life and lifestyles (Aldaya et al. 2010; Willaarts et al. 2012; Antonelli et al. 2012).

The qualitative use of water is analyzed using the concept of grey water, which in engineering is a name given to the polluted water. In WFA, *grey water* defines the pollution inflicted on a water body. A good analytical definition of the grey water as an indicator does not exist (Hastings and Pegram 2012; Thaler et al. 2012) and the first quantification have used the amount of water needed to dissolve the pollutant to an acceptable concentration.

5.2.2 Accounting methods

As previously mentioned, accounting is the better developed part of the WFA. Similarly to the way in which a MuSIASEM is performed, the WF accounting also includes the delimitation of the observed system, the classification of water flows, and the estimation of these flow per water type.

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[12] The opportunity cost is defined in economics as the loss of benefit that results when using a resource in a production process that does not give the maximum benefit. It is usually calculated as the difference between the current benefit and the potential. The term is also used to refer to non-economic benefits.

Box 5.1. Overview of Material Flow Accounting

The term Material Flow Accounting (MFA) is in general terms used to refer to both (Kissinger and Rees 2010; Ayres and Ayres 2002), the framework of analysis of the biophysical links of the societal metabolism with nature (relation B of Figure 2.2); and the tool for the organization and analysis of the biophysical flows across the societal system (Fischer-Kowalski and Hüttler 1998; Daniels and Moore 2001; Bringezu and Moriguchi 2002). In its use as a framework, it is put on a level with the field of Social Metabolism, giving an idea of the importance given to the assessment of flows within the field, as commented in Chapter 2.

As a tool, MFA is used to quantify the physical exchange between a system and the environment (Daniels and Moore 2001). It is useful to map the biophysical inputs, outputs and stocks of a system following the principles of the conservation of matter. An MFA covers all the flows that cross the boundary between economy and environment (Bringezu et al. 2003). It is developed following four steps: i) system boundary definition, ii) description of the process to be analyzed, iii) accounting and iv) evaluation. A typical economy-wide bulk MFA and associated indicators is shown in the upper part of Figure 2.3.

MFA has acquired a prominent role as a tool to assess the biophysical dependency of societies (Eurostat 2001, 8). Among its advantages are the adaptability to the scale of analysis required, the accessibility of its results and the inclusion of 'hidden' flows coming from trade. However some criticism has been raised (Bringezu et al. 2003) about the lack of a qualitative definition of the flows; the lack of connection between flow accountability and environmental impact; and the fact that the tool covers one single scale of analysis at a time, what it is not very coherent in the studies of the social-environmental relations in a globalized world (Kissinger and Rees 2010).

The delimitation of the observed system is done using the path of the water flows, taking into account how direct and indirect use relate to each other. As a result, the key issue in the delimitation of an observed system in WF accounting is to set the stages of the supply chain that must be included in the analysis. Including a too short number of processes might leave a great part of the water use out of the scope. This problem is faced by any analyst performing a flow accounting in which the supply chain is considered, and is known as a *truncation issue* (Suh et al. 2004; Majeau-Bettez et al. 2011) and which was originally discussed at length in energy analysis in relation to the assessment of embodied energy as the *truncation problem* (Hall et al. 1986). Including too many processes can add issues of double counting as it would be the case when including the water use for the irrigation of a tomato field within the direct water use of the agriculture and the indirect water use of the people eating the tomato.

The WF network has worked in the development of an standardized protocol for the accounting of the WF called the volumetric method (Hoekstra et al. 2011b), which use principles of *material flow accounting* (MFA)–see Box 5.1- and *life cycle analysis* (LCA) –as explained in section 5.2.1- for the characterization of the water flows. However, due to the truncation and double accounting issues associated to process-oriented analyses -like MFA and LCA (Rowley et al. 2009)-, several studies have used input-output models to assess VW and the WF. In this section both approaches are discussed, as they will be used within the part III for the assessment of the flows and the viability of the water metabolic patterns.

5.2.2.1 The volumetric method

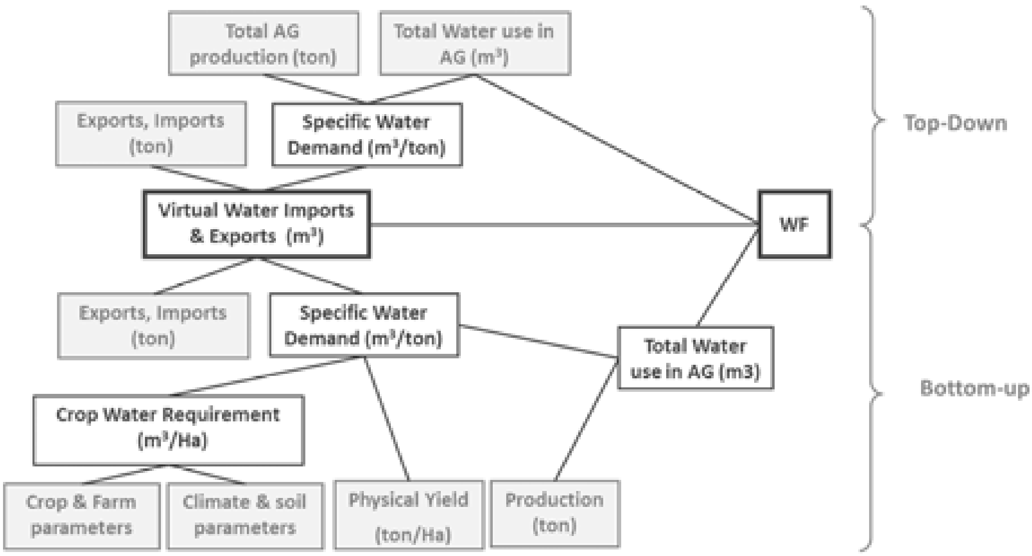
The volumetric method of accounting for the WF is the approach recommended by the Water Footprint Network (Hoekstra et al. 2011b). It is a process-focused method rooted in the estimation of the *specific water demand* (SWD) per unit of product (in mass or monetary value), following the scheme of Figure 5.7. The SWD is then multiplied by the trade flows in order to estimate their VW content. Once the VWi and WVe are determined, the WF is estimating following Eq. 5.2.

$$WF = WU + VWi - VWe \qquad \text{Eq. 5.2}$$

Due to data availability issues, there are two strategies for the determination of the SWD. The *top-down* approach uses aggregate data on total water use by a certain society, sector, or process and compares it with the total production. The *bottom*-up approach, estimates the SWD according to the specifics of the production process. In the examples of agriculture presented in Chapter 6 these parameters are related to the precipitation and soil retention capacity, the type of irrigation used in the farm, the type and state of the channels that divert the water to the farm, the concrete crop specie, the uses of soil in the farm and plantation patterns, etc. The comparison of both perspectives is useful to perform a congruence check.

The estimation of the SWD in the bottom-up approach usually requires a fair knowledge about the sector or the process under evaluation and data requirement can be very demanding. For example, for the case of agriculture the estimation of the crop water requirement is typically done with tools of agricultural engineering like CropWat (Food and Agriculture Organization of the United Nations 2014c). Indeed, for each stage of the bottom-up approach, the specific methods used for the estimation of variables vary from one study to another. Ideally, the crop water requirement should be better measured because the variability according to the methods used is reduced in a high proportion (Herath et al. 2013, 2014), however this is not always possible, especially for agricultural production systems.

Figure 5.7. Perspectives of the volumetric method for the estimation of the WF in Agriculture



The volumetric method has been used for the estimation of the VW and WF of other type of processes and products including livestock (Chapagain and Hoekstra 2003), and manufactured production (Chapagain and Hoekstra 2008). Naturally, the more the analysis advances in the supply chain, the more indirect water flows must be included, hindering the analysis. In the case of livestock, not only the water used for the maintenance of the cutleries is included in the analysis, but also of the water needed to produce the feed for the cattle.

A specific difficulty faced in WF accounting is the allocation of the responsibility of the water use for processes in which several outputs are produced. This problem has been defined as the *joint production dilemma* by those developing accounting method for embodied energy in the 70s ((Chapman 1974; Leach 1975)). This is the case of, for example, a factory of ketchup where also tomato sauce and tomato soup are produced. In these cases, the general trend is to use a mass fraction and a market value fraction to allocate the responsibility of the water use (Hoekstra et al. 2011b; Chapagain et al. 2006b), which is a frequent practice in life cycle analysis (Hewlett-Packard 2014; Franke and Mathews 2010).

Opposite as it is done for the EF assessments; the geographical variability of the water use has been covered in the WF accounting. At the beginning, the reference was not very precise as the WF of countries was estimated, and the precedence of the flows where usually not included (Hoekstra and Hung 2005; Hoekstra and Chapagain 2007a). However, with the further development of datasets, not only the geographical resolution of the WF analyses -with the location of the origin of the water use and of the processes- has been improved (Vanham et al. 2013; Hoekstra and Mekonnen 2012), but also the temporal variability has been included (Hoekstra et al. 2012; Pfister and Bayer 2014).

5.2.2.2 The Input-Output Analysis

The MFA-LCA related volumetric method is the most widely used tool for WF accounting, followed by *input-output* (IO) analysis. IO originated as a tool to connect the different economic processes (Leontief 1951) and later was used to check the pollution generated by them (Leontief 1970).

IO has been used as a way of dealing with the truncation errors associated with MFA and LCA of energy and material flows (Majeau-Bettez et al. 2011; Suh et al. 2004; Wiedmann et al. 2007; Turner et al. 2007). For the case of water, IO estimations of VW flows include better the direct/indirect water-use loops than the volumetric estimations (Antonelli et al. 2012; Cazcarro et al. 2010).

Figure 5.8uses an iteration of the scheme of Figure 5.6 to illustrate the truncation issues. Let us imagine a network of four societies –A, B, C and D- connected via indirect water use. The direct water use (WU) of the society A (1) is internally transformed in exported VW and feeds the VW imports of society B. The exported WV of B includes the direct water use of B (2) plus the direct water use of A. In the same way, the VW exports of C are the WV imports of D and include the direct water use of A, B and C (3). Last, the VW exports of D add to the former the direct water use of D (4), as the VW imports of A. The VW imports of A and other direct water use of A not represented in the figure are allocated as the WF of society A.

Box 5.2. Overview of Input-Output analysis

Rooted on the structural foundations of Quesnay's "Tableau Economique" (1766), Leontief (1951) developed an *Input-Output* (IO) table to assess the structure of the US economy. He built a lineal model to assess in quantitative terms a fact well known by economists: *"the existence of some kind of interconnection between even the remotest parts of the economy"* (1951, 3). He treated "*each industry (…) as a single accounting entity (…) with sales entered on one side of its trading account and purchases on the other*" (1951, 4). The model however is only able to recognize the additive properties of an economic system, but not the emergent properties that define a complex system.

Even if it is formalized in monetary units, it does not model prices, but physical quantities

As a result, it has been used to assess the relation between economic and natural systems and has been described as a useful tool in the study of economics as a life science (Hoekstra 2010, 2005; Leontief 1970; Strassert 2002). Daly (1968, 400) wrote about it as *"the most promising analytical framework within which to consider the question (…) How does one integrate the world of commodities into the larger economy of nature?".*

The model reflects the inter-industrial economic transactions organized in a double entry table. Most of the national statistic services compile data in a way that is useful for IO analysis, as supply and use tables. Nevertheless, the construction of symmetric tables is resource and time consuming, and therefore the frequency with which they are built is lower than the resolution of the tables, usually one year.

The above description could be changed to define four processes within the economy, A, B, C and D (let us imagine agriculture, food Industry, research, and tractor production). In this case, the WU is the water directly used by each sector while the VW flows are not necessarily related to international trade, but they can come from another process. In WFA these domestic-trade related VW flows are called the indirect use of water in production and in the volumetric method is the equivalent of counting the water needed for growing cereal feed in the production of meat. The volumetric method has a major challenge when trying to not to account twice the water use, for example, once as the direct use of A and another time as the indirect use -VW imports- of B. In Figure 5.6 a single iteration is represented. However, the number of iterations that are needed to cover all the relations in a society tend to infinite (Miller and Blair 2009). Consequently, in the volumetric method for the WF accounting the system is necessarily truncated at a certain point.

Figure 5.8. Representation of one iteration in the supply chain.

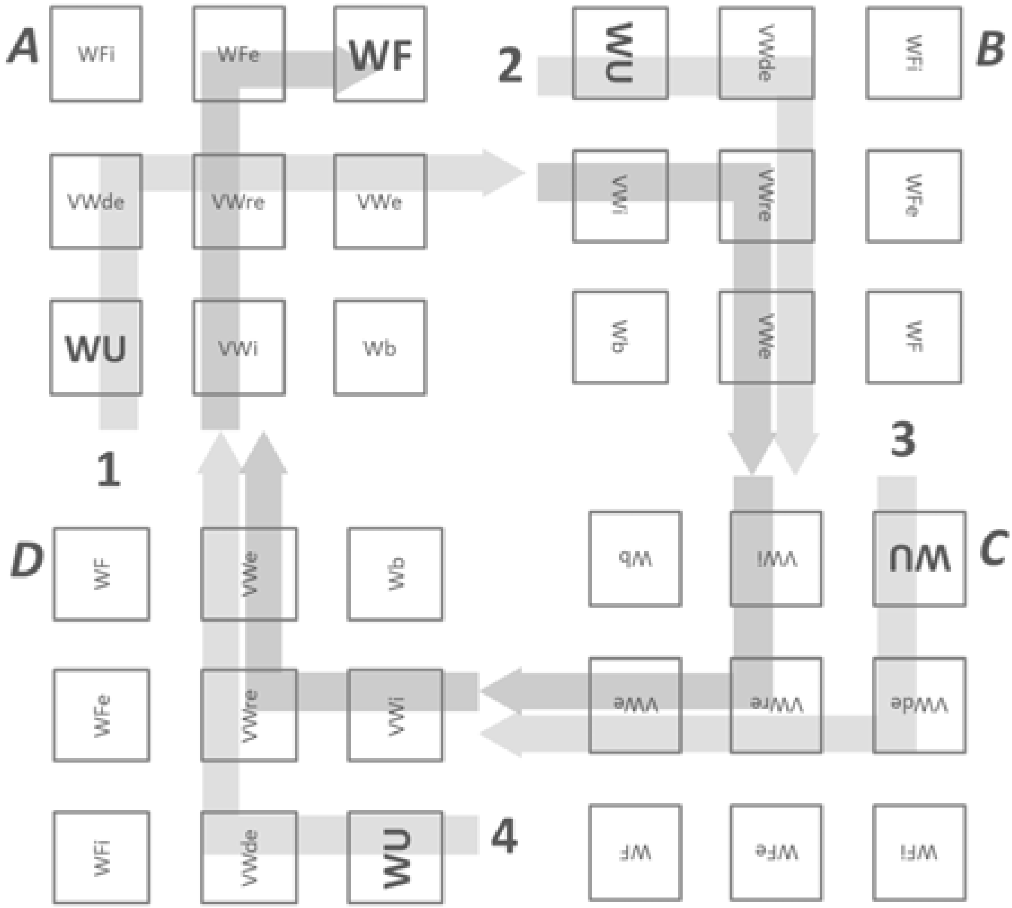


Table 5.1. Example of IO table for a two sector economy (also in Chapter 7)

		Buying Industries		Domestic Final Demand			Exports	Total x_i
		1	2					
Selling Industries	1	z_{11}	z_{12}	c_1	i_1	g_1	e_1	x_1
	2	z_{21}	z_{22}	c_2	i_2	g_2	e_2	x_2
Domestic inputs	Labour	l_1	l_2					
	Water	w_1	w_2					
Imports		m_1	m_2					
Total x_j		x_1	x_2					

As in Table 5.1, in IO analysis a matrix reflects in columns the inputs and in rows the outputs for each sector, in a similar way that the WU and VW imports, and the WF and WV exports are included Figure 5.6. Each of the cells z_{ij} in the matrix indicates the quantity of a certain flow going from row *i* to column *j*. The last columns are devoted to the final consumption –domestic and exported-, whose direct plus indirect water uses represent the WF. The bottom rows are the primary inputs, which can either be coming from the domestic economy –the direct WU- of imported –thus containing a certain VW. The intermediate matrix or *transactions matrix* (shaded in Table 5.1), is the equivalent of the internal transformations that will 'transform' the WU and VWi into the WF or the VWe.

In this way, the point of view of the consumption –the WF- can be related to the point of view of the production –the direct water use. The water budget (Wb) in Figure 5.8 can be decomposed from the point of view of the production into the WU and the WVi or from the point of view of the consumption into the WF and the VWe. In the same way, in IO the total water used can be attributed to the sectors that are using it -directly or as VW- during the production process (the columns) or the sectors that are providing the final demand –domestic (WF) or foreign (VWe) with goods and services (in rows), while the total water used will not change.

5.2.3 The sustainability assessment

The sustainability assessment of the WF is a process of contextualization of the indicator which has only been in development since 2010 as a response of the criticism made to the WF – and other footprints. Criticism came mostly in relation to the lack of meaning of the numbers given by the indicators, which raises the question of their potential to inform policy-making (Blomqvist et al. 2013a; Rees and Wackernagel 2013; Blomqvist et al. 2013b; Giampietro and Saltelli 2014; Goldfinger et al. 2014).

The footprint indicators are described in most sustainability analysis frameworks as indicators of the pressure inflicted over the environment. For example, this is the classification of the WF and the EF within the DPSIR[13] framework used by United Nations (UNEP 2010) and the European Union (European Environment Agency 2010). As a pressure index, the footprints need contextualization not only regarding

[13] DPSIR (Drivers-Pressure-State-Impact-Response) is a framework used for the contextualization of quantitative analyses of resource use with the aim of designing policy responses

the real impact caused over the environment, but also regarding the contribution they make to the society –the drivers.

The WFA proposes three aspects to be examined within sustainability assessments: environmental, social and economic, following the conventional definition of sustainability (Brutland 1987). As a result of its recent materialization, the WF sustainability assessment is still in need of further development in all three areas, but more importantly those related with the identification of drivers: the social and the economic. Indeed, in the WFA, the sustainability assessment "is primarily about making this comparison of the human water footprint with what the Earth can support" (Hoekstra et al. 2011b, 73).

The sustainability assessment can be better defined as a protocol since the methods for assessment are not as standardized as they are for the accounting phase. After the identification of hotspots, a more in-depth analysis of the impacts is proposed (Hoekstra et al. 2011b). Hotspots are defined using a geographical end temporal reference as the location and time spots where one of the following two conditions exists:

- the WF compromises ecosystem's water requirements, or
- water allocation and use is not fair of economically inefficient.

Impacts are also classified into primary and secondary. Primary impacts are the changes of the flows and quality of the water bodies. Secondary impacts are the changes in the provisioning of social and ecosystem services that result from the WF.

5.2.3.1 The environmental aspect

The WFA presents some differences with respect to the EF assessments of sustainability. While the EF uses generic types of land and weight them to do the aggregation, the WF refers to water volumes specifically located in space and time, which are aggregated without using any type of weighting (Hoekstra 2009). Also, the WF is located in space and time. Since the VW flows are in the last instance direct water use performed somewhere else, it is not only important to know how much water it is contained in these flows, but also where and when they are coming from. In this way, the direct water use component of the WF can be compared with the exact situation of the environment where it originates.

The geographical reference of the WF is easier to include in the volumetric method (van Oel et al. 2009; Hoekstra and Mekonnen 2012) because the iteration included in the analysis are limited. With IO, this distinction is done mostly using *multi-regional input-output* (MRIO) to locate the direct water use, the VW imports and exports and the WF among the sectors of different regions (Lenzen 2009; Daniels et al. 2011; Ewing et al. 2012). Both methods have strengths and weaknesses. The volumetric accounting method allows a higher geographical resolution but it should be built from the data-demanding bottom-up approach. The MRIO has to adapt to the geographical resolution and extend of the IO data available but it is able to analyze the complete supply chain.

The WFA has been used to map water use with a geographical component – with more (Hoekstra and Mekonnen 2012) or less (Hoekstra and Chapagain 2007a)resolution. However, it has not yet been combined with *geographical information systems* (GIS) tools to perform a completely geo-referenced assessment. The only exception of GIS analyses actually deal with the environmental requirements of water (Willaarts et al. 2012) but not with the social water use.

Table 5.2. Components of the sustainability assessment in the WFA. From Hoekstra et al (2011b) .

	WF	**Water availability**	**Water Scarcity**	**Sustainability conditions (Hotspots)**
Blue	Consumptive freshwater use from surface masses or aquifers	Subtracting ecosystem requirements from total run-off	Blue WF divided by blue water availability	WF<WA
Green	Precipitation-originated soil moisture used by plants	Subtracting ET of natural vegetation and ET of unproductive land to total ET	Green WF divided by green water availability	WF<WA
Grey	Amount of water needed to dilute an effluent to an acceptable concentration	Total run-off	Grey WF divided by actual run-off	WF<run-off

The WFA method for the assessment of the WF sustainability in a catchment is covered in Table 5.2. The blue, green and grey components of the WF are contextualized with an indicator of *water availability* (WA) with the aim of estimating *water scarcity* (WS). The blue and green WA indexes take into consideration the water requirements of the ecosystems. The grey water WA index is equivalent to the total run-off within the catchment. This scheme is also used for the analysis of WF of products and processes. The WF of a product or a process is defined as environmentally sustainable if the catchments where the WF components originate are not defined as hotspots (with an unsustainable catchment-WF).

5.2.3.2 The social and economic aspects

There is little work done about the social and economic aspects of the sustainability assessment in WFA. Basically the social sustainability is defined in broad terms for a catchment as the WF that allows meeting basic human needs or basic rules of fairness. The economic sustainability is defined as the WF that does not allow an economically efficient water allocation (Hoekstra et al. 2011b). These definitions do not provide a stable ground for the analysis of social water-related issues, since datasets to perform this type of analyses do not exist (Witmer and Cleij 2012).

The problem with the definition of a fair and efficient allocation of water is that it varies depending on the levels of analysis (Allan 1999). At the local level, water efficiency can be evaluated in relation to other technical and economic options. That is, if there is a better technology that can reduce water use or pollution per unit of output -the 'more crop per drop'- or if a water volume can be used for an activity providing more economic profit –the 'more euros per drop', then the WF is considered efficient at that level (Hoekstra and Chapagain 2008).

At the global level, however, the WFA talks about the amount the water savings promoted by VW flows. However, the most efficient global water allocation can result in the most inefficient or unfair local water allocation. The development of the WF is an attempt to escape the focus on local efficiency and to include the contribution of international trade in the uneven distribution of water resources (Hoekstra and Chapagain 2008). However, the connection between the local and the global regarding socio-economic issues is still underdeveloped.

5.3 WFA and MuSIASEM

The WFA is described as a tool that contributes to integrated water resources management (IWRM). It was born within the field of hydrology (Hoekstra 2009), but shares conceptual with metabolism studies for two reasons. First, it deals with the relations between man and nature. The WF is described as an indicator of appropriation which has the aim of highlighting the pressures that human systems create over water masses. To that end, the WFA has some important limitations, particularly regarding the definition of the observation system and the water multidimensionality. These aspects are strengths of MuSIASEM.

Second, WFA also focusses on the flow exchange from the social perspective, which -as described in Chapter 2- is a frequent practice in applied metabolism studies. The focus on the water flows is not necessarily a weakness of the approach, rather a limitation for its use within the assessment of the water metabolism. However, this was never the aim of the WFA. Besides, due to its the flow orientation WFA has been described as one of the pillars socio-hydrology studies (Savenije et al. 2013; Sivapalan et al. 2012, 2014) and resulted in a very suitable framework to assess the difference between the direct and the indirect water use. This distinction is basic in the quantification of the water metabolism -as explained in Chapter 3- and it is a weak point of the MuSIASEM studies.

MuSIASEM and the WFA can complement each other. The accounting system of the WF -including either the volumetric method or the IO method- is necessary within the MuSIASEM framework. In turn, the MuSIASEM framework provides a tool to contextualize the water flows and also, the WF. In Figure 5.2, about the steps of the sustainability assessment in MuSIASEM, the WF can contribute to the step of flow accounting, from the perspective of the societal metabolism –the problemshed.

5.3.1 How WFA can be inserted in MuSIASEM

The conceptualization of the coupled water-human system is different in the WFA and in MuSIASEM. Figure 5.9 shows a scheme of the differences. In the WFA (above) the observation system is delimited using the path of water. The direct water use is the first step in the supply chain and links a society or a process with the water bodies (including soil moisture). This direct use can be blue or green. The society or the process is a black box that allows seeing the water-using processes inside (agriculture, industry, services, etc.) but not how the water contributes to the development of any of them. After use, the polluted water goes back to the water bodies in the form of grey WF. This process involves water bodies from many different places. The path-representation is frequent in hydrological studies independently if they focus on the assessment of VW and WF or in water withdrawal and use (Postel et al. 1996) .

The representation of MuSIASEM (below) shows the typical delimitation of the observation system used for the water grammar presented in section 0. This scheme uses the analytical levels and adds to the focal level represented by the WFA scheme, the upper ecosystem levels and the lower societal levels. With this classification, the taxonomy of water services and dimensions is more complex that the green-blue-grey components used in the WFA. The connection point between the two taxonomies is the direct use of water (in WFA). When WFA's direct use is defined from a bottom up perspective, it corresponds to MuSIASEM's direct water use, as it is the water effectively used by an end user. When the WFA's direct use is defined from a top down perspective is corresponds to MuSIASEM's water extraction as it is frequently accounted as the total water withdrawal needed. For the rest of the dissertation, *water use* will be defined as the water that effectively reaches an end user.

Figure 5.9. Analytical representations of the water metabolism of SES following the path of water within systems of the WFA (top) and following analytical levels in a hierarchically defined SES of MuSIASEM (bottom).

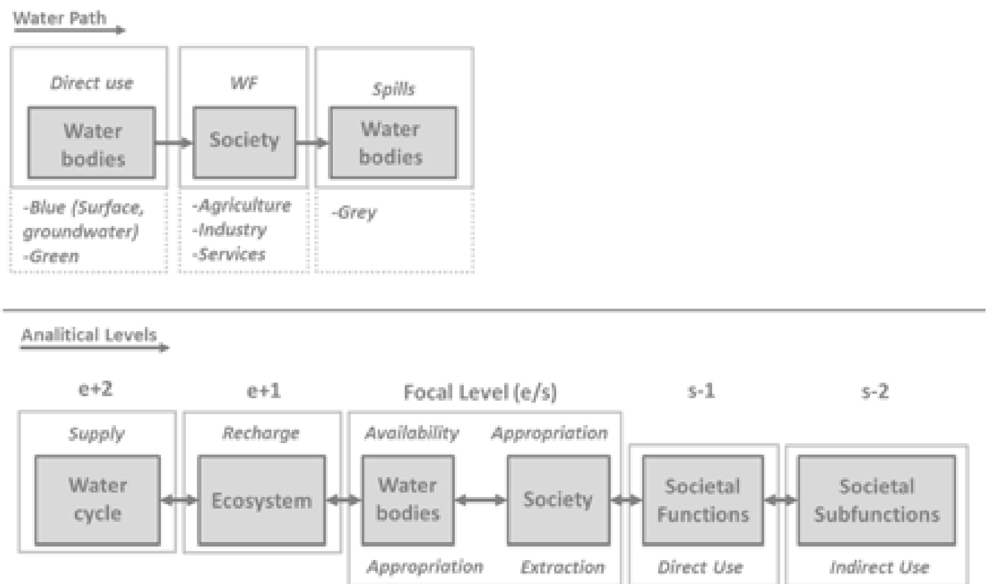
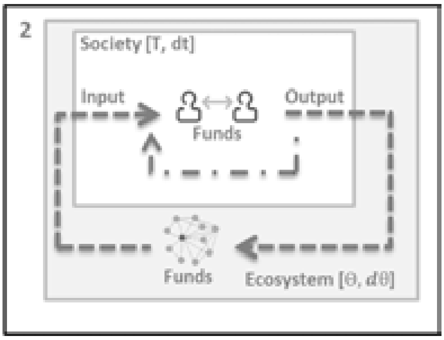


Figure 5.10 shows an adaptation of Figure 3.2 using the concept of flow and fund. It illustrates that changes in ecosystem metabolic patterns can only be perceived at time scales [Θ, dθ] longer than those used to observe societal metabolic patterns [T, dt]. As a result, the assessments of the roles of water as a flow and as a fund cannot be performed using the focal level only. When this is the only analytical level, like in the case of the WFA, the contextualization must be done separately. For example, the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998; Srinivasan et al. 1998) uses time extents in between 10 and 50 years, whereas economic or

social models like IO use time extents of one year only. The differences in the time scales of the ecosystem metabolism and the societal metabolism are key in the translation of pressures (the WF) into impacts either over the ecosystem funds or over the societal funds.

Figure 5.10. Differences between fossil energy metabolism and water metabolism with a flow/fund lens



5.3.1.1 Formalizing a joint sustainability assessment

Opposite to the WFA, MuSIASEM includes the water bodies as funds of the ecosystems and opens the black box of the society to include the social functions. This is reflected in how the stages of the sustainability assessment are formalized and the variables that are used. So far, the integration of the WFA methods of estimation of direct and indirect water use can be integrated within the evaluation of pressures in MuSIASEM (flow accounting). Table 5.3 shows a summary of these differences.

In MuSIASEM, the **drivers** are defined during the viability check, using indicators of unit of water flow per unit of social fund. Any category of water flow can be assessed at this stage, depending on the purpose of the analysis. The categories of water –direct and indirect- use are relevant for this analysis. Use in MuSIASEM includes both consumptive and non-consumptive.

For example, if the purpose is to see how much water is needed to maintain the agricultural sector, the relevant Flow/fund rate will be liters of -direct plus indirect- water end use per hour of human activity devoted to agriculture. If the purpose is the assessment of the centralized distribution system, then it will be interesting to check the volume of centralized water extraction per hour of human activity.

The analysis of pressures is the connection point between MuSIASEM and the WFA (shaded in Table 5.3). The **pressures** are described in MuSIASEM by the water exchange (relation B in Figure 2.2). This water exchange can also be defined from different points of view depending on the analysis. A typical MuSIASEM variable at this stage would be the total water extraction from an aquifer or the amount of pollution spilt to a lake –a measure of qualitative appropriation. In the WFA pressures are defined as consumptive water use, which is more relevant to check the viability of the metabolic patterns. The indirect use, should be translated into direct use of water in a certain location and time to be transformed into a pressure.

Table 5.3. Differences in the sustainability assessment of MuSIASEM and the WFA against the DPSIR protocol.

	Drivers	**Pressures**	**State**	**Impacts**	**Responses**
WFA	--	Blue, green and grey water WF	Availability (total supply - environmental needs)	WF /availability	Not considered[14]
MuSIASEM	**Viability check** Water extraction by distributed/non-distributed water social services Water (consumptive and non-consumptive) direct and indirect use for Life, Citizenship, Economy rights maintenance Flow/fund→ Relation A	**Accounting** Extraction and Appropriation from surface, ground or soil water bodies Flow→ Relation B	**Feasibility check I** Supply Via precipitation or inflow Recharge, of water bodies Flow/fund→ Relation C	**Feasibility check II** Changes in ecosystem funds Eco. Fund→ Relation D	**Desirability Check** Provision of information about option spaces. Soc. Fund→ Relation D

The **state** in MuSIASEM refers to the characteristics of the water funds and it is represented by the relation C in Figure 3.4. The characteristics to be assessed are

[14] The response stage is not considered here because is not comparable. MuSIASEM is a tool to inform policy making, not to make the decisions.

related to the services that the water cycle provides to the ecosystems and the water funds. Variables of state are related to the recharge of the water funds and the supply of water to the ecosystems.

The **impacts** in MuSIASEM are the changes in the structural characteristics of the water and ecosystem funds and are explored in the feasibility assessment as changes in the relation D in Figure 3.4. The impacts are not estimated as the flows taken from nature like in the WFA, but as the changes in the structures that result from these extractions.

The **response** formulation is not a real step in MuSIASEM. MuSIASEM is used to provide options spaces, in a similar way that the WFA provides hotspots, which can guide informed participatory decision making. However, since the framework is substantive, the responses to the information about drivers, pressures, states and impacts is the solely responsibility of the stakeholders. Naturally, with the information provided, a desirability assessment can be conducted.

An example of the flow accounting using MuSIASEM with the integration of the WF components is provided in Part III of the dissertation. An outline of a desirability assessment is provided in Annex .

5.3.2 Synergies

As the section above shows, there is a space for the integration of the WF analysis in MuSIASEM. This will not only result in a stronger analysis in MuSIASEM, but also in a more detailed contextualization of the WF.

WF accounting is defined as a "volumetric method of freshwater appropriation" (Hoekstra et al. 2011b, 127) in which use and pollution are reduced to water flows entering and leaving the social system. Contrary to the definition given by the water footprint assessment manual (Hoekstra et al. 2011b) the volumetric measure of WF is a material flow accounting applied to the case of water. The estimation of flows, the inclusion of the production and consumption perspectives and the hidden (indirect) flows are equivalent in WF and in material flow analyses.

The achievements of the WF with respect of other indicators of water flows are threefold. First, the WF integrates the impact of water appropriation over the complete production chain. Second, it connects local water appropriation with global social processes. And third, it includes in the analysis the water from the soil.

5.3.2.1 Water complexity

Extensive criticism has followed the early developments of the WFA, mostly related to the inability of the WFA for providing a comprehensive framework that can handle water complexity. The LCA community argue that the WF should not be defined as a volumetric measure but as an indicator of impact (Ridoutt and Pfister 2013; Kounina et al. 2013). However, “the water footprint is no more than one relevant indicator in the very broad theme of sustainable, fair and efficient allocation and use of natural resources” and, in order to assess its impacts “ it needs to be complemented with a wide array of other relevant indicators” (Hoekstra et al. 2011b, 115).

The problem is that the indicators needed for the assessment of the impacts over the societies and the ecosystems have different contexts. Indicators of impacts over the water funds move in the analytical levels of the watershed while indicators of water use move within the problemshed. In order to provide trustworthy results, the WF needs a multi-level contextualization (Dabrowski et al. 2008).

5.3.2.2 Classification of water

The WFA classification of water has been extremely helpful for communication purposes, particularly to raise the awareness of the general public and of water –and other, mainly agricultural– managers in three ways. First, the direct /indirect use of water has highlighted the importance of approaching the problemshed in water analyses, including social, economic or political dynamics as part of the water cycle and helping to shape a definition of the global water system (GWS). Second, the distinction between blue and green water has emphasized an important lack in research and policy resulting from the exclusion of soil moisture not only by humans –through agriculture- but also by ecosystems –through vegetation growth. Third, the differentiation between quantitative –blue and green- and qualitative –grey- water use contains an important conceptual idea: that impacting water bodies is also a way of water use.

However, the disaggregation of the components of the WF into blue, green and grey poses two conceptual challenges for the analysis of the metabolism. First, it mixes the problemshed and watershed components of a WHS. Second, when the conceptual separation is taken into practice, it is difficult to separate the soil moisture from the rest of the water (Barron 2013). In metabolic terms, it is much more useful to distinguish the origin of the water (in the watershed scale) and the potential for end use (in the problemshed). Given that social systems can only control blue (fresh) water use, this has traditionally been the main indicator to characterize water use within the social system. When the end use of green and blue water is considered, the important role of the green water in the maintenance of societies can be highlighted (Aldaya et al. 2010).

Table 5.4. The two components of blue, green and grey WF

Dimensions	Blue VW	Green VW	Grey VW
Watershed (origin)	Water bodies	Soil Moisture	Surface water bodies
Problemshed (use)	Any use or consumption (if certain attributes exist)	Plants growth	?

5.3.2.3 Consumptive use

The consideration of consumptive use only in WFA is too narrow and it does not provide sufficient information for either the problemshed or the watershed perspective. In the problemshed, there are non-consumptive water uses that are essential for the maintenance of societies, in particular those related with the generation of electricity, both the water used in a hydropower station and the water used by a thermal station gmay have important impacts on the local society. The necessary appropriation of the characteristics of these water volumes inflicts also a pressure over the local water bodies and ecosystems.

5.3.2.4 Water as flow/fund

WFA only takes into account the role of water as a flow, what has hindered the definition of qualitative appropriation of water. Grey water is a muted indicator in which information is lost due to over reductionism and whose results widely vary depending on the strong assumptions and the methodology used for its estimation (Thaler et al. 2012; Galli et al. 2012). In MuSIASEM, the qualitative pressure over the water bodies is measured like other pressures in total flows, in this case, of pollutants. Then the impacts are related to the characteristics of the water bodies (qualitative characteristics of the ecological fund elements), like pollutant concentration, which are not commensurable in the social levels of analysis when water is considered a flow. In general lines, the WF cannot deal with environmental impacts, because it does not cover the role of water as a fund. Since water funds are excluded in WFA, so are the dynamics of the water cycle, which are the constraints of higher hierarchical rank.

The WF is not put in context with the internal constraints of the SES –that is with the social constraints. The lack of contextualization has resulted in criticism on the WF and the VW about the need of considering other factors of production such as opportunity costs of land, employment or energy use. These constraints are considered in MuSIASEM in the assessments of the water-food-energy nexus (Giampietro et al. 2014a)

5.3.2.5 The direct and indirect use of water

MuSIASEM allows the estimation of direct and indirect end uses of water, however it has not developed a grammar for the accounting of direct and indirect flows. The schemes of Figure 5.6 and Figure 5.8 can be used as a grammar for the accounting of the direct and the indirect flows. The volumetric and IO methods can be used as the tools to estimate the transformation of direct into indirect water use and in WF. This grammar connects domestic water-dependent processes (level s) with those happening at higher problemshed levels (s-1).

5.3.2.6 Inconsistency in quantitative analysis

The number of methods used to analyze the components of the WF is frequently seen as a weakness of the WFA that result in inconsistency and incommensurability issues (Vanham and Bidoglio 2013). In order to contribute a solution to this issue, the WFA community has put a considerable effort into the development of some technical standards (Hoekstra et al. 2011b). However these standards narrow the options for assessment. In MuSIASEM, the semantically open grammars allow the selection of methods that are suitable to fit the purpose of the analysis while the use of low/fund rations keeps the commensurability of the results.

5.3.2.7 Data issues

The volumetric bottom-up approach of WFA seems to be the most suitable method to build a geo-reference of the water use. However, this method is data-demanding. Data available tend to come from different sources and related to different water services. For example, when data of the end uses of water is not available, distributed water or extracted water can be used as a proxy. In MuSIASEM, this is not an issue, because the data about each water service is located in the relevant analytical level. With a congruence check using the Sudoku effect, the gaps can usually be filled.

5.4 Conclusions

The relation of the IWRM with sustainability has been used to connect the methodological framework with the potential analytical tools. The analytical tools of MuSIASEM are oriented to the compilation and organization of data in a way that it is easy to perform the congruence checks associated to the assessment of the feasibility, the viability and the desirability. Sustainability is in this way defined in a semantic manner that depends on the state of the internal and the external constraints within a SES.

In practical terms, this means that MuSIASEM is a good tool to frame results but it lacks specific methods of analysis. This is why the WF assessment has been added to the discussion; also, because it has been described as one of the tools for the assessment of the sustainability useful for IWRM. The question rises then about what are the strengths and the weaknesses of each of the methods, if they can be integrated, and if the protocols used for their integration could be used also for the merging of other methodologies within MuSIASEM.

The analysis of MuSIASEM and the WFA against the DPSIR framework for the assessment of sustainability shows that the WFA has a much narrower scope than MuSIASEM in analytical terms. The WF is an indicator of pressure, but not of state or impact. Also the well-developed and widely acknowledged methods of the WF can be used within MuSIASEM to fill the multi-level matrixes. In this way, the WF finds in MuSIASEM a way to contextualize the flows and MuSIASEM fills its role as framework. In the remaining two examples of the functioning of MuSIASEM (Chapter 6) and of how the integration of the WF within the MuSIASEM framework can been done (Chapter 7) are presented.

Part III Applications

Chapter 6
The viability and feasibility checks. Mauritius Island and Indian Punjab

"Punjab is one of the leading states in terms of development and pioneer in green revolution. However it is also one of the most environmentally affected states of the country"

(Economic and statistical organization Punjab 2011, 2)

6.1 The viability and feasibility checks[15]

As explained in Chapter 5, the *feasibility* assessment is the congruence check between the societal and the ecosystem metabolic patterns. In other words, it is an assessment of the impact that the water flows between ecosystems and societies have over the water and other ecosystem components -funds. This exchange results in the appropriation of certain water bodies. If the appropriation of water impedes that the ecosystems structures perform their functions, then the social metabolic pattern is not feasible. In turn, the assessment of the *viability* has to do with the ability of the water exchange to maintain and reproduce certain societal functions.

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[15] The materials of this chapter are published in the following chapters of Giampietro et al (ed). (2014). Resource Accounting for Sustainability Assessment. The Nexus between Energy, Food, Water and Land Use. Routledge:

Chapter 9. Madrid-López and Giampietro, (2014). The water grammar. Pp 116-134.

Chapter 13. Madrid-López et al. (2014). Punjab state, India. Pp 181-193.

I am grateful to Zora Kovacic (human activity, money flows), Tarik Serrano-Tovar (land), Juan Cadillo (food) and François Diaz-Maurin (energy) who made the estimations of the rest of the biophysical requirements; of the Punjab case and to Tiziano Gomiero for his comments on remittances.

Through the introduction of the feasibility and the viability check, the objective of this chapter is to present an illustration of the adaptation of the water grammar to concrete analyses using as example the case studies of Mauritius Island and Punjab. The case of Mauritius will be used to show how the multi-level matrixes are formed. The case of Punjab illustrates how MuSIASEM can be used to connect the levels of the water metabolism as presented in Chapter 3. The establishment of a quantitative link between the social drivers and the impact over the water bodies without having to reduce the multidimensionality of water is presented as a contribution to IWRM.

6.2 Formalization of the grammar

As explained in Chapter 4, MuSIASEM grammars are flexible tools formed by semantic categories, whose formal meaning can be adapted to the purpose of the analysis. In turn the grammar *must* be adapted to the purpose of the analysis.

This adaptation includes two steps:

- The definition of the sematic categories that will be included in the analysis and
- The formalization of the categories using
    - statistical sources or
    - estimation methods

The semantic categories used in this chapter are presented in Table 6.1.

6.2.1 Formalization of the categories

The semantic meaning of each category is covered in Box 4.3, Box 4.4 and Box 4.5. As explained in Chapter 4, the services of water connect levels of analysis. In this way, the precipitation, for example, can be formalized as the destination of the water involved in Earth dynamics or as the origin of the recharge of the water bodies. The difference in the formalization can be expressed as either:

Ecosocial asset→Fund→Water cycle function→Supply→Precipitation (Top-down)

Ecosocial asset→Fund→Ecosystem function→Recharge→Precipitation (bottom-up)

Table 6.1. Dimensions included in the assessments of Mauritius and Punjab

Levels	Services		Dimensions	Mau.	Punjab
Water cycle (e+i)	**Supply**				
Ecosystem functions (e+1)		*Recharge*	Precipitation	X	X
			External Inflow		
Water Bodies (e)	(Availability) Appropriation		Surface	X	
			Ground	X	X
			Soil	X	X
Society (s)	Extraction	Direct Use	Distributed	X	X
			Non-Distributed		
Societal Functions (s-i)	End Use		Life	X	
			Citizenship	X	
			Economy	X	X
			– Agriculture	X	X
			– Other Paid Work (PW*)	X	

In the first case, the source of information will be climatic models which can assess rainfall. In the second case, hydrological models will be needed which can estimate which part of the recharge of the water bodies –surface, aquifers and soil- comes from the rain. The complete library of possible formalizations for all categories of the taxonomy is presented in Annex IV.

The selection of one option or the other depends also on the data availability. Since freshwater is a scarce and vital resource, it is frequent to find water statistics produced by national or international agencies. The problem is, however, that a homogeneous source of information that includes all the categories needed for a MuSIASEM analysis does not exist. When data for a certain category is not available, a proxy is used. One statistical source might be useful as a proxy for different semantic categories. For example, when water withdrawal is not available, water use statistics might be used as proxy for extraction and vice versa, if the resolution of the grammar allows it.

Due to the difficulties in finding data, top-down and bottom-up approaches to combine the two formalization options presented above. In Punjab, for example, the extraction from surface bodies or aquifers was almost impossible to find, due to the lack of a distribution system that requires their accounting. In this case, data for water *extraction* was estimated with a bottom-up approach from the estimations of direct use requirement and losses. In Mauritius, the *recharge* for each basin (Table 6.4) was calculated from the total data of renewable water resources for the complete island using a top-down approach.

The formal definitions used in this chapter are:

6.2.1.1 Supply (SU)

The supply is originated by the constant dynamics of the water cycle and has as destination the ecosystems. In this chapter it is not considered because these high scales of analysis were not included in the case study.

6.2.1.2 Recharge (REC)

It is the water that reaches the water bodies and contributes to maintain their stability. It does not only contribute a quantitative input to the water bodies but also certain standards of quality that are necessary to maintain the characteristics of the water funds. The recharge depends on the ecosystem condition like the levels of vegetation, etc. as well as on the water supply coming from the water cycle. In this chapter, the only source of recharge is the *precipitation*.

Data sources: Data on *renewable water resources* statistics has been used as a proxy for the recharge of surface water bodies and aquifers in both Mauritius (Aquastat) and Punjab (Regional statistics). The recharge of the soils has been estimated as the effective rainfall using Cropwat and Climwat (Food and Agriculture Organization of the United Nations 2014c, 2014d) in both cases.

6.2.1.3 Appropriation (APP)

An appropriated water body has suffered a modification in its properties that affect its role as an ecosystem fund component. That is, it impedes that water in enough quantity and quality is made available to societies and ecosystems. Since it refers to the role of water as a fund, it cannot be analyzed taking into account flows of water, but changes in the characteristics of the funds. This includes spatial-temporal changes in the quantitative regimes as well as in the qualitative characteristics like temperature, nutrient concentration, or potential energy content.

Data sources: Quantitative appropriation has been defined as overdraft and estimated in both cases comparing recharge with the extraction. Qualitative appropriation is only included in the case of Punjab and estimated using indicators of the state of the water bodies and soils from the regional statistics.

6.2.1.4 Extraction (EXT)

Extracted water is a flow of water that affects the normal functioning of the water dynamics. It is the link between the watershed and the problemshed descriptive domains and as such can be defined by source –surface, aquifer, soil- and by destination –distributed or non-distributed. For the sake of clarity in both cases it is assumed that the extraction is equal to the quantitative appropriation. Distributed extraction includes centralized networks and includes the distribution *losses*. Non-distributed extraction includes *in-stream* extraction like hydropower generation.

Data sources: In both case studies the distributed extraction has been estimated with a bottom-up approach from the estimations of direct use, corrected with the coefficient of losses. For the case of Mauritius the coefficient was taken from the statistics of the public water company in 6 per cent. For the case of Punjab, a generic coefficient of 40per cent was taken due to the bad shape of the channels of the region. The non-distributed extraction equals the direct use of soil water by plants (green water), the water for hydropower generation and cooling.

6.2.1.5 Direct Use (DU)

The water directly used is the one that reached the societal function. It maintains the social fund –the human activity- whose disaggregation in social compartments determines the disaggregation of the water flows. For example, looking at the sector ‘Energy production and mining’ as a whole would give a type of water that can be called ‘energy’, while the separation of this sector in ‘thermal’ and ‘hydropower’ production functions would require the separation of the former in two. For both case studies, the use has been estimated with a combination of bottom-up and top down methodologies.

Data sources: The agricultural water use has been estimated using Cropwat and Climwat (Food and Agriculture Organization of the United Nations 2014c, 2014d) in both cases, separating the water coming from the soil moisture (green) from the water coming from irrigation (blue). Industrial water use has been analyzed for the case of Mauritius only, correcting the statistics of water withdrawal of Aquastat with the perceptual distribution among sectors of the national water company. The use of water in households in Mauritius has been estimated in the same way while in Punjab has been estimated considering the minimum requirements of life and citizenship water provided by Arrojo (2006). The estimations of direct use require information about other elements, such as land use, or energy and food production and information about the amount of water per unit of production used, that were consulted from different sources.

6.2.1.6 End use (EnU)

As explained in Chapter 5, the accounting of the use of water can take into account the water directly used by a social compartment or by the complete supply chain, following the accounting logic of the water footprint assessment. The supply chain can consider the international markets or the internal productive structure or both. In this cases the end use considers the water directly used in the regions of Mauritius and Punjab that were used during the production of the goods consumed locally. That is, the relations of the internal productive structure are not included.

Data sources: End use is estimated as the difference between the direct use and the virtual flows exported, which is both cases refer only to the agricultural sector. For the estimation of the virtual flows exported, the method developed in Chapter 7 was used.

6.2.1.7 Relation between categories

The relation between the categories is covered by the following expressions:

Recharge = Renewable water resources + effective rain

Quantitative Appropriation = Recharge - Extraction

Extraction = Direct use + losses

Direct Use = End use + exported virtual water

6.3 Using multi-level matrixes for the analysis of Mauritius Island

Since independence in 1968, Mauritius has developed its economy by strongly expanding its financial and tourism sectors. In this process agriculture has remained locked in to sugarcane plantations, producing sugar for export with a demanding allocation of resources (Serrano-Tovar et al. 2014). More recently, this allocation of available production factors to sugar is questioned, since sugar exports contribute only 2.5 per cent of Mauritius's gross value added (Kovacic and Ramos-Martin 2014), while the country imports most of its consumed food (84 per cent in energetic terms) and energy (80 per cent) (Cadillo-Benalcazar et al. 2014). Moreover, the ACP sugar protocol program (a form of support from the European Union to the African, Caribbean and Pacific group of states) has been ended, and the prices of sugar are no longer guaranteed.

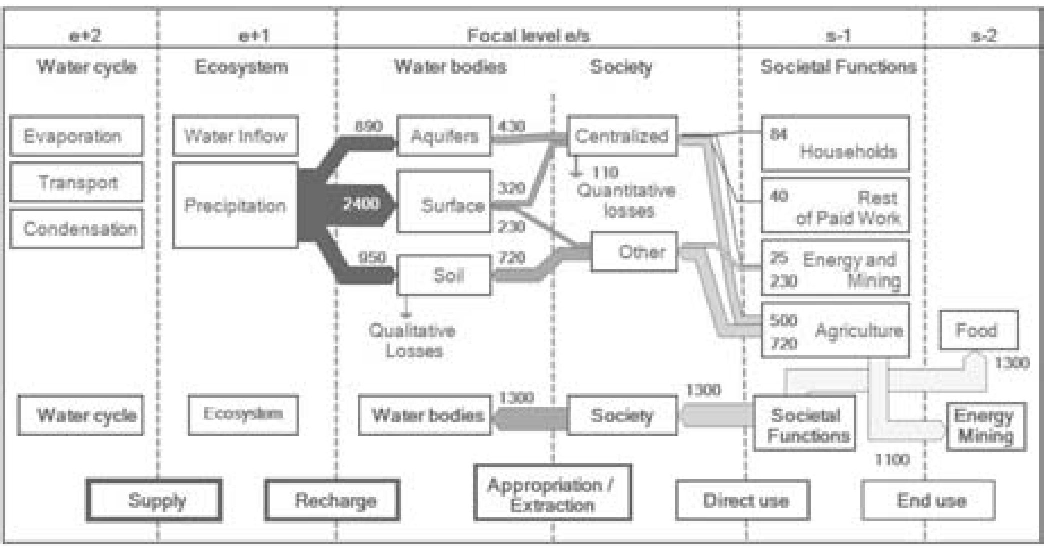
6.3.1 Representation of the grammar

A graphic representation of the water grammar is given in Figure 6.1, showing the quantification of the categories of accounting defined in Table 6.1 for the Mauritius case study. The left side of the grammar (levels e + i and e) represents the external view on the water metabolic pattern –the watershed perspective- and focuses on the water supply and recharge (ecosystem). The level of the water cycle and other processes taking place at this scale are included in the grammar only for illustrative purposes. At level e + 1 the recharge is originated from the precipitation, since there is not inflow possible into an island. In order to guarantee the feasibility of the metabolic pattern of society, the recharge should be able to replenish the quantitative and qualitative loss in the water bodies due to the appropriation of water, and to satisfy the conditions required by the ecosystems. As previously mentioned, the appropriation is divided by source according to the three main water funds: surface, ground and soil water.

The right side of the grammar shows the internal view on the water metabolic pattern –the problemshed perspective- and focuses on water extraction and use within the socio-economic system. At the social domain of the focal level –s- the water extraction of the society as a whole can be observed. This quantity is classified into centralized systems (distributed) and other (non-distributed) water flows. After accounting for the water losses in the distribution system the direct use is obtained. The direct use is classified into four socio-economic compartments: the household sector, energy and mining, agriculture, and the rest of the paid work. It is here, at the local level, that it can be defined what attributes 'water' must possess to qualify as an input flow for the funds in the socio-economic system, as explained in Chapter 3 and Chapter 4.

The classification of the various direct uses of water into societal compartments may vary with the purpose of the analysis. For example, in the characterization of Mauritius in Figure 6.1, evapotranspiration from soil and irrigation are local water direct uses that take place only in the agricultural sector, mostly for sugar cane production. However, when the end use is examined most of the sugar cane is exported for the production of bioethanol, thus becoming a flow of virtual water exported and contributing to the end water use of the energy production somewhere else. Also Mauritius Island imports a significant part of the vegetables consumed domestically, thus increasing its end use of water for food production, while not increasing the direct use –and the extraction and appropriation- of water.

Figure 6.1. Water grammar for the case of Mauritius (hm^3). The arrows show opposite direction to indicate the level where the feasibility check is performed.



6.3.2 *The problemshed perspective (levels s, s-x): direct use and extraction*

The multilevel matrixes described in Chapter 5 are the tool used within MuSIASEM for the organization of the information including different levels and water dimensions. These come from the tabulation of the data represented in the grammar into vectors, which form the rows of the matrixes. Each row characterizes the water use in a certain compartment without reducing the rest of the dimensions of water.

Table 6.2 shows the quantification of the water use types per social compartment and their aggregation in extracted water. For example, the water direct use in agriculture in the grammar is divided between water from the soil (720 hm^3) and irrigation (500 hm^3), that are covered in the last row of the table –in bold-, showing the pattern of the agricultural sector (numbers in the grammar representation are rounded).

As explained in Figure 4.2 of the description of semantic categories of a PhD thesis, this arrangement is not fixed. While in the case of Mauritius water used for drinking, cooking and showering (life) is set under the type ‘distributed’, for the case of Punjab this type would be mostly nested under the non-distributed water. The variation of the arrangement of water types from one case to another is also a qualitative explanation of their metabolism. The Table 6.2 also shows how not all types of water are relevant for all societal compartments. In general lines the direct use of life and citizen types are only relevant within the households. Water used for drinking during working hours is included in the Economy rest type. In the same way, irrigation and ET water types are relevant for agriculture only and cooling and hydropower, for the energy and mining sector. From this information we already see the high contribution to direct water use of the agricultural production, since this compartment at level n-2 is the one with the higher water consumption (1,218 hm^3). The difference between the use and the extraction are the losses, which for the case of Mauritius sum up about 100 hm^3.

When the data available does not fit into the grammar proposed, some estimations must be done. For the case of water use it is rare when the data is available with the level of detailed needed for an analysis of the water metabolism, especially regarding some water types. For the case of life and citizenship water, statistics simply do not exist, because there are no counters for the measurement of such volumes within the households. In this case, an indicator of direct use of life and citizen water needed per capita (26 and 65 Lpd respectively in Mauritius) is multiplied by times the population and corrected with the working time. These indicators are not fixed, especially the one for the citizen type that must be adapted to the ways of life of the society in question. Also the definition of the types might change from one society to another. Showering might be seen as essential for life in some societies and as part of the citizen right in another. The water required for energy purposes depend on the productivity and technology of the power plants. Like in the case of life and citizen waters, it requires of a unitary coefficient that is multiplied times the energy production, which must be frequently searched for in the technical literature.

Table 6.2. Multilevel matrix that summarizes the social metabolic pattern or problemshed perspective for the case of Mauritius. From Madrid-López & Giampietro (2014)

Indicator/ Compartment	EXT	DU	DISTRIBUTED				NON-DISTRIBUTED		
			Life	Citizen	Econo*	Irrig.	ET	Cooling	Hydr.
Whole (n)	1,706	1,599	11	73	66	498	718	4	228
per cent of USE	-	100	1	5	4	31	45	0	14
per cent of Extraction	100	94	1	4	4	29	42	0	13
HH (n-1)	98	84	11	73	0	0	0	0	0
HH-Urban (n-2)	41	35	5	31	0	0	0	0	0
HH-Rural (n-2)	57	49	6	42	0	0	0	0	0
PW (n-1)	1,608	1,515	0	0	66	498	718	4	228
PW-SG (n-2)	17	15	0	0	15	0	0	0	0
PW-TR (n-2)	1.72	1	0	0	1	0	0	0	0
PW-BM (n-2)	27	23	0	0	23	0	0	0	0
PW-EM (n-2)	262	258	0	0	26	0	0	4	228
PW-AG (n-2)	1,300	1,218	0	0	2	**498**	**718**	0	0

Water devoted to the agricultural sector was important in all three cases. Its estimation is more complicated because the unitary value that must be multiplied times the area under production is estimated with FAO's Cropwat, which requires data about climate, soil and crop types in order to estimate the water needs per unit of land. The detailed method for the estimation of the direct water use in agriculture from the crop characteristics is explained in Chapter 7.

These indications for estimations are given as a secondary strategy for the assessment when fieldwork is not possible. For the assessment of water use in households, the best option would be to explore the use of water in pilot households or to conduct interview that would help us determine: i) to what extend are water daily needs considered a human or a citizen right; and ii) the volumes of water devoted to each of them. In the same way, the water use by the energy and mining (EM) sector would better be analyzed if the data of real water throughput in the power stations were known. Also, the best quantification of water use for irrigation would be that done by counters. However in some cases, direct quantification cannot be done, or requires of advanced technical equipment, like in the case of the water used for evapotranspiration coming from the soil (ET).

6.3.2.1 Opening the problemshed matrix

As mentioned above all the categories of water and social compartments in the multilevel summarized matrix can be open until the levels of aggregation needed for the analysis.

Table 6.3. Opening the AG compartment. From Madrid-López & Giampietro (2014)

	Production (ton)	Area harvested (ha)	Direct Use (hm^3)		End Use
			Irrigation	ET	Virtual Export
Cereals, Roots, and Pulses	24,772	1,880	0	6	0
Meat, Milk and Products	71,741	7,000	72	0	0
Vegetables, Fruits and products	91,561	5,683	0	22	0
Oil crops, oil and fats	2,083	214	0	1	0
Stimulants	7,380	698	0	7	0
Sugar crops	4,362,118	58,710	426	680	1100
Others	2,784	310	0	1	0
Non Food	310	213	0	1	0
AGRICULTURE	4,562,749	74,707	**498**	**718**	1100

Given that agriculture generally represents the main water end use in society (77 per cent in Mauritius). Table 6.3 illustrates the procedure for assessing water use in agriculture by disaggregation of the agricultural sector into typologies of crop production. Note that almost all the agricultural water used in Mauritius goes into sugarcane production, which is almost totally exported for its transformation into bioethanol.

6.3.3 The watershed perspective: extraction and appropriation

The problemshed and watershed views on water metabolism meet when studying the implications of the appropriation of water in relation to ecological processes. To perform a feasibility check on the societal metabolic pattern of water, the water extraction has to be compared against the processes beyond human control that guarantee the stability of ecological funds. Table 6.4 shows an example of how to proceed with such a feasibility check.

For this check, the total area of Mauritius was subdivided into basins using as a proxy the water supply systems which closely follow the natural limits of river basins. Water appropriation is then estimated for each of the supply systems and compared to the recharge of the water funds in order to check its feasibility. When considering the impact of societal metabolism on the metabolic pattern of the ecosystem, the extraction has to be transformed into appropriation from specific funds that are defined following the ecosystem logic. Supply systems can be considered a proxy of ecological compartments (at the 'shadow' levels e − 1, e – 2 presented in Chapter 4).

Table 6.4. Multilevel matrix for the feasibility check. From Madrid-López & Giampietro (2014)

Indicator/Compartment (Supply system)	**Extraction TOTAL**	**Recharge**			**Appropriation (per cent)**
		to Surface	**to Ground**	**Total**	
Territorial System Covered (e-1)	1,492	2,055	778	2,834	53
Mare Aux Vacoas-Upper (e-1)	252	344	130	474	53
Mare Aux Vacoas-Lower (e-1)	**193**	**88**	**34**	**122**	**158**
Port-Louis (e-1)	291	562	213	775	38
North (e-1)	291	259	98	358	81
South (e-1)	247	383	145	528	47
East (e-1)	229	464	176	640	36
Uncovered (e-1)	214	820	311	1,130	19
TOTAL (e)	**1,706**	**2,875**	**1,089**	**3,964**	**43**

Looking at the water appropriation for the whole island (level e) in Table 6.4, there seems to be no issue with feasibility; the extraction does not exceed the ecosystem water recharge at level e. However, when we analyze the situation at a lower hierarchical level, we see that in one of the supply systems, Mare aux Vacoas–Lower, extraction (193 hm^3/year) exceeds recharge (122 hm^3/year). In this case, we have a feasibility breach of the societal metabolic pattern of water at the local scale (a violation of local external constraints). If not corrected properly, this could lead to structural damage to the water funds under exploitation in one of the supply systems. Thus, when carrying out a feasibility check, the specific local-scale identity of the water fund affected by the extraction matters! This example flags the importance of linking this type of assessment to spatial analysis.

The transition of the water extraction from the societal to the water compartments must be done carefully. Extraction is a category set up for the societal levels and within the ecosystem levels its meaning might change. In the societal matrix, extraction meant the water extracted from somewhere (in the island) that later on would be used within each of the societal compartments. At the ecosystem level extraction means the water extracted from each water system at level e-1, that will later on be used somewhere in the island. The total water extracted remains invariable, but the imputation to each compartment varies.

6.4 Quantification of the water metabolism: the case of Punjab

The broader *region* of Punjab is located within the Indus river basin. Its name is related to water abundance and literally means 'the five rivers'. In 1947, with the separation of British India the region was split between India and Pakistan. This case study focus on the Indian state, and from now on 'Punjab' will refer to this region only.

6.4.1 The situation of Punjabi agriculture

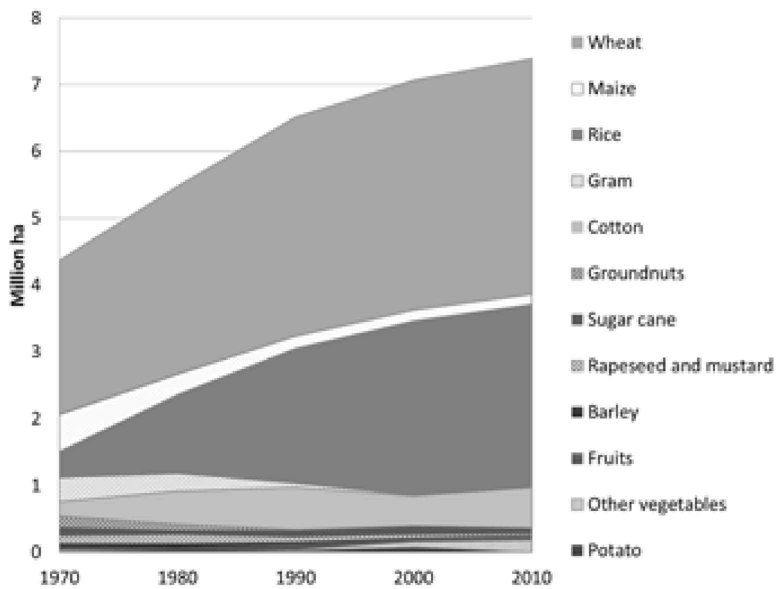
Punjab, like the other Indian states, is subject to country-level regulations regarding resources management, energy subsidies, food distribution policies and international trade. However, looking at the socio-economic characteristics, Punjab presents a peculiarity compared with the other Indian states with similar GDP per capita and countries with similar agricultural contribution to GDP: the Punjabi GDP per capita is relatively high, about 1,100USD (nominal, in 2010), in spite of having a large contribution to the GDP from the agricultural sector (31 per cent) (see Table 6.5). Owing to Punjab's location in important river valleys; its soils are extremely fertile. This has motivated Indian public investment in farming in the state. Agricultural production has been actively promoted ever since the green revolution in the 1970's and this has resulted in a strong specialization in cereals, particularly rice and wheat, as shown in Figure 6.2.

The Food Corporation's Act 1964 of India through the Food Corporation of India has established a national food distribution policy that induces Punjab to cede a significant part to the central pool of food grains. In 2010 Punjab provided about 45per cent of the wheat and 25per cent of the rice entering India's central pool, corresponding to the procurement by the central government of about 70per cent and 80per cent of Punjab's total production of wheat and rice respectively (Government of Punjab 2012). The food flow to the central Indian pool of food grains is actively encouraged by the MSP and by energy and trade policies.

Table 6.5. Socio-economic variables for Punjab, India, selected states with similar GDP per *capita*, and countries with similar contribution of agriculture to GDP. From Madrid-López et al. *(2014)*

Country	Agriculture, value added (per cent of GDP)	GDP (current 10^9 USD)	GDP per capita (current USD)	Life expectancy at birth, (years)	Population, 10^6 people
Benin	**32**	6.6	690	58	9
Rwanda	**32**	5.6	520	62	11
Togo	**31**	3.2	500	55	6
Malawi	**30**	5.4	360	53	15
India	18	1,400	880	65	1,200
Uttarakhand	10	12	**1,200**	–	10
Punjab	**31**	**42**	**1,500**	**72**	**28**
Kerala	16	51	**1,600**	74	33

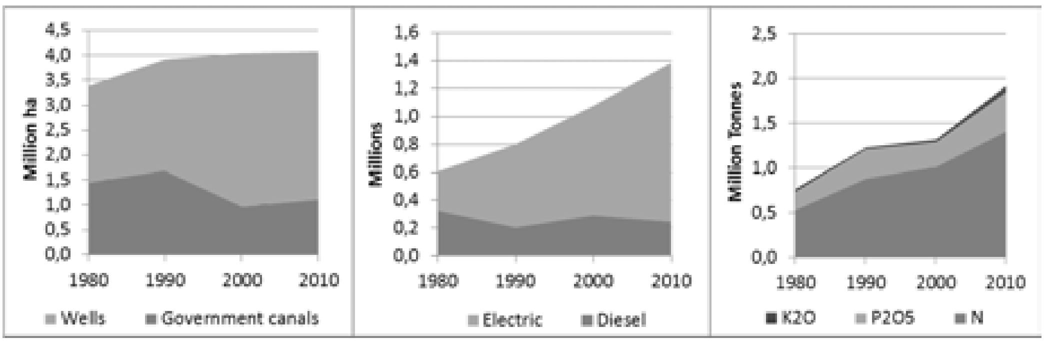
Figure 6.2. Specialization of the agricultural land in Punjab. From Madrid-López et al. *(2014)*



The Government of India establishes the Minimum Support Price (MSP) for procurement of food grains so as to ensure the livelihood of farmers. The price is estimated each year on the basis of the evolution of the cost of inputs and negotiated with each state individually. Punjab has the highest MSP for rice of all Indian states; providing a high percentage of the central pool it has acquired strong negotiation power. In practice, costs of agricultural production are fairly low because the farms are frequently family-run, and energy for irrigation is highly subsidized.

Indeed, as part of the energy planning, the Government of India provides high subsidies on electricity for groundwater pumping in Punjab, despite India's bourgeoning energy deficit –about 95per cent of its Gross Energy Requirement is imported– and the raising awareness about the need for a more conscious use of energy resources (Government of India 2006). India's ability to provide reliable and adequate energy supplies for other sectors of the economy is heavily dependent on how efficiently water for crop production is managed (Kumar et al. 2013). The relatively high MSP in Punjab ensures that labor does not leave the agricultural sector for more profitable sectors by keeping the economic labor productivity in agriculture at an artificially high level (International Food Policy Research Institute 2007). Indeed, critical voices have suggested that the MSP provides a wicked market stability in the region that prevents the diversification not only of the economic structure but also of the agricultural activities (Bhullar and Sidhu 2007).

Figure 6.3. Evolution of the irrigated surface in Punjab per source (left); the number of wells per pump type (center); and use of fertilizer per type (right). From Madrid-López et al. *(2014)*



Intensive agricultural production in Punjab has resulted in severe environmental impacts. Not surprisingly, as about 90per cent of the total state surface is devoted to agriculture, most of it under irrigation and receiving mineral fertilization. Intensely irrigated agricultural production presently covers about 85per cent of the land (against 2per cent of rain-fed agriculture). Out of this surface, about two thirds are irrigated with ground water withdrawn from the aquifers and one third with surface water provided by governmental canals (Government of Punjab 2012).

Currently most of the water for irrigation is withdrawn from aquifers with the support of electric pumps, a tendency that has grown over time, as shown in Figure 6.3. As a consequence, ground water exploitation has surpassed the natural recharge, reaching an overexploitation of 150 per cent of renewable groundwater resources, lowering the water table level every year and further increasing the electricity needed for irrigation.

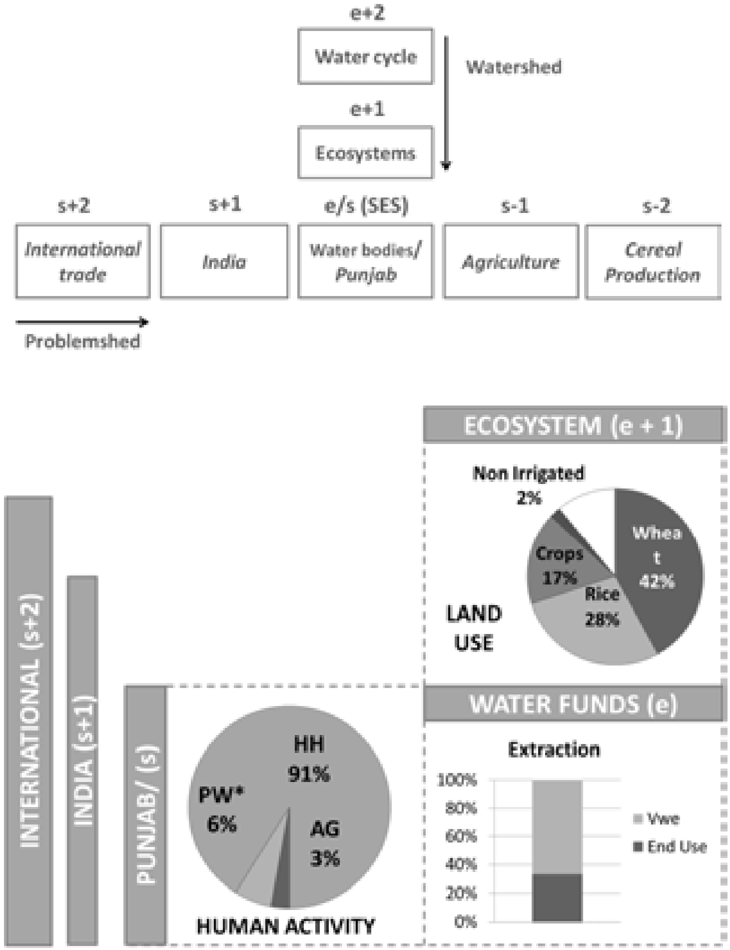
Intensive agriculture in Punjab has also depleted its rich soils of nutrients. Figure 6.3 shows the evolution of fertilizer use in the state over the last 40 years. The soils of 16 out of 22 districts have run out of nitrogen and ten districts now only have a medium level of phosphorous (Indian Institute of Soil Science 2012). Increased fertilizer use is closely linked to the price control and subsidies implemented by the Indian Fertilizer (Control) Order of 1985 and drives Punjabi agriculture towards a deeper dependence on fertilizer imported from India.

6.4.2 A metabolic description of Punjab

The above background information portrays a state whose natural resources are being depleted in order to sustain the strategy of national food security imposed by the central Government of India. In the following, MuSIASEM is used to establish a formal link between the socio-economic processes described at the upper levels of analysis (India and international markets) and those described at the local scale (Punjab and rural households) with the impacts over the water bodies.

The interrelation of the various levels of analysis considered in this case study is shown in Figure 6.4. Since Punjab is the focal level of the analysis, the state is represented as level *s*, India –in horizontal- as level s+1 and the international markets as level s+2, thus showing the ‘shadow levels’ presented in Chapter 4. At level s-1 the household (HH) and paid work compartments are considered, while at level *s-2* only the agricultural sector (AG) is distinguished from the rest of the paid work sector (PW*). The ecosystem levels –in vertical- have been adapted to the case study. We have kept at level *e* the water funds that are included within the geographical area of the state. The upper levels of ecosystems and the water cycle processes are considered at levels *e+1* and *e+2* respectively. Subdivisions at level *e-1* have not been considered, contrary to the case of Mauritius Island, in which the supply systems where used as a proxy for the basins.

Figure 6.4. Multi-axis classification of the analytical levels for the assessment of Punjab (above) and distribution of the funds at the focal level (below). Adapted from Madrid-López et al. (2014)

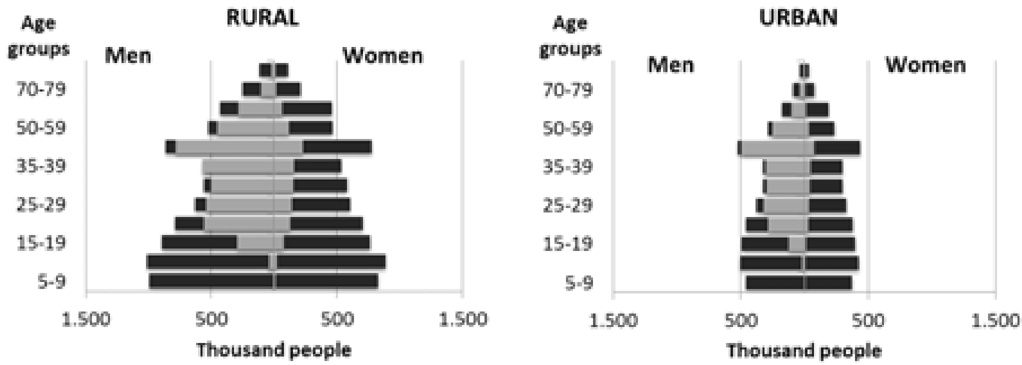


A first look at the funds human activity and land at the focal level *n* (Punjab) and below shows that about one third (30 per cent) of the paid work is devoted to agriculture. Regarding land, most of the Punjabi area is devoted to agriculture (89 per cent), leaving a mere 11 per cent of the surface classified as non-managed land. Most of the total land (70 per cent) is under cultivation of rice and wheat. Also, regarding the water flows, only 35 per cent of the agricultural water extraction is to produce cereal consumed in Punjab –transformed into end water use-, while 65 per cent is transformed into virtual water exports (VWe) going to India.

6.4.2.1 The problemshed view: the viability check

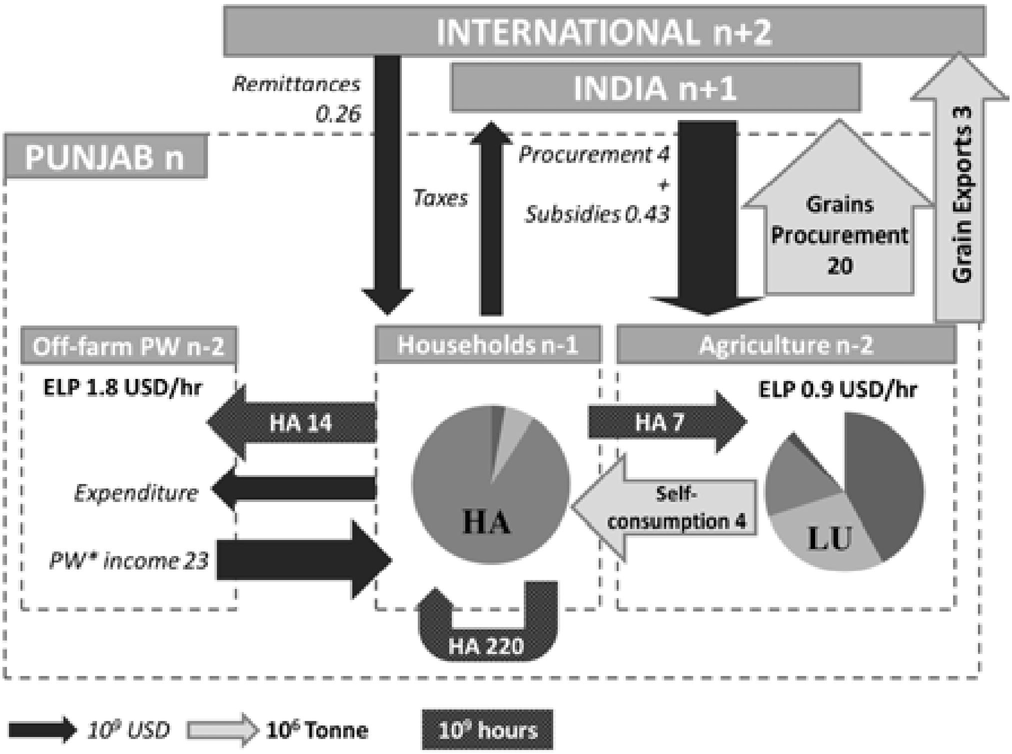
The population pyramid for rural and urban Punjab, indicating the working population, is shown in Figure 6.5. Note that working population includes only registered or paid work; unpaid household and farm work is not accounted for here. The urban population (37 per cent) is about half the rural population (63 per cent). Registered work is mainly performed by men in both rural and urban areas, where the working age is lower.

Figure 6.5. Age and gender structure of the rural (left) and urban (right) population of Punjab. The working population is represented in light grey. From Madrid-López et al. (2014)



As previously mentioned, Punjab presents simultaneously a high percentage of state GDP from agriculture and a high per capita GDP, a combination that is not found in other Indian states or other countries. Also, the larger part of the land is devoted to irrigation farming, which is largely maintained by unpaid human activity (family). To better understand this situation the relation between monetary flows, food grain production and human activity is detailed in Figure 6.6. This graph focuses on Punjab (level s) and its interactions with the upper societal levels (s+i). Monetary flows are represented by dark grey arrows, food grain flows are represented by light grey arrows, dotted arrows represent the allocation of the fund human activity, and traced arrows show the connection with the ecosystem. The interface with the market, including export/import of food grains and monetary flows is this time represented at the top. Note that food grain production for export is mainly destined to India (87 per cent); only a small share is sold on international markets (13 per cent).

Figure 6.6. The problemshed perspective of the production of cereals in Punjab. Adapted from Madrid-López et al. (2014)



Most of the human activity (220 × 10^9 hours) is allocated to the household (HH) compartment to maintain the fund human activity. The rest of the human activity is dedicated to the production of food and other agricultural products and to other paid work (PW*), mostly within the service and government sector. In this context, the MuSIASEM accounting system makes it possible to individuate a peculiarity in the metabolic pattern of households in Punjab. Given the fact that in Punjab a large share of the work is engaged with agricultural activities, which have a low economic labor productivity (ELP), it is unclear how it is possible that the state of Punjab enjoys a relatively high income per capita compared to other Indian states. This apparently anomalous situation can be explained by the existence of other sources of income entering the local economy, like 1) central grain procurement payments through the MSP program; 2) subsidies on electricity from the government of India; and 3) remittances from abroad.

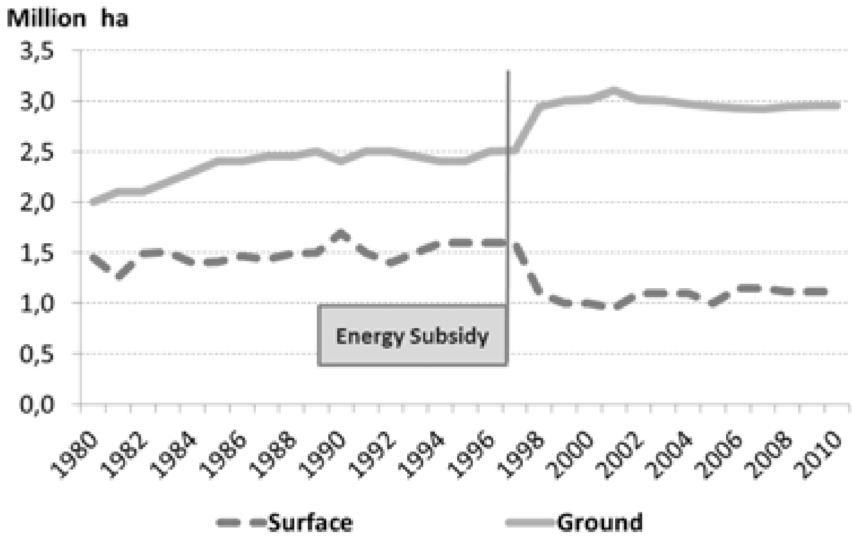
The livelihood of rural households is mainly determined by the flow of money entering from agricultural activities. With a monetary flow of 4 billion USD entering into the sector of grain production through the central procurement of 20 million tons of grain and 7 billion labor hours in agriculture, a rough estimate of the monetary flow from the central grain procurement per hour of labor in agriculture gives a low ELP of 0.9USD/hour. As may be expected, this is less than the economic labor productivity of the off-farm sector in Punjab, which is 1.8USD/h. This low level ELP explains why subsidies are essential for making the pumping of underground water for irrigation economically feasible for farmers.

Indeed, the role of remittances is especially relevant, as they accounted for more than 10 per cent of the GDP of Punjab in the period 2000–08 (RBI 2013), twice as high as for India as a whole. Thus, paradoxically, remittances to Punjab are currently instrumental in the viability of the metabolic pattern of the rural Punjabi population (considering the household level, $n - 1$), and hence for the viability of the entire Punjabi socio-economic system (at level n) and, indirectly, for the food security of India as a whole (at level $n + 1$). Unfortunately, the flow of remittances shows a negative trend (it dropped to 8 per cent of the GDP of Punjab in 2010), probably owing to the economic crisis in the countries of origin. If this negative trend continues, a difficult situation in Punjab (and in India!) may arise in the near future.

With the subsidies for electricity the government of India aims not only to ensure the livelihood of rural households but also to encourage intensification of agricultural production. Indeed, subsidies for electricity are a key factor in maintaining high yields (biophysical productivity) in grain production. Looking at a historical series of surface and underground water consumption data for Punjab, it is evident that availability of water is not the only factor determining the extent of its use for irrigation.

As illustrated by Figure 6.7, in humid years (1990) the overall sources and extent of irrigation did not change significantly. On the other hand, the introduction of subsidies for the use of electricity for irrigation (1996/97), alleviating the internal constraint represented by the excessive cost of electricity, generated an immediate shift from surface water to underground water utilization by farmers.

Figure 6.7. Evolution of the area of irrigated land (surface and ground water) before and after the implementation of electricity subsidies (1997). Adapted from Madrid-López et al. (2014)

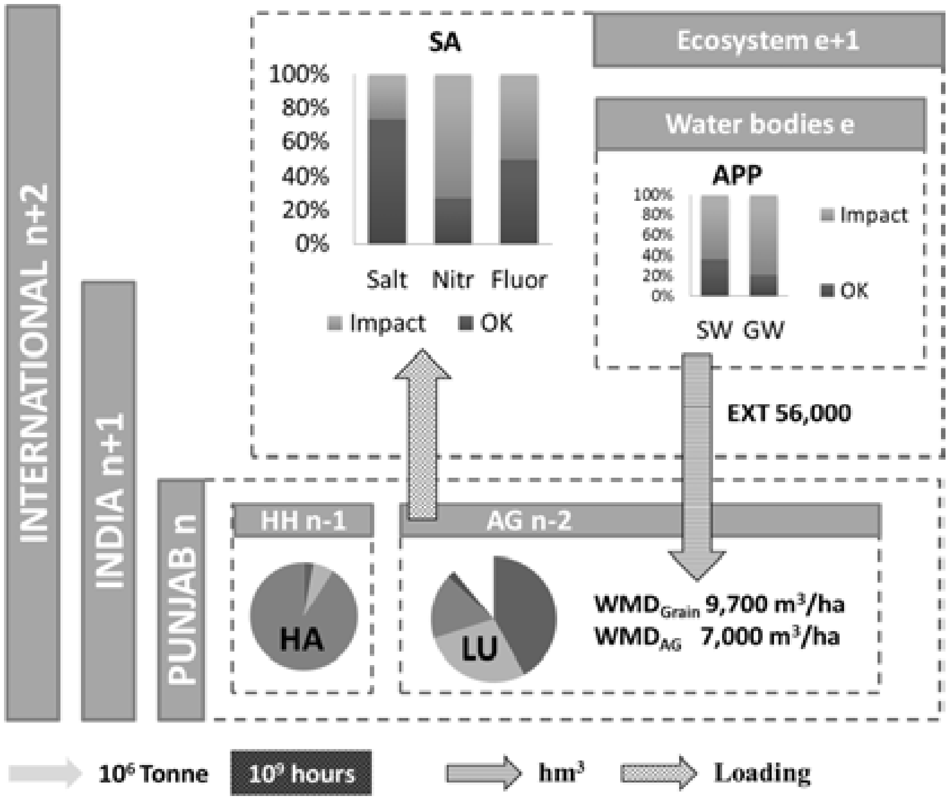


Unfortunately, these subsidies also have negative side-effects, such as an increase in the impact on underground aquifers and the quality of soil of Punjab (Bhullar and Sidhu 2007). From this viability analysis, it is clear that the specialization of Punjab's economy in the production of wheat and rice is a consequence of the national food security policy of the Indian government and not of the economic return that this activity provides to the state. This national policy causes a lock-in of the system, preventing the economy of Punjabis from diversifying not only its economic activities (outside agriculture) but also the types of crops cultivated (within the agricultural sector).

6.4.2.2 The watershed: feasibility check

The monetary flows entering Punjab from India and from abroad are promoting a progressive environmental degradation in a region that has a small margin for self-management of its natural funds, especially water.

Figure 6.8. Appropriation of water (APP) and soil (SA) in Punjab. Adapted from Madrid-López et al. (2014)



Owing to institutional settings (international treaties with Pakistan and government decisions affecting Rajasthan and Haryana) a large amount of surface water is diverted before reaching Punjab. As a consequence, irrigation pumped from the aquifers is offered as the main solution and is encouraged with subsidies from the central government. However, the resulting progressive intensification of agricultural production has resulted in a severe impact on environmental funds as illustrated in Figure 6.8.

The water appropriation (APP) – that is, the extraction compared with the recharge- of the water funds equals 150per cent of the water fund recharge. More specifically, about 75per cent of the aquifers are considered as over drafted and about 60per cent of the surface water monitoring stations report high levels of fertilizer components, heavy metals and biological contamination. Part of this water appropriation results in a *soil appropriation* (SA) as a result of nutrients leaching or fertilizers transport processes. The lack of control over water use (regulated mainly through electricity prices) has frequently resulted in over watering. Figure 6.8 shows that as a result of intensive agriculture more than 60per cent of the Punjab districts have Nitrogen-impoverished soils and that the percentage of salt and Fluor-impacted soils is already significant.

6.4.3 The problemshed/watershed interface

Looking at the factors affecting the viability of the metabolic pattern of India as a whole (national level, n+1) we find worrying trends. It is reasonable to expect in the future a constant increase in the international price of energy (energy is needed at the local scale for irrigation and at the local and national scale for making fertilizers) and, as a consequence, in the international grain prices. An increase in international prices will make it more difficult for India to import grains from abroad, and hence the central government is likely to press for further intensification of grain production in Punjab. These developments may force the central government to 1) augment subsidies or 2) adopt higher procurement prices, in order to prevent Punjab from exporting its food production abroad. Otherwise the economic situation would stress rural households and increase social tensions in the state of Punjab.

Looking at the effects that these trends will have on Punjab at the state level (n) we obtain an equally worrying picture. The population of Punjab is still growing, while foreign remittances are shrinking. The policy of heavy subsidies to electricity use in rural areas will have to be reconsidered sooner or later because of its high cost and negative side-effects (Bhullar and Sidhu 2007). This means that we should also expect a future decrease for this second source of economic assistance to the local economy. This new situation would pose a serious threat to rural livelihoods. As a matter of fact, even to maintain current levels of agricultural production, more electricity will have to be consumed in the immediate future to pump water from lowering water tables. This additional consumption of electricity, if not compensated for by subsidies, will further decrease the already low economic labor productivity of agriculture in Punjab, at the very same moment at which quite strong institutional settings prevent diversification of its economic activities.

When considering the ecological compatibility of the metabolic pattern of rural Punjab in relation to the preservation of local ecological funds (ecological level e) the situation seems to be scaring. So far the socio-economic tensions within Punjab and between Punjab and India have been externalized to local ecosystems in the form of an increasing overexploitation of aquifers and soil degradation. The big question is for how long these tensions within the societal metabolic pattern -expected to grow further in the future - can be mitigated by a further increase of the environmental load to local ecosystems (stressing its stability) before a dramatic negative feed-back will cause the entire agro-ecosystem to collapse.

This case study is just an example of the tight connections existent between the problemshed and the watershed sides of the water metabolism and of how including both perspectives can enrich the discussion of water-related issues. A focus on the environmental impacts that ignores the relevance that water has for the social system shows the same incomplete view as those analyses approaching the value of water without considering the hydrological dynamics. A thorough analysis that includes both perspectives is complex to carry out; however, it is not so difficult to coordinate under the framework of the water metabolism. Figure 6.9 shows how the analysis at both levels can be related using the multi-level matrixes of MuSIASEM.

The connection between both domains is not only done in quantitative terms, but it also includes the environmental lodging indicators for appropriation. Figure 6.9 shows a simplified version of the matrix set of the water metabolism of the cereal production in Punjab. The upper tables show the relation between the watershed -external view- (left) and the problemshed -internal view- (right) with an organization of the information that shows the water dimensions relevant for each of them. The quantitative connection of their totals is made by the losses in distribution.

The problemshed domain shows the societal compartments and the differentiation between the water used for the internal production (direct use) and the part of that which is required for the internal consumption (end use). The direct use of water is included to make it the connection of the impacts that virtual water has over local water bodies. The watershed domain shows how the quantitative appropriation can be expressed in qualitative indicators, avoiding the use of the volumetric method and the grey water footprint. With an exercise like this, the bottlenecks can be identified. Observing the fact that 110 aquifers are overexploited, it can be argued that the water metabolic patterns of the production of cereals in Punjab are clearly not feasible.

Figure 6.9. Relation between the internal and the external views in Punjab. Adapted from Madrid-López et al. (2014)

Watershed

Appropriation	Distrib	Non Dis	Total
Underground	12	0	12
Surface	36	0	36
Soil	0	26	26
TOTAL	48	26	74

\-

Quantitative Losses
0
8
0

=

Problemshed

Direct Use	Distrib	Non Dis	Total
Underground	12	0	12
Surface	28	0	28
Soil	0	26	26
TOTAL	40	26	66

	Appropriation	River	Aquifer
Quantitative	Recharge (km3)	21	21
	Interntl. Use Rights	25%	100%
	Dam Reserve (km3)	11	N/A
	Blocks (no.)	N/A	138
	Extraction (km3)	15	31
	Overexp. Blocks (no.)	N/A	110
Qualitative	RAMSAR in Risk	3/3	N/A
	Regions Over Salinity	N/A	6/25
	Regist. Over Nitrate	N/A	16/25
	Regist. Over Metals	N/A	10/25
	Max. BOD (mgL)	50	N/A

Direct use	Distrib	Non Dis
HH + PW* (n-2)	1	0
PW (n-1)	39	26
AG (n-2)	39	26
Rice & Wheat (n-3)	36	23
TOTAL (n)	40	26

End Use	Distrib	Non Dis
HH + PW* (n-2)	1	0
AG (n-2)	10	9
Rice & Wheat (n-3)	7	6
TOTAL (n)	11	9
Expeditions India	28	16
Expeditions %	71%	64%

6.5 Relation between the conceptual framework and MuSIASEM

The conceptual framework of the water metabolism presented in Figure 3.4 might seem rather abstract for its application in a numeric analysis. In fact, this framework shares the epistemological foundations of MuSIASEM. All six relations presented in the conceptual framework have been included in the water grammar of MuSIASEM.

Figure 6.10. Water metabolism: adaptation of the MuSIASEM grammar to the theoretical framework.

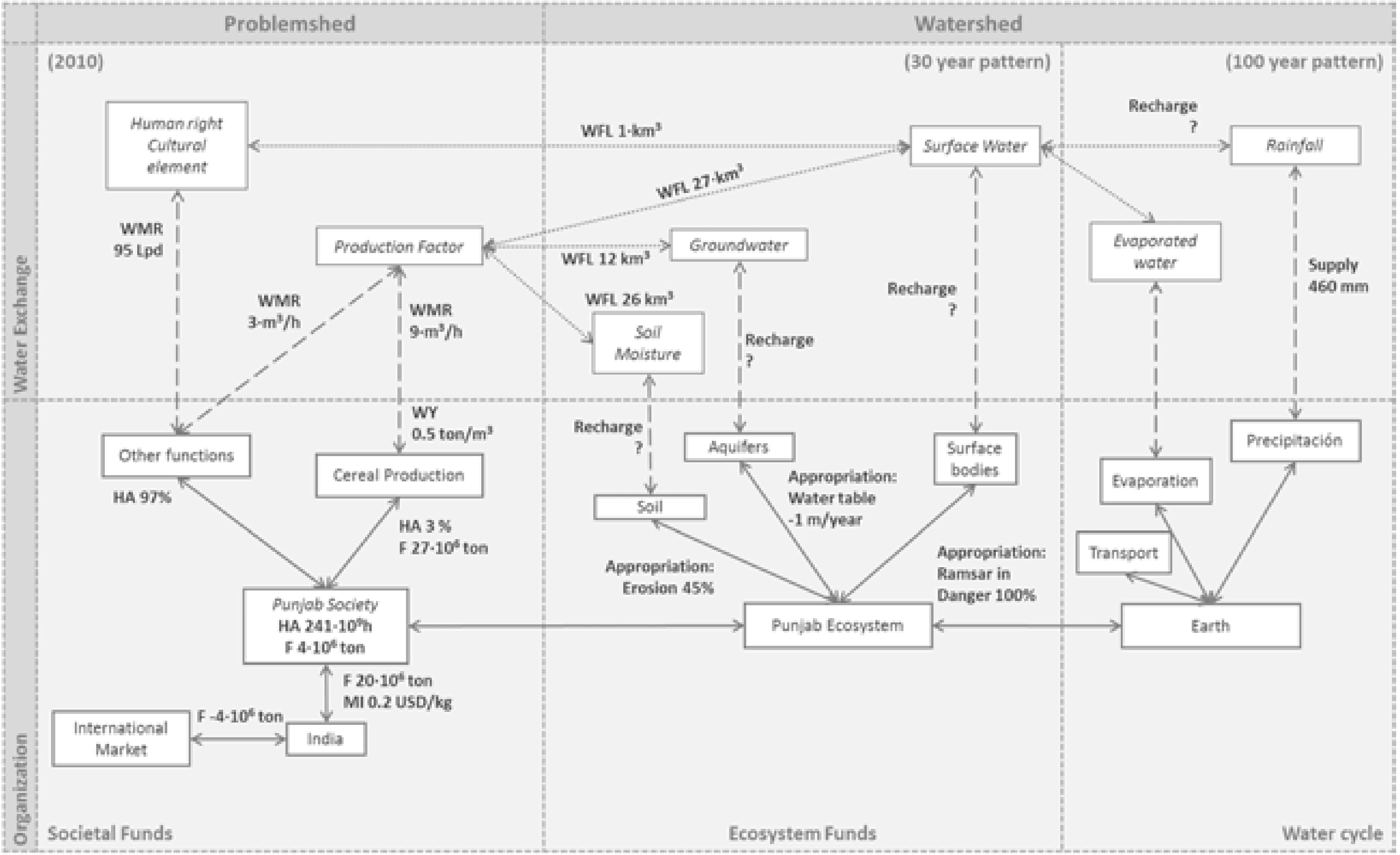


Figure 6.10 presents the integration of MuSIASEM metabolic indicators in the conceptual framework of the water metabolism using the example of Punjab. The upper part of shows categories of water flows important for societies (left) and ecosystems (right), and coming in the last instance from the water cycle. The lower part shows categories of funds for societies (left) and ecosystems (right) relevant for the analysis. The relation between them is given by flow/fund relations. A time frame of one year is sufficient to observe changes in the metabolic pattern of society, but a longer period (up to 30 years) will be necessary to see changes in ecosystem metabolic pattern.

The specialization of Punjab in the production of cereals (F, for food) and the export to India of almost all of it (20 out of 27 million tons) for an agreed support price to the central pool generate an average monetary input (MI) of 0.2 USD per kilogram. The share of the societal fund (Human Activity, HA) devoted to this activity is at a high 3per cent of the total human activity of the state. Punjab's production of cereals has a *water metabolic rate* (WMR) of nine cubic meters per hour of HA, much higher than the rest of the productive sectors (including other agricultural production), which show an average of three cubic meters per hour of HA (more on WMR in Chapter 7).

This water flow (WFL) –direct use- is accounted for as a production factor and is extracted from soil moisture (22 cubic kilometers), groundwater (12 cubic kilometers) and surface water (24 cubic kilometers out of a total surface water flow of 27, the remainder being devoted to other functions). In addition, the Punjab population has access to 95 liters of water per person and day, the quality of which does not follow WHO recommendations, making this a human rights/cultural issue.

The ecosystem water supply remains unstudied in most parts of India and hence the pressure on water bodies is largely unknown. However appropriation can be estimated by observing changes in ecosystem dynamics. For instance, intensive agricultural activity has resulted in over exploitation of aquifers (drop in water table of one meter per year), pollution of surface water bodies (with three out of three RAMSAR wetlands in danger) and heavy erosion of 45per cent of the soils, diminishing its water retention capacity. The water metabolism of this SES receives a natural supply of 460 mm of precipitation per year (with a tendency to diminish due to climate change) plus an unknown amount of water coming from transboundary basins.

This example shows how the integration of metabolic indicators can strengthen SE-hydrological studies like the WF or VW flow assessments. It provides a way of connecting social, environmental, and Earth levels, thus dealing with the weakness of the WF in the definition of environmental impacts. The 'unreality' of the VW flows –a constant criticism to the concept– is also addressed: it is clearly stated that water is not flowing between countries, but that the resource is essential for the production of traded products. Studies related to political ecology that usually do not account for physical flows can also be accommodated within this frame through indicators like access to water. The ecosystem's role in the maintenance of the water flow exchange is made explicit.

6.6 Conclusions

This first application of MuSIASEM suggests that it is indeed a useful framework for the study of the water metabolism. The Multi-level matrices are accessible tools easy to apply, as they adapt to the specifics of the case study. The disaggregation of the compartments –the rows- and the dimensions included in the analysis –the columns- can be selected for each case, while remaining comparable their results.

The feasibility and the viability assessment follow different logics. While the viability focusses on the role of water as a fund and it is measured accordingly, the changes inflicted over the water funds cannot be measured with social flows. Instead, the changes in their identity are considered. As shown by the case study of Punjab state, relevant interrelations between food, energy and water can be identified and explained in relation to the viability settings. This case study has also shown that it is possible to identify relevant characteristics (prices, subsidies, remittances) of socio-economic processes in relation to the viability and the feasibility of the metabolic pattern at different levels of analysis (the agricultural sector, the aquifers, the whole state, the international market).

The feasibility of the water metabolic pattern of society depends on its compatibility with external constraints. These constraints are determined by the availability and integrity of water funds. The stability of the societal appropriation of water can be analysed in quantitative and qualitative terms on both the supply side (water extraction) and the sink side (water waste). Indicators of degradation of water resources seem a better option for the assessment of the impact of the societal metabolism (level of stress) on the actual water funds.

Since the results presented in this chapter have the goal of illustrating the possible applications of the MuSIASEM toolkit, relevant narratives about the sustainability of the state of Punjab have been individuated. This is possible because with MuSIASEM the data refer to an integrated set of different external referents. However, the results require a reality check by experts of the area and local actors.

Chapter 7
Tools for the analysis of the water exchange. Andalusia and Spain.

Tomate,
¿qué culpa tiene el tomate, que está tranquilo en su mata?

(Traditional Andalusian Fandango)

7.1 Merging the water exchange in MuSIASEM and WFA[16]

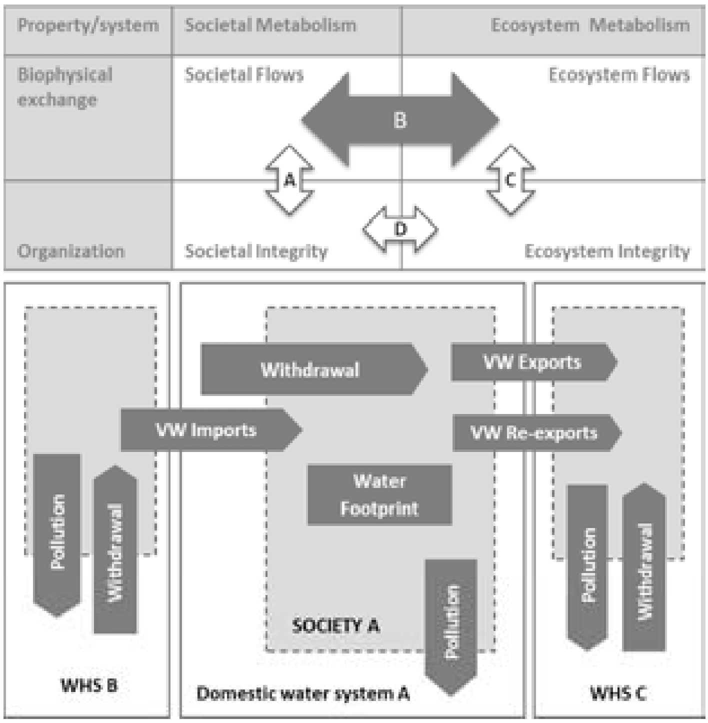
As mentioned in Chapter 2, most of the works developed within the Social Metabolism studies focus on the assessment of the biophysical exchange between the society and the ecosystem. As explained in Chapter 3, water flows are usually not included in the accounting of metabolism studies. In turn, most of the analyses approaching the water exchange between the society and the ecosystems use WFA, as covered in Chapter 5. Figure 7.1 shows the formalization of the relation B in the conceptual framework of the metabolism of SES and an outline of the water flows involved in it under the logical scheme (path-driven) of the WFA.

The WFA scheme represents the relation between three *water-human systems* (WHS). WHS A is the focal point of the analysis while WHS B and C represent the relations produced via international trade. In system A, two possible relations are

[16] Part of the contents of this chapter are published in Madrid, C and Velázquez, E. 2008. El metabolismo hídrico y los flujos de agua virtual: una aplicación al sector hortofrutícola de Andalucía (España). Revista Iberoamericana de Economía Ecológica 8: 29–47.

established with domestic water system: the quantitative (withdrawal) and the qualitative (pollution). The withdrawn water is used by the functions of society A, however this use is not represented in the picture due to its *black-box approach*. The internal needs of water of society A is not only provisioned by the domestic water resources, but also complemented by the virtual water flows associated to the imported goods coming from social system B. At the same time, society A, for whatever reasons, exports goods to social system C, thus creating extra virtual water flows associated to its exports. The net requirements of water of Society A are then understood as the water withdrawal, plus the virtual water imported minus de virtual water exported, which forms the indicator of water footprint.

Figure 7.1. Representation of the water exchange following the path of water of WFA.



In the MuSIASEM grammar (Figure 7.6), only the water relation that takes place between a society and its local water system is considered as water exchange. This can be considered as *appropriation* of water funds –from the point of view of the ecosystem– or as the *extraction* from water funds –from the societal point of view. However, due to the globalization of social dynamics, the institutional arrangements[17] of system A will affect those of society B and C, thus affecting their water exchange. This is the fundamentals of the problemshed perspective, which in Figure 7.1 are covered as virtual water imports and exports.

The difference between the WFA and MuSIASEM logics is that in the logics of WFA the *withdrawal* and *pollution* of water in system B is accounted as *extraction* and *appropriation* of system A, which is not true. Water from system B contributes to the stabilization of the social funds of society A, that is, to its *end use* of water. However, due to the fact that water is deeply attached to the land, the impact is inflicted over the water bodies in system B by the *extraction* and *appropriation* of water performed by society B. This is why in MuSIASEM grammars it is so important to distinguish between *end use* and *extraction/appropriation* and between the descriptive domains where each semantic category can be better evaluated. *End use* is better assessed with a problemshed perspective, while the *appropriation/extraction* of the water bodies is better approached using the watershed perspective. Also, they both are related by the *direct use* of water. As explained in Chapter 4, this distinction is relevant for policy-making as it identifies the target point within the water metabolism in need of policy action.

The differentiation between water extraction, direct use and end use is not an easy task when it comes to the detailed quantitative assessment. The purpose of this chapter is to explain how to perform this flow analysis using the combination of MuSIASEM grammar and WFA volumetric and IO methods. The presentation of the volumetric method focusses in the case of the fruit and vegetable production and trade from Andalusia, South Spain, to the rest of the world during the period 2004-2013. The IO analysis is resented for Spain 2005.

7.2 The WFA volumetric method revisited

Since agriculture contributes about 70 percent in average to the world's direct use of water (UN World Water Assessment Programme 2009), the volumetric accounting of WFA has focused in the assessment of the production, trade and consumption of agricultural products. The variety of indicators and methods involved

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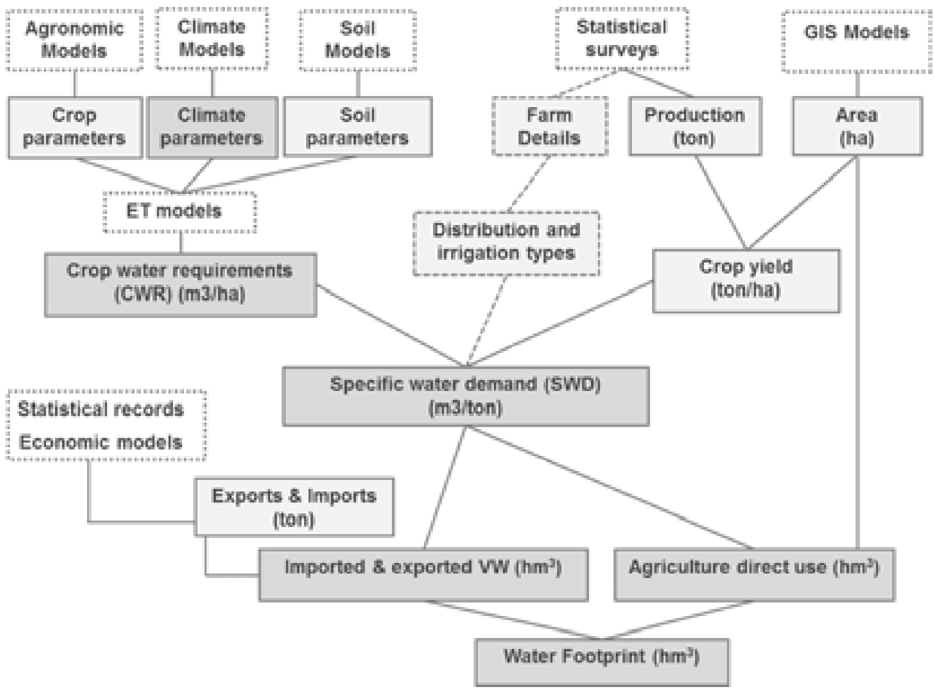
[17] Institutions described á la Ostrom, as sets of formal and informal rules that guide the social life.

in the estimations of water use in agriculture provide an excellent case to show how water complexity can be treated in this type of analyses. As explained in Chapter 5 the volumetric method uses a coefficient of *specific water demand* (SDW) multiplied times the local production or the traded physical volumes to transform local water withdrawal and pollution, on the one hand, and virtual water flows, on the other hand, into an indicator of the water footprint. Expanding the scheme presented in Figure 5.7, Figure 7.2 sketches the combination of methods and data sources included in an assessment for the case of agriculture.

Figure 7.2. Combination of methods and data sources in the estimation of VW and WF.



Models using different non-equivalent narratives are represented by dotted boxes (hollow) whereas the derived indicators are shown by shadowed boxes. The shadow is darker in those indicators like climate parameters or SWD which are related to water. The farm details (like drop or spring irrigation) and the type of distribution (like channel or pipe) are presented with dashed lines because they are not always included in the analyses of the WFA. The multi-scale definition of the water metabolism is implicitly included in the diagram of Figure 7.2, as in the last instance the water is coming from the supply of the water cycle. The supply is a process studied with climate models and included among the climatic parameters necessary to assess the *evapotranspiration* (ET) that maintains plants. The ET is taken as the value of the *crop water requirement (*CWR). In most of the literature, the default software employed for the estimation of the ET –and CWR– is Cropwat (Allen et al. 1998; Food and Agriculture Organization of the United Nations 2014c) which is fed by the climatic database Climwat (Food and Agriculture Organization of the United Nations 2014d).

As explained in Figure 5.10, climate and soil models usually refer to those broad scales of analysis that can see Earth and ecosystem patterns slow changes. The statistical surveys and records or the economic models from which production and trade data are obtained, can appreciate changes happening in much shorter time scales. *Geographical information systems* (GIS) can indeed be used for either step of the analysis, as they provide an environment to perform studies rather than a concrete analytical methodology (Aspinall and Serrano-Tovar 2014). However, they are necessarily attached to areas of land (Serrano-Tovar and Giampietro 2014) and are frequently used to double-check harvested surface statistics.

The technical –engineering– dimension of the water is included in the volumetric analyses occasionally, when the details of the farms are taken into account. Naturally these details are only relevant for the accounting of distributed water (usually, blue water in WFA) since the water coming from the soils (green water) does not require any infrastructure. The addition of the details on irrigation and channeling efficiency can deeply affect the results of the analysis. Discussions exist about the over or under estimation of the SWD when these farm details are included or not (Gerbens-Leenes et al. 2009b, 2009a; Maes et al. 2009).

These discussions and very useful as they highlight two parts of the reality of the water needs of the society: direct use and extraction. This differentiation can, for example locate the role of the water losses as the link between extraction and use. When the farm details are omitted (Hoekstra and Hung 2005; Chapagain et al. 2006b; Hoekstra and Chapagain 2008; Mekonnen and Hoekstra 2010; Vanham et al. 2013; Dumont et al. 2013) the SWD is estimated as the CWR, which is the direct use of water needed by the crops in order to grow, independently of it source. When irrigation and channeling types –and also farming practices– are included (Chapagain and Orr 2009; Howell 2001; García Morillo et al. 2014), the SWD is an indicator of water extraction, as it indicates the total water that has to be taken from the water bodies so the CWR can be met. Obviously the results of each type of analysis are not commensurable with the results of the other because they have different semantics.

The WF community has tried to 'solve' these incommensurability issues by promoting the use of one of the methods over the rest (Hoekstra et al. 2011b). However, the homogenization of methods seems in this case counterproductive, as it only hinders the understanding of the complexity of the water-human systems.

The characteristics of the irrigation practices and infrastructures are not only relevant for the distributed water. They might also affect other non-distributed water types like harvested rain, which largely relies on the availability of infrastructure, and on its state. In MuSIASEM, the distinction between *extraction* and *use* contributes a way to 'not solve' the complexity of the water systems, and to interpret how each method can be used for the assessment of the different parts of the water metabolism. The results of each of the methods are located in a different analytical level making the results comparable. For example, it is possible to compare an analysis that does not take into account the specifics of the farm with other that does, if a coefficient of efficiency in irrigation and channeling is added to the discussion.

With the purpose of showing how the specifics of the method and the semantics deeply influence the results of the water exchange analysis, a comparison of the two options described above is presented. On the on hand, the withdrawal was calculated using a SWD defined as the CWR and equivalent to the estimation of direct water use. On the other hand, the specifics of the irrigation type and the supply infrastructure were added to the CWR in order to estimate the SWD as a coefficient of water extraction. Since the purpose of the analysis is to show the differences between including or not technical aspects in the analysis, only the water from irrigation was taken into account. That is, green water –although very relevant for the sector and the region (Dumont et al. 2013)– is not included.

7.2.1 Volumetric estimations

The CRW has been estimated for the years 2004, 2009 and 2013 for a list of 31 crops –a list in Annex II– in each of the eight Andalusian provinces. The ET method used was Cropwat, and the climate data is taken from Climwat (Food and Agriculture Organization of the United Nations 2014c, 2014d). The climatic records were taken from the closest station available and the stations were assigned to each farm using GIS. The Irrigation farms census of the Andalusian Government (version 2002)[18] (Consejería de Agricultura y Pesca 2002) is the source for the location of the farms.

[18] An updated version published in 2011 exists. However the Guadalquivir basin authority did not accept my application for the information, despite it should be of public access.

The census classifies F&V in the six compartments presented in Table 7.2, Table 7.3 and Table 7.4 and data on seed surface was cross-checked with the statistics of the Andalusian Ministry of Agriculture and Fishing (Junta de Andalucía 2014a). Data on international trade was taken from the Spanish Custom Service (AEAT 2014). The study included traded F&V under the codes 07 and 08 of the combined nomenclature, that is, fresh, conserved or frozen. With these flows, 90 per cent of the F&V trade from and to the region has been covered.

The CWR is defined as the irrigation needed by the plant in order to maintain its ET. It was calculated with Cropwat as in Eq. 7.1.

$$CWR_c^p = ET_0^p \; x \; K_c \qquad \text{Eq. 7.1}$$

Where CWR_c^p in m^3/ha is the crop water requirement of crop c in province p; ET_0^p is the potential evapotranspiration in province p; and K_c is the growth coefficient of crop c. The crop yield in ton/ha is calculated as in Eq. 7.2.

$$Y_c^p = \frac{Prod_c^p}{Surf_c^p} \qquad \text{Eq. 7.2}$$

Where Y_c^p is the yield of crop c in province p; $Prod_c^p$ is the production of crop c in province p; and $Surf_c^p$ is the seed surface of crop c in province p. The SWD in m^3/ton was calculated differently for the estimation of the direct use (Eq. 7.3) and for the extraction (Eq. 7.4).

$$SWD\;(DU)_c^p = \frac{CWR_c^p}{Y_c^p} \qquad \text{Eq. 7.3}$$

$$SWD\;(EXT)_c^p = \frac{CWR_c^p}{Y_c^p} \; x \; \frac{1}{R_c} \; x \; \frac{1}{T_c} \qquad \text{Eq. 7.4}$$

Where $SWD\;(DU)_c^p$ is the SWD for the analysis of the direct use (DU) of water; $SWD(EXT)_c^p$ is the SWD for the analysis of the water extraction (EXT); R_c is the efficiency coefficient for the irrigation system of the farming system where crop c is predominant; and T_c is the efficiency coefficient of transfer infrastructure for each crop c. The efficiency coefficients are estimated for each farm system and used as the standard for the associated crops. This is a limitation of the analysis that could be solved by using the new irrigation farms census of 2008, if it was accessible to the general public[19]. However, this proxy is sufficiently strong for the aims of the article. The value of the indicators are covered in Table 7.1.

Table 7.1. Values of the coefficients for irrigation system and infrastructure efficiencies. (Consejería de Agricultura y Pesca 2011)

Indicators	Value	Coefficient
Irrigation system	Flood	0.72
	Sprinkler	0.85
	Drip	0.92
Transfer infrastructure	Pipe- good condition	0.95
	Pipe- normal condition	0.90
	Pipe- bad condition	0.85
	Open- good condition	0.85
	Open - normal condition	0.80
	Open - bad condition	0.75

The direct use (DU) and the extraction (EXT) are estimated as in Eq. 5 and Eq. 6.

$$DU_c^p = SWD\ (DU)_c^p\ x\ Prod_c^p \qquad \text{Eq. 7.5}$$

$$EXT_c^p = SWD(EXT)_c^p\ x\ Prod_c^p \qquad \text{Eq. 7.6}$$

The virtual water flows for imports (VWi) and exports (VWe) can be interpreted as either a direct use or an extraction of water as in Eq. 7 and Eq. 8.

$$VW\ (EXT)_c^{px} = \sum_{r=1}^{5} SWD'^p_c\ x\ Trade\ _c^{p,r,x} \qquad \text{Eq. 7.7}$$

$$VW\ (DU)_c^{px} = \sum_{r=1}^{5} SWD_c^p\ x\ Trade\ _c^{p,r,x} \qquad \text{Eq. 7.8}$$

Where $VW\ (EXT)_c^{px}$ and $VW\ (DU)_c^{px}$ are the virtual water flow x (imports or exports) from the point of view of the extraction and the direct use, respectively; and $Trade\ _c^{p,r,x}$ is the trade flow x (import or export) of crop c, going to/coming from region r and coming from/going to province p. Virtual water imports are defined using the *theoretical VW* approach –described in Chapter 5– as the savings of water. The results have been aggregated for each of the eight provinces and five world regions:

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[19] A census for 1998 exists which was accessible and provided by the Andalusian Government. The update for 2008 was published in 2011 and is divided between the Andalusian internal river basins - which cover about 20% of the territory of the region- and the Guadalquivir basin –which is property of the River Basin Authority (RBA) While the Andalusian government provided its part in 2011, the RBA has deny the access to the information for three years.

North America, Central America, South America, Africa, Asia and Europe.The water footprint was calculated from both points of view as in Eq. 7.9 and Eq. 7.10.

$$WF\ (EXT)_c^p = EXT_c^p + VW\ (EXT)i_c^p - VW\ (EXT)e_c^p \qquad \text{Eq. 7.9}$$

$$WF\ (DU)_c^p = EXT_c^p + VW\ (DU)i_c^p - VW\ (DU)e_c^p \qquad \text{Eq. 7.10}$$

Where $WF\ (EXT)_c^p$ and $WF\ (DU)_c^p$ are the indicator of the water footprint from the point of view of the extraction and the direct use, respectively.

An indicator of *water metabolic density* (WMD) of the VW flows has been added to the set of the WFA indicators. As explained above direct water use and extraction are indicators defined from two non-equivalent narratives and as a result they are not comparable in absolute terms. The WMD is an indicator of flow/fund relation (water throughput/land use) that makes possible the comparison. The WMD is defined from both perspectives –direct use and extraction- for each crop, each province and each world region following Eq. 7.11 an Eq. 7.12.

$$WMD\ (DU)_c^{p,r} = VW\ (DU)_c^{p,r}\ x\ VSurf_c^{p,r} \qquad \text{Eq. 7.11}$$

$$WMD\ (EXT)_c^{p,r} = VW\ (EXT)_c^{p,r}\ x\ VSurf_c^{p,r} \qquad \text{Eq. 7.12}$$

Where $WMD\ (X)_c^{p,r}$ is the water metabolic density of the VW flows in m^3/ha from each of the two perspectives direct use (DU) and extraction (EXT), referring to crop c, going to/coming from region r and coming from/going to province p; $VW\ (EXT)_c^{p,r}$ is the VW flows from each of the perspectives. $VSurf_c^p$ has a twofold interpretation. On the one hand, for the export flows, it is the fraction of the land needed for the production of exported crop c in each province p. On the other hand, for the imported flows, it is the savings of land caused by the imports of F&V. In this way the virtual imports of land are considered as 'theoretical' imports in line with the description of the VWi.

Last the *water metabolic rate* (WMR) in l/h has been estimated with the purpose of contextualizing the water requirements of the F&V sector within the region and to show why it is important to establish clearly if the water flows refer to use or extraction. In MuSIASEM the WMR is defined in relation to the social fund –the human activity- and calculated as in Eq. 7.13.

$$WMR^{f,z} = \frac{DU^{f,z}}{HA^{f,z}}\ . \qquad \text{Eq. 7.13}$$

Where $HA^{f,z}$.is the human activity devoted to a certain social function f at a level of analysis z, and it is estimated as in Eq. 7.14 by multiplying the number of workers –persons for the households- times the yearly activity time. Data on employment and working time has been obtained from the Spanish National Statistic Institute (INE 2014a, 2014b).

$$HA^{f,z} = No.workers^{f,z}\ x\ effective\ working\ time$$ Eq. 7.14

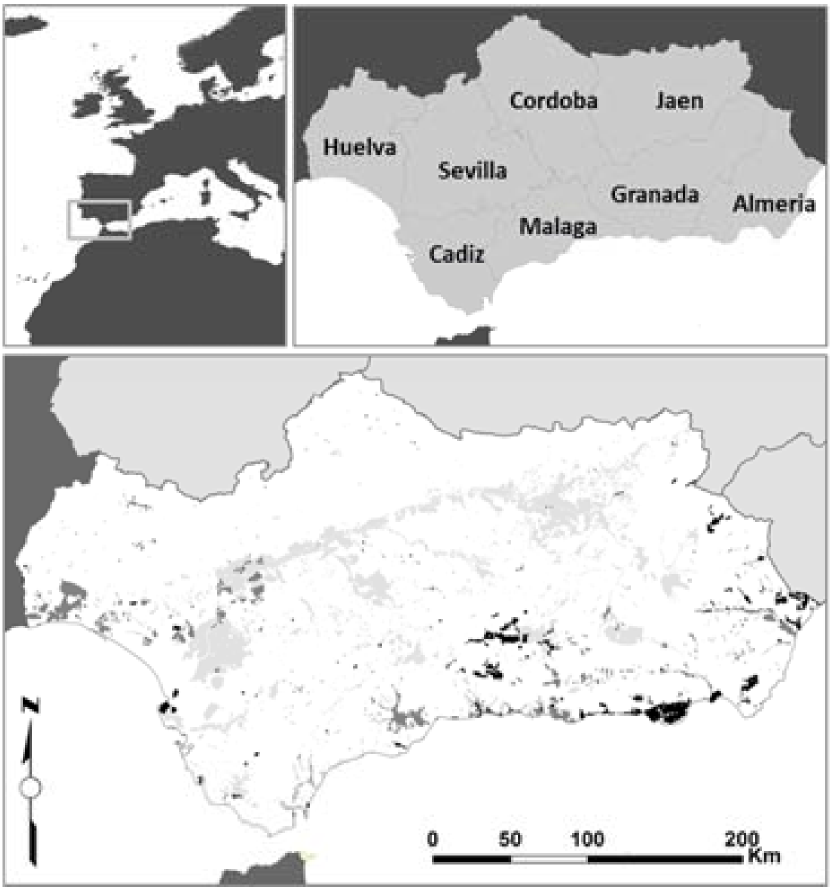
7.3 The irrigation systems in the fruit and vegetable sector in Andalusia

Andalusia is a region located in the south of Spain (Figure 7.3) that represents 17 per cent of its territory. Due to its Mediterranean character, the region's climate has a strong seasonal variability. Average temperatures are relatively warm -in between 10 and 20ºC – and precipitation is relatively low (Junta de Andalucía 2014b). Long periods of drought contrast with torrential rains. Dry summer periods coincide with high temperatures that increase potential evapotranspiration (ET). With its more than 300 sunny days per year and rich sedimentary soils, the region presents extraordinary conditions for agriculture, except for the scarcity of water.

The Andalusian economy relies on tourism activities, which contribute around 20 per cent to the regional GDP (Instituto de Estadística de Andalucía 2014). However, its agriculture sector is a strategic function for the region, for the rest of Spain, and for Europe. In particular, the production of fruits and vegetables (F&V) in Andalusia represents 70 per cent of the green house surface of Spain. In volumes, the region contributes 33 per cent of the vegetable, 25 per cent of the citrus fruit and around 80 per cent of the strawberry production of Spain (Ministerio de Agricultura, Alimentación y Medio Ambiente 2013).

Except for the strawberry –which is located by the side of a national park in the west– the production is concentrated in the in the arid coastal provinces of the east. Figure 7.3 (bottom) shows the location of the irrigation fields in Andalusia. The production of vegetables is concentrated in the south east provinces –Malaga and Almeria- and it is marked in black. The fruit production is shown in dark grey and includes an important production of subtropical crops which is hosted mainly in the coast of Malaga. The light grey color indicates other irrigation fields, which go along the Guadalquivir basin.

Figure 7.3. Location of Andalusia and irrigation systems. Vegetable production is drawn in black; Fruits is filled in dark grey; and the rest is drawn in light grey. Data from Junta de Andalucía (2002).



The modernization of the Andalusian agriculture during the last 40 years together with the access of Spain to the EU markets has resulted in a spectacular increase of the fruit and vegetable cultivated area. About 55 per cent of the Andalusian F&V production has as destination international markets, mostly Europe (AEAT 2014). This increase has been especially relevant in two of its provinces – Almeria and Huelva– which are frequently nicknamed as 'vegetable factories' (Delgado and Aragón 2006). The European and the Spanish investments in the Andalusian rural society is a symptom of the relevance of its agriculture. The new Andalusian Rural Development Plan is supported with 1,800 million Euro of which

1,400 come from European funds and almost 900 will be spent in the improvement of infrastructures, farms and industries (Junta de Andalucía 2014c).

The intensive agricultural activity of the region requires 81 per cent of its water extraction and has severely affected the local water funds. Indeed a high number of the surface and groundwater bodies are classified as endangered under the premises of the WFD (Consejería de Medio Ambiente y Ordenación del Territorio 2013). The water needs of the local population –around 5,200 hm^3/year- exceed the total renewable resources –of about 4,600 hm^3/year (Consejería de Medio Ambiente y Ordenación del Territorio 2013).

Table 7.2. Distribution of the main irrigation technique used by crop type. Data from Consejería de Agricultura y Pesca (2011)

Crop	Irrigated surface (ha)	Flood (%)	Sprinkler (%)	Drip (%)
Strawberries	10,572	0.1	0.0	99.9
Other Fruits	43,717	39.1	0.1	60.8
Citrus fruits	80,880	19.8	0.2	79.9
Subtropical fruit	19,231	22.2	0.0	77.8
Uncovered vegetables	93,820	34.6	23.2	42.2
Green houses	37,025	0.6	0.1	99.3

Water scarcity is a challenge in the complete region, but even a bigger issue for the F&V sector which relies on irrigation for its production. One of the most important issues is the lack of modern irrigation and water supply systems that increases substantially the volume of water that has to be taken from the water bodies. This lack is less frequent in the green house fields of Almeria, where drip irrigation and pipe transfers are a must and water is paid as another production factor. However, in the arid east the problem is not one of efficiency in water use but of the volumes of production. In the locations that grow less profitable crops or where water is not so scarce, practices like flood irrigation are more frequent. Even when the crops are not located homogenously, there is a certain level of specialization that allows identifying six types of farming systems, which are also used in the Census of Irrigation Fields of the regional government. Table 7.2 and Table 7.3 show these differences.

Table 7.3. Location, water source and water price by crop. Data from Consejería de Agricultura y Pesca (2011)

Crop	Main Province	Main Water Source	Max water price (€/m^3)
Strawberries	Huelva	Surface (69%)	0.16 (Surface)
Other Fruits	Mix	Surface (67%)	0.13 (groundwater)
Citrus fruits	Cadiz	Surface (69%)	0.16 (Surface)
Subtropical fruit	Malaga	Surface (72%)	0.21 (groundwater)
Uncovered vegetables	Sevilla	Surface (85%)	0.06 (groundwater)
Green houses	Almeria, Granada	Groundwater (56%)	0.39 (desalination)

Water-transfer systems also have an irregular distribution and condition. For most of the crops the percentage of the surface that receives the water from a pipe is over 80 per cent. However, there are still some farming systems which receive about 40% of their water from a traditional acequia. Note that for the regions where strawberries and citrus fruit are grown the share of 100 per for the use of pipes is not realistic. This is the number given by the Andalusian Ministry of agriculture and Fishing (Consejería de Agricultura y Pesca 2011) for the region where most of this crops are gown. However, the distribution of the crops might not only be reduced to these locations. The numbers are used to give an idea that a high percentage of the surface for strawberry and citrus fruit fruits receives the water from a pipe.

Table 7.4. Percentage of the area by type of supply infrastructure and its condition, good (1), regular (0) and bad (-1). Data from Consejería de Agricultura y Pesca (2011).

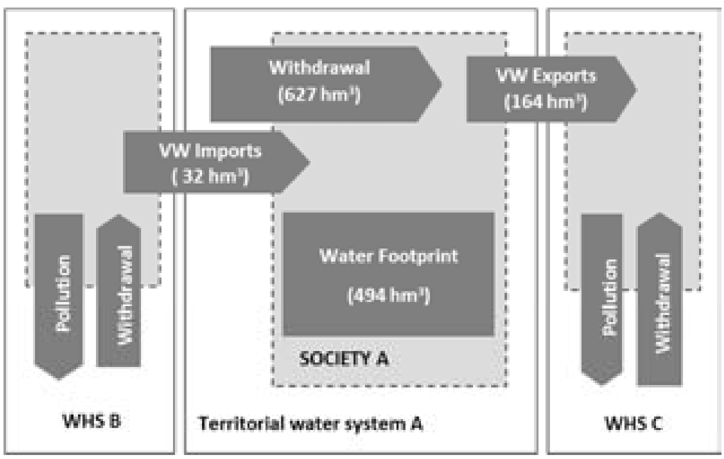
	Pipe (%)				Canal (%)				Acequia (%)			
Crop	**1**	**0**	**-1**	**Area**	**1**	**0**	**-1**	**Area**	**1**	**0**	**-1**	**Area**
Strawberries	91	9	0	100	–	–	–	0	–	–	–	0
Other Fruits	79	20	1	38	44	38	18	23	14	33	53	39
Citrus fruit fruits	91	9	0	100	–	–	–	0	–	–	–	0
Subtropical fruit	79	14	7	63	20	20	60	18	3	4	93	19
Uncovered vegetables	94	5	1	82	47	38	15	14	14	9	77	4
Green houses	90	8	2	84	18	63	19	6	98	1	1	10

7.4 The water exchange in Andalusia

7.4.1 The exchange with a WFA lens

As explained in Chapter 5 the volumetric analysis is very useful to explore the quantitative and geographical dimensions of the water flows. A first look to the water flows of the F&V sector in Andalusia shows that this social function 'manages' a water exchange of about 1,000 hm^3 of water, which supposes 25 per cent of the water demands of the complete region. This water movement is divided between the water taken from the domestic ecosystem and the water which is taken from the ecosystem somewhere else. Figure 7.4 shows an example of the quantification for year 2009. A total of 627 hm^3 were taken from the water bodies of WHS A with the purpose of fulfilling the demands of the F&V social function. From this amount, 164 hm^3 are virtual water imports and satisfy the demands of other societies' needs for food. The physical trade balance is negative for the F&V sector, as the volume of exports is higher than the volume of imports, which also results in the region being a net VW exporter, with VW imports of only 32 hm^3. Indeed, the imports can be considered insignificant in relation to the exports (Figure 7.5).

Figure 7.4. Definition of the water exchange under the perspective of the WFA. Andalusia 2009.



As previously mentioned, the quantitative values of these flows vary depending on the approach used for the analysis. Table 7.5 shows the differences between the values when SWD includes the irrigation and infrastructure parameters (extraction) and when it does not (direct use). The difference is about 30 per cent, as shown in Table 7.6.

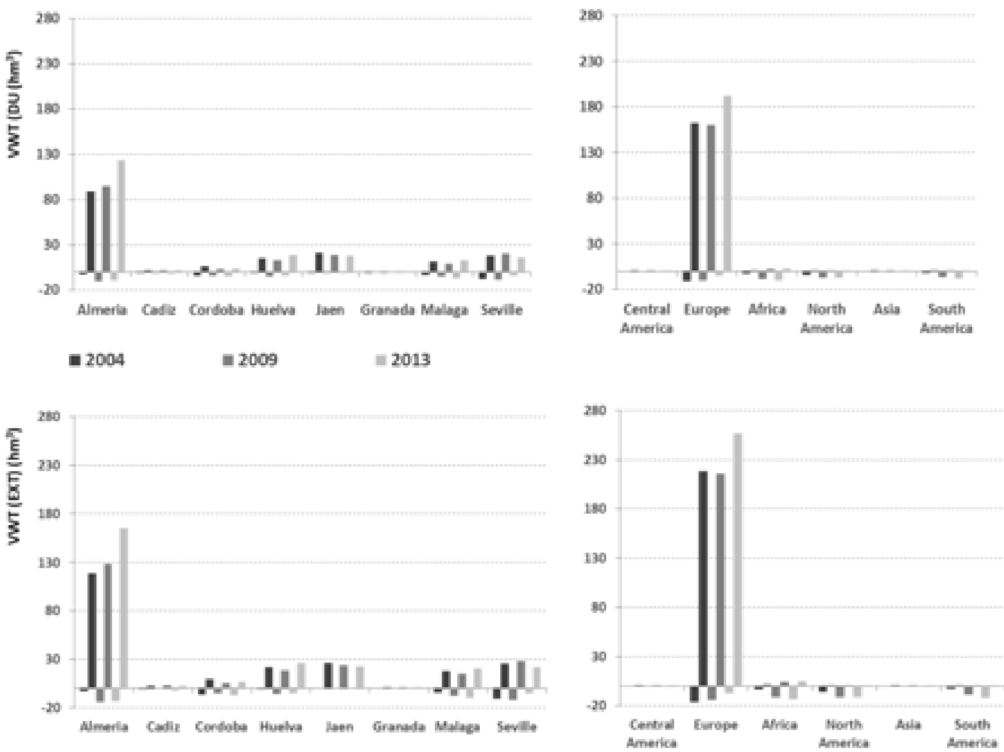
Table 7.5. Difference in the values of the VW exports and imports and their WMD, using extraction and direct use of water.

Hm^3	Extraction			Direct Use		
	2004	**2009**	**2013**	**2004**	**2009**	**2013**
Water Withdrawal	740	838	–	571	**627**	–
VWe	221	221	264	164	**164**	196
VWi	*28*	*47*	*45*	*19*	***32***	*30*
WF	*547*	*664*		*426*	***495***	

The interest of the volumetric method relies in the possibilities for disaggregating geographically the flows involved in the water exchange. In Figure 7.5, the geographical distribution of the VW flows shows a clear concentration of the production for exports in Almeria, which is the driest province in the region (169 mm annual average).

Also there is a clear specialization in the European markets, concretely in Germany, France and United Kingdom, where consumers are willing to pay higher prices, due to higher purchase power and/or more limited options for F&V production. Also, the tendency within the period is to the increase of the water dedicated to the production of exported goods. For year 2004 this is justified by a drier year, in which irrigation needs increased –increasing the CWR of Figure 7.2. In 2009 the stronger increase could be caused by the need of the regional economy of exporting higher volumes as a counterpart for the economic crisis. In any case, the VW imports (in negative values) are insignificant when compared of the volumes of the VW exports.

Figure 7.5. VW flows estimated using a direct use SWD (top) and an extraction SWD (down) per province (left) and region (right). 2004-2013. Exports show in positive and imports in negative values. Data tables can be consulted in Annex II.



7.4.2 *The water exchange in MuSIASEM*

Within the scheme of Figure 7.4 there is no space where a differentiation between the water extraction and the water use flows can be located, because both are equal to the category 'withdrawal'. The only option within the WFA logic is to draw another scheme where the quantities change. However, as explained above, in MuSIASEM terms both approaches show just different dimensions of water.

Figure 7.6. Water direct use, extraction and VW flows framed within MuSIASEM

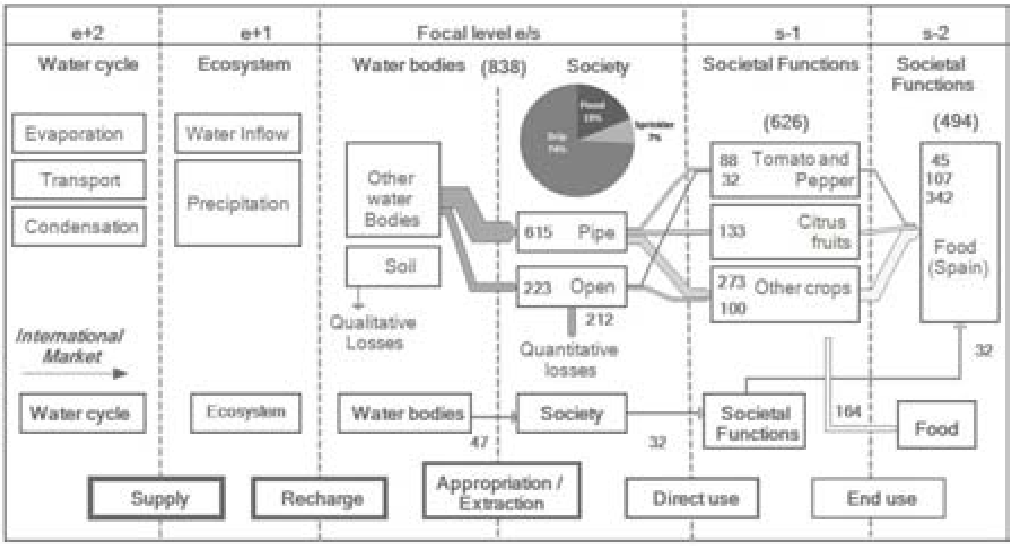


Figure 7.6 shows the results of the volumetric method for year 2009 represented in a MuSIASEM grammar. As usual, left analytical levels show the watershed narrative, which are not used in the study. The Andalusian water system (WHS A) is at the top half while the rest of the world is shown as WHS B and C at the bottom. Since the characteristics of the productive system in the rest of the world are not interesting for this case study, the processes happening within these analytical levels are not shown. Also, WHS B and C are connected to WHS A via international trade, including the shadow analytical levels described in Chapter 4. This connection is only relevant at the level of the societal function because it increases the options for water end use. However as previously mentioned in section 7.2, the water extraction processes and the impacts over the domestic water funds are inflicted by the domestic social systems only.

The differences between both volumetric measurements acquire in MuSIASEM a different perspective in three ways. First, the black box is open in MuSIASEM showing on the one hand lower hierarchy analytical levels and, on the other hand, the compartments –or processes- observable in each of them.

Second, as a result, the extraction can be located within the societal level and the direct use at the level of the societal functions. The difference between them is therefore interpreted as the losses of water caused by inefficient distribution systems or irrigation practices.

Last, this disaggregation can be used to better characterize the system, adding to the geographical location given by the volumetric method, some other information about the system using the water. The detailed estimation of the differences between water use and extraction per irrigation and transfer system and per crop are covered in Annex II. In the grammar, the extraction has been divided between the part of the water that is transferred using closed pipes and open canals and acequias, as their efficiency in the transfer of water is quite different. For the year 2009, from the total extraction of 838 hm^3, 615 hm^3 were transferred using a system of pipes and the rest, 223 hm^3, was transferred to the farms via open canals and acequias.

The direct use is shown in the grammar in two ways. On the one hand, the water is distributed between the social compartments using the water within the F&V sector, per transfer infrastructure. Also, the irrigation practices are shown as percentage of water that is taken to the plants using each of the methods. The graphic shows how most of the irrigation id provided to the plans using drip systems (71 per cent), followed by flood systems (19 per cent). This shows a F&V sector that uses either high technology or very traditional methods for irrigation, with a low percentage of the irrigation provided using sprinklers (7 per cent). The societal functions have been divided between the production of tomato and pepper, citrus fruits and other crops, for different reasons. Tomato and pepper are the most exported products within the region and citrus fruits are the crops with higher CWR. They together amount a total direct use of water of 626 hm^3, indicating that about 212 hm^3 are lost due to the type and the state of transfer and irrigation systems.

The direct use of water is performed by the social functions with the purpose of producing food. This food can go to the Andalusian society (which also includes the Spanish, as the trade data only account for international trade), or can go to international markets, which in turn also provide food to the Andalusian system. The balance between direct use, imported VW and exported VW is the end use of water. The end use of water is the need of water that the society has to maintain its consumption patterns, independently of this water was taken from the domestic water system or from abroad. The end use and the direct use are equivalent to the 'WF of consumption' and the 'WF of production' (Hoekstra et al. 2011b) respectively.

7.4.3 The context of the water exchange

Besides the possibility of relating incommensurable categories used in the water exchange, MuSIASEM provides a framework for the contextualization of the flows, which are limited in the explanation of social and environmental dynamics. Using the relation between flows and funds of MuSIASEM, the water metabolic rate (MWR) and the water metabolic density (WMD) of the water exchange can also be analyzed.

Figure 7.7. WMD using of direct use SWD (top) and extraction SWD (down) per province (left) and region (right). 2004-2013. Exports show in positive and imports in negative values. Data tables can be consulted in Annex II.

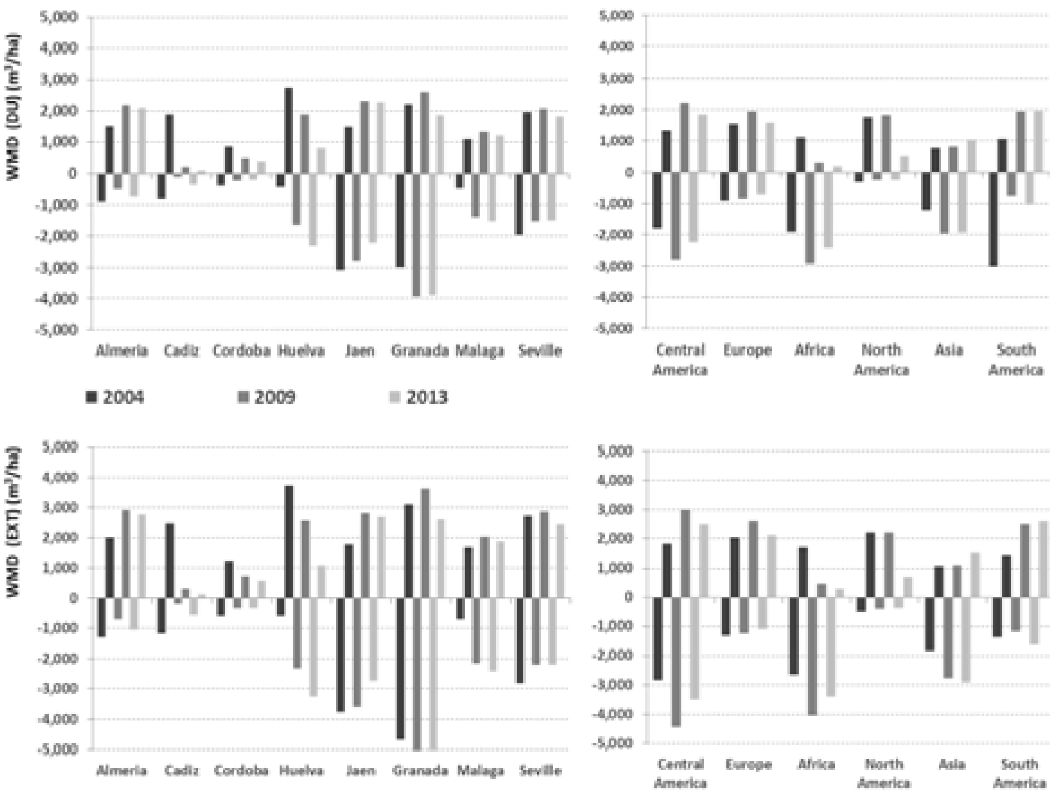


Figure 7.7 shows how the WMD of both extraction and end use is higher in the case of the imports that in the exports, supporting the argument that VW flows can be considered savings of water (Allan 1998a; Allan and Mirumachi 2012). In absolute terms, more VW is associated to exports than to imports, but when compared to the land use, the imports are more costly in terms of water than the exports. In other words, more hectares have been irrigated thanks to the current trade relations. If part of the DU was needed to produce the imported crops, more area devoted to exports

would have to be left unproductive than the area invested in the new production. It is important to remember that the increase of the water endowments for agriculture is difficult in the region, as the current demands already exceed the recharge of the water funds. It is particularly significant that the imports from Africa also have a higher WMD, as main countries providing these imports are also in a situation of water stress.

A closer examination of the differences between imports and exports is presented in Table 7.6, which shows the difference between extraction and direct use as the rate between them. Extraction is around 1.35 times the direct use for exported VW, while for the case of imports is in general higher. If this difference is interpreted as distribution losses, then it can be argued that the state of the irrigation infrastructure is better in the irrigation communities that produce export crops rather than in those which produce the crops that are imported[20]. Indeed, most of the European and Spanish subsidies for the improvement of infrastructure reach the intensive farming systems of the coastal east and west that already use water quite efficiently because of the price they have to pay for it. This works to the detriment of the more extensive irrigation farms on the interior, where the transfer with acequias and flood irrigation are common practices.

Table 7.6. Variation rate between the extraction and direct use approaches.

	Extraction/Direct Use		
	2004	**2009**	**2013**
Water Exchange	1.29	1.34	–
VWe	1.35	1.35	1.34
VWi	*1.46*	*1.47*	*1.49*
WMD e	1.35	1.35	1.34
WMD i	*1.46*	*1.27*	*1.49*

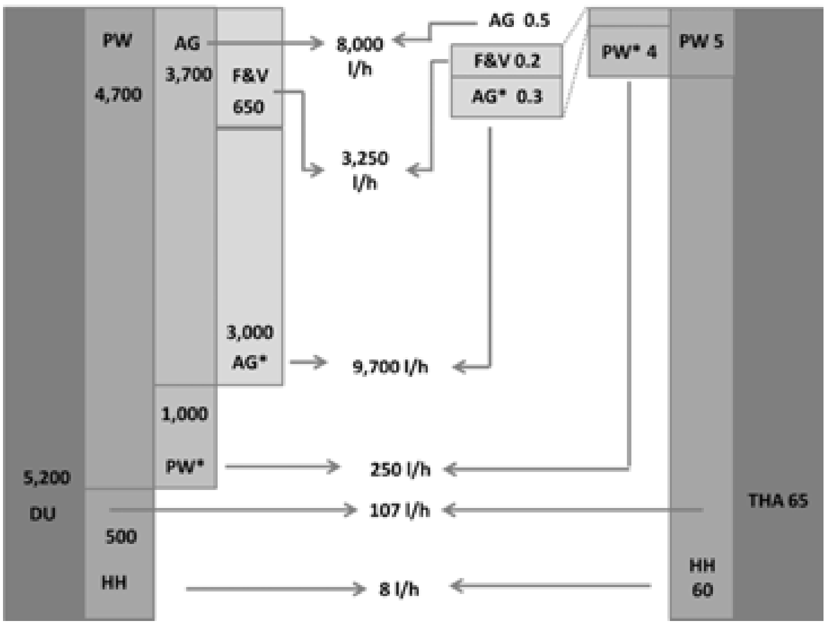
More information can be extracted from the water exchange when the water flows are put in context with the societal funds. Figure 7.8 pictures an overview of the contribution of the water exchange to the regional stability of the society. The functioning of a dendrogram is explained in Figure 4.5. The water exchange (left) is related to the *human activity* (HA) (right). As with the case of other flows, their distribution among the functional compartments of the Andalusian society is

[20] All 31 crops included in the study are produced locally, including those that are also imported.

asymmetric. While most of the direct use of water goes to the paid work (PW) sector (4,700 hm^3), most of the human activity in a society is devoted to the household (HH) components. Within the PW, most of the water goes to agriculture (3,700 hm^3), that has the shortest contribution to HA (0.5 Gigahours).

As described in Chapter 5, the value of the WMR defines the type of metabolic patterns. In this way the contextualization of the water exchange can be used to give information about the characteristics of the funds. The values of the WMR for selected social compartments in Andalusia are shown in the central part of Figure 7.8. The WMR is estimated for each of the selected compartments following Eq. 7.13 using a direct use approach, as this is the relevant data for the analytical level of the social compartments.

Figure 7.8. Contextualization of F&V direct water use (DU) in hm^3 Andalusia (2009) using human activity (HA) in Gigahours for different social compartments. Numbers are rounded. Data from Consejería de Medio Ambiente y Ordenación del Territorio (2013) y INE (2014a, 2014b).



The total direct use of water (DU) and the total human activity (THA) give a metabolic rate of 107 l/h. This means that in order to maintain an hour of the human activity in a society like the Andalusian, 107 liters of water are required for direct use per hour of HA. This number can be considered ‘unreal’ as it comes from the organization of the lower societal levels. For example, the HH activity requires 8 l/h while the agriculture (AG) needs 8,000 l/h. The comparison of WMR can be used to explain some of the characteristics of the F&V sector within the Andalusian society, particularly if the qualitative description of water is included.

The F&V sector has a lower WMR that the agriculture average and also lower than the average of the rest of the agriculture (AG*), indicating a water use compatible with drip irrigation systems and transfer pipes, as presented in section 7.2. Also, since the scheme represents distributed water, the high values of 9,700 l/h of the WMR of AG* show a social compartment highly dependent of centralized infrastructures. Since water analyses are recent in MuSIASEM, a set of benchmarks for the comparison of type of productive system has not yet been developed.

7.5 Using IO to assess direct and end use

In order to transform direct water use into end use without truncation issues a number of connections between societal functions and institutions have to be considered. When the end use is estimated as a balance like in the volumetric method,–as explained in Chapter 5- part of the supply chain is left unexamined. Input-Output (IO) analysis is a macroeconomic accounting system developed by Leontief (1951) and which has gained recognition in WF and VW assessments as a way of avoiding truncation issues (Duarte et al. 2002; Huang et al. 2005; Velázquez 2006; Dietzenbacher and Stage 2006; Dietzenbacher and Velazquez 2007; Guan and Hubacek 2007, 2008; Llop 2008; Zhao et al. 2009, 2010; Blackhurst et al. 2010; Cazcarro et al. 2010; Aviso et al. 2011).

The Environmentally Extended IO (EEIO) has been applied since the 1970’s for the linear analysis of the flows involved in the biophysical exchange between humans and nature, including extraction and pollution (Daly 1968; Leontief 1970; Isard 1972; Leontief and Ford 1972; Victor 1972). EEIO combines economic flows and physical flows (Hoekstra 2010) and is the foundation of the NAMEA framework (National Accounting Matrix with Environmental Accounts), adopted by international organisms as the environmental accounting system (United Nations et al. 2014; United Nations 2012). In its application to water, the combination of monetary and physical flows is used to establish the relation between the water exchange and the variations in production, final demand and productive structure.

The model has received substantial criticism for the strong assumptions that guide the relations between sectors and for its inability of representing the structural components of the system (Giampietro and Mayumi 2009). As Georgescu Roegen (1971) pointed out, EEIO has implicit the idea that a system can be completely described by its flow coordinates. However, when it is taken as a flow accounting method, EEIO has also important advantages. First, as commented above, it is an extended method for which data is created regularly (Kissinger and Rees 2010; Hoekstra 2010). Second, the assumptions are straightforward and can be taken into account in the interpretation of results. Third, it reaches a fairly good level of resolution in the division of sectors. And last, it has already been used to differentiate between the roles played by the producer and the consumer in the creation of a biophysical exchange (Serrano and Dietzenbacher 2010b)

In the following sections, the use of EEIO within the MuSIASEM framework is illustrated. EEIO is used to calculate the difference between direct use and end use and also the WMR in each of the perspectives. The results of direct use are related to the relevant economic sector while the end use is related to the metabolic function it fulfills.

7.5.1 Formulation

Leontief (1951) proposed for each single accounting entity –the equivalent to social compartment- a definition of the total output rooted in the intermediate and final demands following the Eq. 7.15[21] .

$$x_i = \sum_{j=1}^{n} z_j + y_i \qquad \text{Eq. 7.15}$$

Where x_i is the total production of industry i, z_j is the intermediate consumption of each industry j of inputs of i and y_i is its final demand. The complete interindustrial relations are then described by Eq. 7.16

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \qquad \text{Eq. 7.16}$$

where

[21] Matrixes are here indicated with capitals while lower case name vectors, they are both in bold letters. Vectors are defined as columns. A transposed –row- vector is indicated by (‘) and diagonalization is marked by (^).

$$\boldsymbol{A} = \boldsymbol{Z}\,\widehat{\boldsymbol{x}}^{-1} \qquad \text{Eq. 7.17}$$

Here total output, $\boldsymbol{x}$, is the sum of interindustrial consumptions, $\boldsymbol{Z}$, and final demand $\boldsymbol{y}$. $\boldsymbol{A}$ is the matrix formed by the *technical coefficients* a_{ij} which describes the production of industry i needed for a unitary production in j. The solution comes as Eq. 7.18, where $(\boldsymbol{I} - \boldsymbol{A})^{-1} \equiv \boldsymbol{L}$ is the *Leontief inverse* and each l_{ij} describes the production of sector i needed to fulfill a final demand of j equal to one.

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{L}\,\boldsymbol{y} \qquad \text{Eq. 7.18}$$

While matrix $\boldsymbol{A}$ describes the relation between total and intermediate production, matrix $\boldsymbol{L}$ is the key that relates total production and final consumption processes.

7.5.1.1 Transforming Direct to indirect water use

The model of resource use intensities developed by Proops (1988) is the most frequently used to estimate the vector of end water use by sector. If $\boldsymbol{w_b}$ is the vector of Direct Use (DU), the flow/flow rate DU per unit of total production $\boldsymbol{w}^*$ comes from Eq. 7.19.:

$$\boldsymbol{w_b^{*\prime}} = \boldsymbol{w_b^{\prime}}\,\widehat{\boldsymbol{x}}^{-1} \qquad \text{Eq. 7.19}$$

And the assignation of end water use $\boldsymbol{ew}$ is given by Eq. 7.20.

$$\boldsymbol{ew_b^{\prime}} = \boldsymbol{w_b^{*\prime}}\,\boldsymbol{L}\,\widehat{\boldsymbol{y}} \qquad \text{Eq. 7.20}$$

7.5.1.2 The Vector of Human Activity

The human activity measured in hours per year is in this case estimated as the vector $\boldsymbol{ha}$ as in Eq. 7.*21.*

$$\boldsymbol{ha}' = \boldsymbol{l}'\,\widehat{\boldsymbol{d}} \qquad \text{Eq. 7.21}$$

Where $\boldsymbol{l}$ is the vector of labor measured in full-time equivalent jobs per year and $\boldsymbol{d}$ is the yearly effective working time. This vector contains the quantitative values of the activity directly allocated for each of the sectors and necessary to obtain the total production of each of them.

From this, we obtain the vector of direct human activity per unit of total production, defined as in Eq. 7.22:

$$\boldsymbol{ha}^{*\prime} = \boldsymbol{ha}'\,\widehat{\boldsymbol{x}}^{-\mathbf{1}} \qquad \text{Eq. 7.22}$$

It is also interesting for the further estimation of metabolic indicators, to find the total distribution of human activity $\boldsymbol{eha}$, which is the human activity needed to produce one unit of final demand of the sector, related to the end use of water. This measures the direct plus indirect needs of human activity of each sector.

$$\boldsymbol{eha}' = \boldsymbol{ha}^{*\prime}\,\boldsymbol{L}\,\widehat{\boldsymbol{y}} \qquad \text{Eq. 7.23}$$

7.5.1.3 Estimation of the water metabolic rate with IO

As commented in previous sections, metabolic indicators show the relation between the flows crossing a system and the funds which maintained by those flows.

Vector $\boldsymbol{wmr_b}$ contains the WMR of direct use of each sector and is estimated as in Eq. 7.*24*.

$$\boldsymbol{wmr_b}' = \boldsymbol{w_b}'\,\widehat{\boldsymbol{ha}}^{-\mathbf{1}} \qquad \text{Eq. 7.24}$$

Similarly, the end use WMR $\boldsymbol{ewmr_b}$ is estimated as in Eq. 7.25.

$$\boldsymbol{ewmr_b}' = \boldsymbol{iw_b}'\,\widehat{\boldsymbol{\iota ha}}^{-\mathbf{1}} \qquad \text{Eq. 7.25}$$

7.5.1.4 Data sources

Most of the data has been taken from the Spanish National Statistics Institute (INE). The year selected in 2005 because, even when the IO tables are elaborated every five years, the tables for 2010 are not yet published. The symmetric IO table for 73 compartments and data on full-time equivalent jobs come from the national accounts. The data processing for the reduction of the matrixes from 73 to 24 compartments is covered in Annex II. Data on effective working time comes from the Survey of Active Population for all compartments except for the agriculture, which has been taken from the working time survey of the International Labor organization (ILO). The vector of direct water use is taken from the water satellite account.

7.5.2 The differences between direct use and end use among compartments

The results of the analysis are covered in the multi-level matrix of Table 7.7, where the differences between the direct use (DU) of water and the end use (ENU) appear clearly. The first thing that should be noted is that the total amount of water used within the country does not vary. The amount of water that is extracted from the natural funds –at level s- does not vary, and the differences between the end use and the direct use are only matter of what function needs the water. In this case it is assumed that all the products consumed are produced locally, which is unrealistic.

Table 7.7. Multi-level matrix showing Water flows, social funds and rates

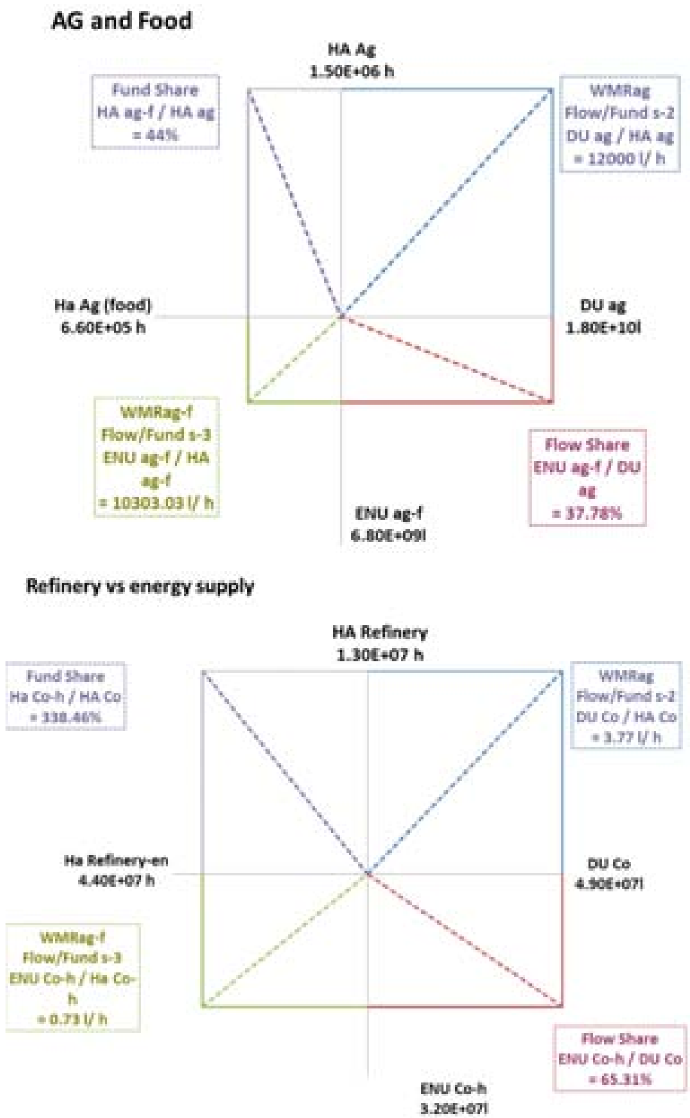
Level	Compartment	DU 10^6 m^3	HA 10^6 h	WMR l/h	ENDU 10^6 m^3	HA	WMR
S	**Spain**	21,997	375,446	59	21,997	375,446	59
S-1	**HH**	2,674	346,775	8	2,674	346,775	8
S-2	**PW**	19,324	28,671	674	19,324	28,671	674
s-3	Agriculture	17,942	1,503	11,939	6,771	664	10,203
s-3	Fishing	0	67	0	9	66	133
s-3	Mining-Energy	3	15	221	0	0	295
s-3	Other Mining	12	46	271	3	11	265
s-3	Food Industry	92	669	138	7,183	1,670	4,302
s-3	Textile Industry	10	341	28	168	350	481
s-3	Leather Industry	5	109	50	98	168	581
s-3	Wood Industry	2	180	13	49	44	1,126
s-3	Paper Industry	15	348	42	85	177	481
s-3	Refinery	49	13	3,622	32	44	719
s-3	Chamical Industy	85	238	359	137	336	408
s-3	Rubber Industry	51	194	265	55	101	544
s-3	Extraction non metal	28	340	83	20	115	173
s-3	Extraction metal	47	753	62	52	361	145
s-3	Machine Industry	9	356	25	40	381	106
s-3	Electronics Industry	9	268	33	47	331	141
s-3	Motor Industry	27	459	60	154	922	167
s-3	Other Manufactures	8	393	19	75	373	202
s-3	Water Supply	32	62	507	21	55	382
s-3	Energy Supply	63	53	1,183	29	65	441
s-3	Construction	48	4,063	12	449	5,058	89
s-3	Water administration	0	1,828	0	175	2,221	79
s-3	Sewage	79	103	765	62	108	574
s-3	Services	707	16,268	43	3,609	15,052	240

However, since the purpose of the exercise is to show how the IO can be used for MuSIASEM analyses, this weakness does not interfere with the purpose of the analysis. In order to have an analysis that can be used for decision-making the direct use should be calculated using the IO matrix for the internal production, while the end use does not need any changes. Surprisingly, Spain is a net importer of VW in the agricultural sector (Garrido et al. 2010), while a net exporter as a whole (Duarte et al. 2013) – an example of the different identities expressed at different levels highlighted in Part I and Part II of the dissertation. As a result an analysis that differentiates between internal and total production will show that the direct use is higher than the end use for Spain as a whole while the agricultural sector expresses the opposite behavior.

Also the water use within the households and the paid work (PW) remains equal for the direct and end uses. This is due to the fact that all water used within the households fulfills a social aspect needed for the maintenance of the society for cooking, drinking etc. However, within the PW, the water is used indirectly to produce another service, as for example food provision. In this way, the direct use of agriculture (about 18,000 hm^3) is the amount that the complete compartment uses, while the end use (about 7,000 hm^3), is the part of that which was required in the production of agricultural products that reached the households and that, in general lines, can be considered food. The same logic applies for all sectors.

When this IO analysis is implemented within MuSIASEM, intensive variables like the WMR can be explored to better understand the way in which the water is used. The high WMR for the direct use of water agriculture (about 12,000 l/h) is caused by the combination of a high direct use and low amount of HA devoted to the agricultural production (0.4 per cent). If compared for example with the WMR of the cereal production in Punjab in Figure 6.10 (9,000 l/h) and knowing that the HA devoted to agriculture is higher in the Indian state than in Spain (7,200 10^6 h), then the WMR of the Spanish agriculture does not seem so water demanding. These numbers are called *benchmarks* in MuSIASEM and are used to establish typologies of metabolic patterns in relation to water, in this case the agriculture seems more dependent of irrigation than the Spanish. However, in order to confirm this view, the cereal production of Spain and not its complete agricultural sector should be used for the analysis.

Figure 7.9. Direct and end uses of water and needs of human activity of food agriculture (top) and energy supply refining (bottom).



A multi-level exploration of the extensive variables of flows –direct and end water use- and funds –direct and indirect human activity- and their relation –WMR- is crucial to understand how the water contributes to the maintenance of societies –what in Figure 2.2 was called relation A. Figure 7.9 shows graphically these relations for the compartments agriculture (top) and refining of fuel energy sources (bottom). Each of the graphs shows in the upper part the total human activity devoted to one function and in the left side the part of that HA that was required for the production that reached the households. Regarding flows, the lower part covers the water needed to produce the good that reached the households while the right side shows the total direct use of the compartment.

In the case of agriculture, the share of funds and flows that is used to provision other households is quite similar, 44 and 38 per cent, and so are the metabolic rates, with a variation of 2,000 l/h. Beside identifying rates these multi-level graphs are used to identify internal constraints. The provision of food in Spain needs about 10,000 liters of water per hour of human activity. This is an internal benchmark denoting the specifics of the Spanish agriculture. However, this is also the water saved when the food is imported, which can explain why the Spanish agriculture –against all odds- is a net water importer.

The case of the refinery has been chosen to illustrate the opposite In this case the end use of water is also lower, but the HA increases threefold. This is possible because in the end use not only the HA directly used by the refinery is included, but also that HA from other sectors needed in order to provide the refinery with the inputs it needs. The fact that the water share decreases while the HA share increases means that the social compartments provisioning the refinery have a lower WMR that the refinery itself.

7.5.2.1 The reclassification of life, citizen and economy water

A last remark is included to show how the categorization of a water flow in MuSIASEM is never fixed. Table 7.8 shows the reclassification of Table 7.7 changing social compartments by social functions. The quantitative amounts of water that are relevant for each function have been estimated taking into account the conversion of categories presented in Annex II.

The table shows a classification of water into economy, life and citizenship that corresponds to the dimensions of water relevant for the end users. For this case study it has been chosen that the economy water belongs completely to the water service direct use, while the life and citizen water are accounted as indirect use. This option has important connotations.

For example, by including the end use of water for the provision of food within the life category, the human right to the access to food is acknowledged. This is the case as well for the dressing and the housing categories. No one would deny that water directly used for food production is in fact maintaining the biological life of the individuals of the society. However in certain societies the access to a save house might not be seen as requisite for the maintenance of the biological life, thus including the water needed for the maintenance of this societal function within the dimension citizen. This is how, as it has been mentioned, the analysis is influenced by the choices of the analysts.

Table 7.8. Direct use of economy water, and end uses per water dimension

Function	Economy (DU)	Life (ENU)	Citizenship (ENU)	Total ENU
Food	18,034	13,963	0	13,963
Dressing	15	266	0	266
Energy	115	0	60	60
Housing	48	449	0	449
Transport	27	0	154	154
Electronics	18	0	87	87
Manufactures	10	0	75	75
Other consumption	946	0	4,011	4,011
Supplies	111	257	0	257
Households	2,674	0	0	2,674
Total	21,997	14,936	4,387	21,997

7.6 Conclusions

In MuSIASEM, when it is not possible to access data for the formalization of the grammars, the quantitative analysis has to be done using estimations. The results of the estimations will highly depend on the methods chosen but also on the analyst's narrative. Regarding the volumetric method and IO, both options are good choices for the accounting of flows, particularly regarding the direct and end use differences, while the metabolic patterns are better described using the relation between flows and funds. That is to say, the water exchange needs further contextualization.

This contextualization is done by referring each method to the analytical level of assessment for which they are relevant. Neither the volumetric estimations nor the IO analyses can be used to assess the viability or the feasibility of the metabolic patterns because they are methods of flow accounting. In the same way that the recharge of the water funds would not be used for the assessment of the amount of water that is available for human purposes[22], the direct water use –and much less the indirect- cannot be used as an indicator of impact. However, their conceptualization using –depending on the purpose- the water metabolic density or the water metabolic rate is a step forward towards an integrated analysis of the water metabolism.

However both methods find their space within the social levels of analysis, namely s to s-i, in which the societal functions are highlighted. The quantifications of the WF prove that the indicator represents an advancement with respect to the typical water withdrawal indicator, however it cannot substitute it in water metabolism analyses because, as seen in both cases, the direct use of water has a different role in the water metabolism than the end use. In order to connect the analytical levels both have to be acknowledged and included in the analysis in their respective places within the grammar.

Each of the two accounting methods has its strengths and weaknesses. The volumetric method has the advantage of allowing a very detailed level of disaggregation. In the case of Andalusia the direct use, VW flows and end uses were calculated with a resolution of provinces, countries and crops. With these detailed resolution, the volumetric method can be combined with GIS techniques. However, it faces the truncation problem described in Chapter 5. This issue is solved using IO analyses which in turn have some issues regarding assumptions about lack f reference, constant technical coefficients and the joint-production dilemma. Also, the data available is highly influenced by the limits of the social spatial-temporal scales and do not present, for example, a monthly resolution useful to assess the seasonal appropriation of water. Even when IO analyses can include the relation between some regions, a geographical reference is for the moment not available.

The differentiation of the end use from the direct use brings new light over the viability assessment. The indirect use of water might seem irrelevant in analytical terms when it is treated as the water needed somewhere else. However, when the end use of water is given a metabolic interpretation as the water needs of the society, its comparison with the direct water use can show clearly when the viability domain is limited to the domestic SES of if other economies have to be taken into account. The

[22] The availability depends on the technical possibilities of the society as much as on the water recharge.

IO analysis performed here had the limitation of using the same matrix data (total of production) for the estimation of both direct and end use, however this ca be solved using interior matrixes for the determination of the direct use and the total matrixes for the determination of the end use.

Once that the integration of methods within MuSIASEM has been tested, it can be argued that the results are promising and that it should be expected that the integration of other methods is as smooth as for the case of the water footprint. Since they both are methods of measurement of social flows, it would be interesting in the future to test the inclusion within the MuSIASEM framework other methods for the estimation of the social and the natural funds. More efforts are needed to bring to MuSIASEM methods that deal with the ecosystem dynamics, as this is the most weakness point at the moment.

EPILOGUE

Conclusions

Connecting the conclusions

The argumentative line of the dissertation began with the presentation of the current water discourse as the asymmetric interaction of different narratives. Currently the water discourse -in Europe and to a certain point at a global extend- follows the paradigm of the reflexive modernity. This paradigm combines the social, economic and environmental concerns of the new water culture, which are hold within the objective of reaching an integrated management of the water resources (IWRM). With a slower pace, water science is also adapting to the integration of concerns and moving from the conventional view of Hydrology to what has been called Socio-eco-Hydrology. However, each of the concerns of the reflexive modernity highlights different dimensions of water such as production factor, human right or ecosystem service. As an instrument for the establishment of the new water culture within decision-making environments, IWRM faces the challenge of finding ways to integrate narratives and SE-Hydrology faces the challenge of finding analytical frameworks that allow it.

The reflexive modernity does not only frame water but also Sustainability Science. A key piece within the field is the concept of the metabolism of societies, a biological analogy that describes the societies as living systems. As such, societies have unavoidable biophysical ties with their context –the surrounding ecosystems- and cannot the examined in isolation from them. This has taken the scientific community to talk about socio-ecosystems (SES) as complex entities formed by the interaction among and between social and ecosystem components. The metabolism analogy comes to the front burner recurrently following important resource crises and has reached such relevance that metabolism-related analyses can be considered a scientific field. The field of Social Metabolism acknowledges the relation between the two components of the SES because of the obvious biophysical exchange that supports it. However, it struggles with the conceptualization of their complex organization that link the exchange with the internal social and ecosystem components. When this complexity is acknowledged, the consideration of a process as a metabolic process is expanded beyond the biophysical exchange to include the biophysical dependence of societies and ecosystems as the societal and the ecosystem metabolism.

The need of water science –as the intellectual organ of the water discourse- for the integration of social, economic and environmental concerns is a strong reason for including water in metabolism studies. Contrary to the expected, water is excluded from this type of analyses. Rooted in the social energetics of the late 19th century, the epistemology of the Social Metabolism is closely related to the irreversible-socially relevant dynamics of fossil fuels. In this scheme here is little option for the framing of resources that follow a cyclic pattern -like water- and which can be at the same time a social requirement, a component of the ecosystems, or a process of the dynamics of the Earth. The understanding of these cyclic resources need the combination of non-equivalent descriptive domains that can understand the processes happening at the shorter social scales, on the one hand, and the longer natural scales, on the other hand. In the case of water, the multiplicity of descriptive domains, results –as previously explained- in a multidimensionality that strikes with the conceptual inertia of Social Metabolism. Instead of the justifications often argued for the neglect of water –lack of matching data or high volumes- this is the true reason why water is avoided in metabolism studies.

The need of including the specificities of the resource under consideration in metabolism is a reason to seek the combination of its knowledge about SES with the knowledge of other fields about the specific resource –the metabolite. This has happened for the case of the metabolism of energy, which is a frequent discussion topic in both Social Metabolism and Energetics. Water science has a history in dealing with the cyclic character of water and its multidimensionality. SE-Hydrology suggests the definition of *coupled water-human systems* –and the *global water system* in the last instance- to frame the movements of the water cycle and to assess how the social dynamics affect them. However, the social and ecological sides of hydrological studies move respectively within the descriptive domains of the problemshed and the watershed. This results in the lack of a background to frame water issues within the complex relations of the SES. If the global water system –or the specific cases of coupled water human systems- are framed within Social Metabolism using not only the exchange, but also the water dependency of the societies, ecosystems and earth, the societal, ecosystem and earth metabolism of water can be connected. That is, the water metabolism of SES is the equivalent of the metabolism of coupled water-human systems.

Once identified that the multidimensionality of water is a key issue in metabolism studies and that the watershed and the problemshed are both important approaches –NAMED– in the framing of the water processes –TAO–, the next issue is the definition of a methodological framework able to embrace these two levels of complexity. MuSIASEM is presented as a suitable analytical tool, able to deal with this complexity without 'solving' it. It has been designed as a methodological framework for the accounting of natural resources in relation to the sustainability of complex systems' metabolic patterns.

Metabolic systems in MuSIASEM are defined as holarchical, open and dissipative systems which express different identities depending on the spatial-temporal scale of observation. With the connection of these identities, MuSIASEM provides the space for the communication between different narrative that so needed is in IWRM. The identities of the systems at a certain levels are explored with the characterization at each of the level of their metabolic patterns, a relation between flow elements and fund elements. *Flow* elements are related to the biophysical exchange of the metabolism and defined as the quantities of elements that are transformed during the time extend of an analytical representation. Fund elements represent the quantitative concretization of the abstract internal organization of systems and, as such, they remain during the representation. MuSIASEM's ability of dealing with the changing and emergent properties of the SES relies of the fact that flows and funds are *semantically open* categories and that the same element can be a flow or a fund depending on the level of the analysis, as in the example of the tractor.

The connection of the levels at which a MuSIASEM analysis is performed requires a set of functioning rules called *grammars*. A grammar establishes the definition of the biophysical requirement at each of the levels and also the limits of the observed system. The adaptation of the MuSIASEM to the assessment of water has required the creation of a grammar for water, which did not yet exist because the frame has mostly used for the assessment of energy and land use. Differently to other grammars, the water grammar needs two scale axes that support the definition of analytical levels. The social processes are defined using the *problemshed* perspective and promote a definition of levels in line with *virtual water theory*. In the problemshed axis water is a *flow element* that links social functions –mostly of production and consumption- not only via international markets, but also within the same society. The water-related ecosystem levels are defined following a *watershed* perspective, using the structure of the water *funds* –like water bodies, water ecosystems or the processes of the water cycle. Following principles of eco-Hydrology, the water funds are defined not as resources but as the structures that provide services to the rest of the ecosystem and social processes.

The result is a multi-level setting in which the upper levels are defined following the dynamics of water funds (water cycle, ecosystem and water bodies) and the lower levels are determined by the societal dynamics (the society, and the societal functions). The upper levels form the external view of the water metabolism while the lower levels forms the internal view that opens the back-box perspective in which only biophysical flows are examined. In between both there is a *focal level* that combines the flow and fund roles of water and where the problemshed and the watershed domains meet. The integration of the two approaches in the water grammar is complemented with the development of a *water taxonomy.* Departing from the definition of water as an *ecosocial asset* and its role as flow or fund, social and ecosystem water services and relevant dimensions are classified according to relevant analytical levels. In this way, the challenge of IWRM of integrating narratives and methods of analysis is met both in conceptual and in analytical terms.

After the conceptual reflection and the definition of the methodological framework, the next question treated is the formalization of the analysis, which is framed within the broader discussions about how to define the sustainability of the metabolic patterns. In MuSIASEM this analysis is done by assessing how the water exchange promoted by the societal metabolism affects the water-related dynamics of the ecosystem metabolism in the *desirability*, the *viability* and the *feasibility* checks. The purpose of creating a bridge between those domains which assess from very local (a crop, a household)- to very global (climate) processes is met in MuSIASEM by framing the analysis and the results within an analitical level. In quantitative terms, the results are organized in *multi-level matrixes* formed by the vectors of extensive and intensive quantifications and qualifications describing the metabolic patterns of a certain societal or ecosystem component, like agriculture or a certain river. The *congruence check* between and among the vectors' elements determines the sustainability of the metabolic patterns.

Since it would be practically impossible to explain in this dissertation the integration within MuSIASEM of all the methods used for the assessment of water metabolism processes, the Water Footprint Assessment (WFA) is taken as example. Rooted in the quantifications of virtual water, the WF is an indicator of the water needed to maintain certain metabolic patterns and as such it indicates the pressure associated to a certain water exchange. The methods of accounting –volumetric and

IO analyses- and the possibility of distinguishing between direct use of water and end use of water are very important within the MuSIASEM framework because the difference between the end use needs and the direct use performed determines the viability of the water metabolism. However, the WF needs further contextualization to explain the drivers and the impacts of the water use, which can be done with MuSIASEM.

The framing of the analyses is done in MuSIASEM in parallel with the adaptation of the grammar. That is why some case studies are presented to illustrate i) how to adapt the grammar to the specifics of a case study, ii) how to use multi-level matrixes for the sustainability checks and iii) how to integrate other methods –WFA in this case- in the MuSIASEM frame. The Mauritius and Punjab case studies form part of a project on the nexus in which the societal levels were determined by the needs of combining water analyses with energy and land use, and food production. For this analysis, different categories of water dimensions and services were used, showing that the water taxonomy serves as guidance and that it does not need to be included completely for each case study. The feasibility assessment in Mauritius shows how the multi-level matrixes can be adapted to the societal and the ecosystem analysis and how the congruence check works to highlight that even if in the island as a whole the water metabolic pattern is feasible, this is not case for all of the basins that form it. The Punjab case study adds an analysis of the viability of the system, showing that the granary of India remains stable due to sources of income alien to the cereal sells. Energy and other subsidies that maintain the system viable pushes the region towards an unfeasible pattern of water use both quantitative and qualitatively. In both cases, the feasibility check is performed in the watershed domain, that is, with the analysis of the state of the water funds and not using volumetric methods of water withdrawal and pollution, which belongs to the problemshed domain.

The analysis of the water exchange in Andalusia and Spain was presented to show how the volumetric and IO accounting methods of the WFA can be inserted in MuSIASEM. In the case of the F&V sector in Andalusia, there is a certain distinction between the way coefficients are estimated in the volumetric method –including infrastructure or not. This difference is seen by the WF community as an issue of lack of homogeneity that hinders the commensurability of the results. However, this differentiation results from the accounting of the water exchange at two different analytical levels in which the relevant water services are extraction and direct use. In the case of Spain, the IO analysis is used to transform direct use of water in end use avoiding the truncation problem. In both cases, once the flows are framed within the relevant analytical levels, its comparison against the social fund human activity illustrates much better the dynamics of the system.

The answers to the research questions

The general objective of developing a language for the accounting and assessment of the water metabolism in line with the concerns of IWRM presented in Chapter 1 has been met in two steps. On the first hand, the conceptual discussion in Chapter 2 and Chapter 3 helped to identify the analytical challenges of the assessment of the water metabolism and sets the 'map' where current narratives can be located. On the other hand, MuSIASEM has been adapted to the water specifics and used as a language for the communication between narratives. The MuSIASEM grammar for water presented in Chapter 4 can bridge non-equivalent descriptive domains and methods, as pictured in Chapter 5. This language -if further developed and implemented- can provide the integration pursued by SE-Hydrology and needed in IWRM, related to the better integration of assessments.

The issues faced by the current water discourse and IWRM

The current water discourse has escaped the simplicity of the hydraulic mission. Fifty years ago the water issues were relatively simple to solve, and reduced to a matter of access to economic resources and technical knowledge. The transition from this old water culture to a new water culture and to the reflexive modernity has not taken these worries out. On the contrary, it has summed social and environmental concerns and a proliferation of water definitions, which expand the description of water from the idea of freshwater resources –which has been avoided in the dissertation- to Federico Aguilera-Klink's *Ecosocial Asset* as presented in Chapter 3.

Managing the ecosocial asset is no easy task for two reasons. On the one hand, it holds the idea that the water is never consumed and that what is consumed is its ability of providing a service. As explained in Chapter 3, even the Millenium Assessment is struggling with the definition of the water services, as these relate not only to the exchange of flows but also to the very complex organization of the SES.

On the other hand, civil society, water scientists and policy makers still have a long way to go in order to reach a mature new water culture, as described by Allan and Aguilera Klink in Table 1.1. This means that the moment in which the integration and coordination of narratives is not seen as a menace of some established thinking is not yet close resulting in the partial integrations of IWRM described in Chapter 1. As an example, the three years that the Guadalquivir Basin Authority is holding the new census of irrigation fields –footnote in Chapter 7- show that there is certain resistance in some decision-makers to some of the principles of the reflexive modernity.

In sum, the issues faced by IWRM are one of complex system analysis and one of coordination of narratives, mostly among scientific fields but also between these and the rest of the actors forming the water discourse. In order to deal with the challenge on orchestrating the different narratives a map of the current development in water and sustainability science has been developed with the scheme of the water metabolism of SES.

How to integrate Hydrology and metabolism studies

The analysis of the epistemological problems of water accounting in Social Metabolism suggests that the neglect of water is more related to the difficult conceptualization of the accounting than to issues of data availability or excessive volumes. As a result, the main step towards the integration of Hydrology and Social Metabolism would be to acknowledge that the cyclic nature of water requires a conceptualization of the process of metabolism different from the current black-box approach. The water services of *supply*, *recharge*, and *availability/appropriation* take place within the ecosystem and the Earth dynamics. As a result, these processes are –in general- much slower than the social *extraction*, *direct use* and *end* use; and cannot be observed within the linear and socially focussed analysis of the flows currently developed within Social Metabolism.

However the epistemology of metabolism is not fixed and can evolve towards the inclusion of complex descriptions of the relations between man and nature, like the one presented in Figures 2.2 and 3.4. In this way, the metabolism defined within the complexity of the socio-ecosystems and formed by a set of nested processes that determine each other. Problems of scale arise in this case, like the different identity of the system observed by the different non-equivalent descriptive domains approaching the SES, which is in part one of the reasons why it is so difficult to combine the different narratives of water. However the adoption of the SES metabolism as a conceptual root has its advantages for the assessment of the water metabolism. In particular, it is similar to the description of the Global Water System developed in water science.

So Hydrology and Social Metabolism epistemologies can be integrated using the conceptual connection between SES and the GWS. In the social domain, -the problemshed- hydrological conceptual tools like the theory of virtual water can be used to define the dimensions of water as a political tool or as an economic resource or a human right. In the water-ecosystem domain –the watershed- eco-Hydrology has developed analyses to understand the role that water has for the ecosystems. Naturally the use of VW theory and the classification of water services for the definition of water as a metabolite within metabolism studies can be questioned. However they seem to match very well the purpose of supporting Social Metabolism in understanding the water resources and. In turn, this junction facilitates the inclusion of some metabolism and complexity principles in the study of the coupled water-human systems a relevant aspect for IWRM.

How MuSIASEM has to be modified to include water

Due to its semantic flexibility MuSIASEM always has to be adapted to the concrete analysis for what talking about a modification is not completely correct. The basics of MuSIASEM are the complex definition of the metabolism, the flow/fund model and the use of dendrogram-grammars and multi-level matrices; which are adapted to the specifics of the metabolites. This means that any adaptation bringing new insights to the formation of grammars of the definition of levels is a further contribution to the improvement of the framework which, if relevant, can be used for the analysis of other biophysical requirements.

For the case of water, there are two main adaptations. First, the water grammar uses two descriptive domains –watershed and problemshed- in separate axes (Figure 4.4). Even if the axes are integrated in a one-axis dendrogram (Figure 4.5), the 'shadow levels' remain part of the analysis providing the ground for the integration of international markets in another line of the grammar (the down part of Figure 4.7). In energy grammars, for example, the external view (left side of Figure 4.3) combines the domestic extraction of primary energy sources from the local ecosystem with the imports coming from another economic system. In the case of water there are two external views, the ecosystem and the external social dynamics, which connect a local social system with an alien ecosystem, like in the case study of the Andalusian F&V sector in Chapter 7.

Second, the taxonomy was modified to include the definition of water as an ecosocial asset that can be a flow, a fund and even a system –that consumes solar energy- at very broad temporal scales. As a result, the water taxonomy not only includes more semantic categories (the services) that the energy grammar but also a flexible relation between the categories and the final labeling of the water according to end uses (the dimensions). For example, the superficial water can be the source of the *extraction* or the destination of the *recharge* services, connecting both levels of analysis –ecosystems and water funds- and improving the options of matching data from different sources without losing coherence. On the other hand, the interpretation of water volumes as elements carrying services is taken from the description of energy carriers[23] in the energy grammars.

An important distinction of the water taxonomy is made between the *end use* and the *direct use*. As explained in the case studies of Andalusia and Spain, this importance is relevant regarding IWRM because distinguishes the responsibility of the production and the consumption processes within society. This differentiation has been done in the grammar of food and land, but not in an organized manner and acknowledging that they belong to different analytical levels.

How to formalize the MuSIASEM framework in its application for water

The process of formalization is the transformation of the semantic categories of water services and dimensions into real variables, measured with numbers. It has three stages. First, the levels and the dimensions of water that will be included in the analysis have to be defined, setting the limits of the analytical system. Second, the sources of data or the methods that will be used for the estimations are chosen. And third, the relevant intensive and extensive variables are defined and estimated.

The delimitation of the analytical levels, compartments and water dimensions is relevant because it is used for the structuring of the multi-level matrixes. As explained in Chapter 6 and Chapter 7, not all the level, compartments and dimensions have to be included in the analysis, which can be tailored depending on the needs of the analyst. Also a certain system can be used as the formalization of a different level of analysis for two different purposes. For example, in the case of Punjab or Andalusia regions within countries are chosen as focal level. India, a country, could also have been chosen as the reference point, but the importance of the analysis was the cereal production within Punjab and how the institutional settings of India influenced these from the outside.

Social compartments are frequently associated with economic sectors in MuSIASEM, with a first partition between paid work and unpaid work, as picture in Figure 4.6. However, this classification is flexible and can be done according to parameters like gender, age, or the rural vs. urban distinction. The case studies proposed here all follow the divisions in economic sectors when the direct use of water is analyzed. However, in the case of Spain, the IO framework is used to

[23] Energy carriers are those flows that take the energy from the transformation sites to the final end users and are classified in thermal (fuels) and mechanical (electricity).

transform this division into a classification of metabolic activities like housing, transport or nutrition. The same applies to the selection of the ecosystem levels, using the water bodies as a connection but with a division in sub-basins that can change during the formalization. For example, in the case of Mauritius, the supply systems were used instead of the river basins, because data was not available and there was not enough time to use a method for their delimitation within the project duration.

Depending on the levels and the compartments chosen, the water dimensions included in the analysis will vary. In the case of Andalusia and Punjab the water for energy production was not included, as it was not relevant for the production of F&V and cereal, which in turn uses much energy for water extraction. When the analysis focusses on the population who has access to a reliable source of water, the dimensions of life and citizen water are essential for the analysis. As explained in Chapter 5, the widely accepted separation of water into blue, grey and green has not been chosen as dimensions in MuSIASEM because they mix attributes belonging to different analytical levels. However this does not mean that once the analysis is done the dimensions of water cannot be grouped into blue and green if it serves the purpose of the analyst.

The design of the multi-level matrixes follows the delimitation of the systems. The compartments chosen form the rows of the multi-level matrixes while the water dimensions and associated services are covered in the columns of the matrixes. The most challenging part is not to structure the matrixes but to fill them. It is advisable is to use direct measurements to fill the matrixes, when possible. However this is normally not the case and estimations are more frequent that direct measurements or statistical sources, which tend to have aggregation levels that do not match the disaggregation needed. The analytical methods are inserted in MuSIASEM within the level of assessment for which they are relevant. The WFA methods used in this dissertation were included within the levels of the societal functions with the aim of showing their utility in the assessing of the flows forming part of the water exchange and how these can be framed. As explained in Chapter 5, the WFA is well developed for the accounting of flows but not for the analysis of impacts, that is, the WFA is not suitable for the assessment of appropriation or recharge of water funds. It is acknowledge by the WF community that the WF indicator needs to the contextualized for the assessment of impacts and its integration within the MuSIASEM framework can also be used to complete the assessment stage of the WFA.

Each of the two accounting methods used in Chapter 7 has its strengths and weaknesses. The volumetric method has the advantage of allowing a very detailed level of disaggregation. In the case of Andalusia the direct use, VW flows and end uses were calculated with a resolution of provinces, countries and crops. With these detailed resolution, the volumetric method can be combined with GIS techniques. However, it faces the truncation problem described in Chapter 5. This issue is solved using IO analyses which have some issues regarding assumptions about constant returns to scale and no joint-production. Also, the data available is highly influenced by the limits of the social spatial-temporal scales and do not present, for example, a monthly resolution useful to assess the seasonal appropriation of water. Even when IO analyses can include the relation between some regions, a geographical reference is for the moment not available.

Both methods are compatible, however, with the estimation of flow/fund relations which -as explained before- as essential for the sustainability check. In this dissertation the water metabolic rate (l/h), the water metabolic density (m^3/ha) and the economic labor productivity (€/h) have been used to determine the viability and the feasibility of the metabolic patterns –in Chapter 6- and the contextualization of the water exchange –in Chapter 7. The metabolic patterns are *viable* if the domestic water exchange can maintain the relation water flow/social fund required to maintain the social organization. The patterns are *feasible* if the relation water flow/ecosystem fund does not inflict any damage in the ecosystem organization. The *desirability* is related to the perception of the stakeholders about the water exchange and the patterns it determines at each of the levels.

Why the water metabolism and its analysis with MuSIASEM contribute to IWRM

IWRM is formed by a mix of scientific, civil and politic narratives. Regarding research, IWRM lacks an analytical framework that can deal with the complexity of coupled water-human systems and the non-equivalent descriptive domains that approach them from natural and social sciences. The water metabolism and MuSIASEM can provide, respectively, the conceptual and methodological ground for the integration of this type of analyses using the connection between the SES and the global water system. As explained in Chapters 3 and 4 respectively, the schemes of the social and water metabolism can be considered a map of this possible options in which current narratives and methods can be identified and classified. Then once every narrative is identified and located, MuSIASEM can establish bridges between them. This will solve the discussion within IWRM about the meaning of the integration and the description of the elements to be integrated.

Neither MuSIASEM nor the water metabolism concept can help with the power asymmetries that favor narratives pushing IWRM away. However, the explicit formalization of MuSIASEM grammars that makes transparent the analyst's choices contributes to promote better informed processes of public participation and the use of MuSIASEM as a governance tool. Indeed, MuSIASEM reaches its full potential as a prospective tool in the identification of current metabolic bottlenecks when different descriptive domains are combined. More concretely, the use of vectors and matrices instead of individual numbers for accounting can make easier to identify trade-offs in the development of transition policies, and to avoid the maintenance of unsustainable practices hidden behind the novelty of IWRM.

Last, the relation between water and other resources is implicit in the idea of IWRM. The metabolic roots of the water metabolism can be used to design analyses that include the physical nexus between water and other flows such as energy, land or food via the social dynamics. In operative terms, the MuSIASEM provides the common link of the fund human activity for the assessment of the nexus.

Reflections and perspectives

The work presented here is a first attempt to connect Hydrology with Social Metabolism and as such it has some limitations. The fact that Water Metabolism tackles challenges of both fields suggests possible interest for future development of the research line in either of them.

As already pointed out in the introduction, the limitations of this dissertation are related to three issues. On the first hand, MuSIASEM has not yet been completely developed for the ecosystem analysis. Since this part is quite important for water, the limitation opens as well an option to continue the research. In this line, the integration of other methods is a key issue, particularly those like the *SWAT* (Soil and Water Assessment Tool) which could help with the characterization of the supply and the recharge of the recharge of the water funds, connecting the ecosystem metabolism with the Earth metabolism.

Second, regarding the focus on water, in conceptual terms, the framework for the classification of the metabolic relations presented in the Figure 2.2 could be expanded for the assessment of other elements. Particularly interesting would be to use the division between society/ecosystem and biophysical exchange/organization to develop a metabolic version of the DPSIR framework. Besides, the framework could be used to perform a thorough bibliographical review of all the metabolism-related works to identify the lacks of the field. Another option is its adaptation to the assessment of other metabolites that present a cyclic behavior and that come from ecosystem funds, like the use of biomass. This line is already opened within the IASTE group as a way to examine the interface of the ecosystem and the societal metabolisms commented above.

Last, the methods used have been too focused to agriculture analysis and the integration of the water footprint accounting. Obviously I have been biased by my close relation to the assessments of virtual water that brought me to consider the option of doing my PhD studies. Since these are the methods I better know, they have been the first integrated within the MuSIASEM for water. However, finding that they fit well within MuSIASEM encourages the view that other could also find their space within the frame. In fact, this integration is the idea for what MuSIASEM has been chosen as framework to describe the metabolism.

In line with the integration of other methods, is the integration between the elements studied with MuSIASEM. The methodological novelties of the application of MuSIASEM to the water analyses could be used to complement the level definition on the food and energy grammars, and to add the differentiation between the direct and the end use of energy, or a better framing of the imports of primary energy sources. In general, the problemshed perspective is not unique for water and can be expanded no assess any other biophysical requirement, including the use of IO assessments. In this last issue, it would be very interesting, for example, to assess the HA involved in the activities that consume the Life and Citizen water in order to distinguish what type of household water metabolism forms the society.

The desirability assessment is also an undeveloped issue in MuSIASEM. The test presented in Annex II shows the potential of the analysis, especially in the use of MuSIASEM as a decision-support tool towards IWRM. The development of the desirability check would contribute a better connection between the metabolic flows and the assessment of conflicts, an area underexplored in the field of Political Ecology. In this way issues like water grabbing, centralization/decentralization of water supply, access to water and sanitation, mining conflicts, etc. could be studied with a metabolic and multi-scale lens.

GIS techniques have been used in the cases presented in this dissertation as a support tool. In Chapter 6 GIS was used to locate the impact over the water funds in the case of Mauritius Island. Also, the irrigation farms were associated to a certain climatic station using this tool in the study of the Andalusian F&V sector in Chapter 7. However, so far no geo-referenced analysis has been developed in MuSIASEM for water nor for any other biophysical requirement apart from land use (Serrano-Tovar and Giampietro 2014). It would be interesting to go further with this research line because the geographical reference is essential to map the ecosystems funds, among them water. The difference between performing a geo-referenced analysis and using GIS to locate parts of the analysis is that in the first case a third axis is included in the determination of the analytical levels.

This line has been tested at the Instituto de Altos Estudios Nacionales in Ecuador in July 2014 with the purpose of producing a geo-referenced system of water accounts for the country. However, due to the relative novelty of GIS as a tool for planning and of the costly software needed to complete this type of analyses, the geographical reference is not very frequently included in the design of the frameworks. Still, in its role as ecological fund, water is attached to the land and the ecosystems it feeds making the use of GDB essential for its accounting.

Part of these options is in my mind already for the medium term. To begin with, I will explore the integration of research-conflicts, water-energy-land, and local water issues-global dynamics using as a case study the fracking activities. Also, I will follow closely the coordination of the characterization of the water metabolism of Ecuador, and the implementation of a geo-referenced system of water accounting in the country. One of the options is to supervise a PhD student who wants to develop this system. Most of My work on IO has not been included here, however, the integration of the flow/fund model of Gerogescu-Roegen within the truncation-free IO settings is an idea to explore. Finally the integration of the social, ecosystem and Earth metabolism of water, land and energy is the topic of a coordination project for horizon 2020 whose application we will probably coordinate from UAB with Mario Giampietro.

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Acronyms

Anexes

Annex I Outline of a desirability check: the case of Ecuador

The desirability of the metabolic patterns in Ecuador

As explained in Chapter 5, the desirability of the water metabolic pattern is defined as its acceptance against the social expectations. It is related to the design of responses of the DPSIR framework as it maps the perception of the stakeholders about the current situation and the feasible and viable scenario options (the option space).

In June 2014 Ecuador's National Agency of Planning and Development (SENPLADES) together with the scientific association Liphe4 developed a project for the biophysical characterization of Ecuador. As part of this project, a pilot study was carried out to assess the options for the inclusion of the desirability check within the evaluation of the water metabolism of the country. The desirability check focused on the access of the public to the services of water supply and sewage.

The check is done using the water-related indicators of Ecuador's Population and Housing Census 2010, developed by the National Statistics Institute (INEC), as shown in Table AI.1. The data is disaggregated by parroquia, the smallest management unit and, to some extent, equivalent to European neighborhoods.

For each indicator, a number of options exist –the conditions-, which are given a value of desirability. This value is multiplied by the number of people who are under each condition and divided by the total population multiplied by the score of the most desirable option, following Eq. AI.1:

$$\boldsymbol{D_i^p} = \frac{\sum(\boldsymbol{\omega^p}_v \cdot \boldsymbol{p^p}_v)\,\mathbf{100}}{\boldsymbol{\omega_{max}} \cdot \boldsymbol{P^p}} \qquad \text{Eq. AI.1}$$

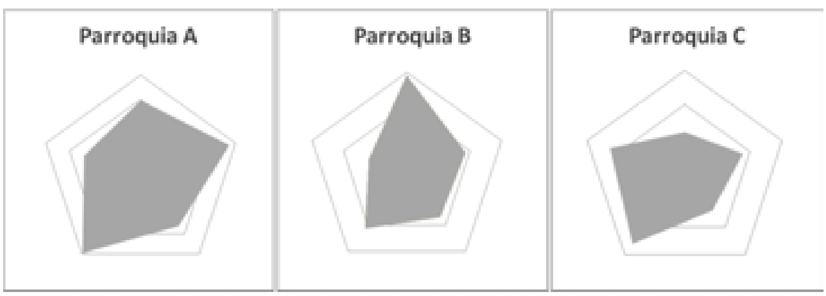
Where $\boldsymbol{D_i^p}$ is the actual desirability for each indicator i and parroquia p; $\boldsymbol{\omega^p}_v$ is the value given to each condition v in each parroquia p; $\boldsymbol{p^p}_v$ is the population that lives under condition v in parroquia p; $\boldsymbol{\omega_{max}}$ is the maximum valuation possible for each indicator and $\boldsymbol{P^p}$ is the total population in the parroquia. The conditions and its values $\boldsymbol{\omega^p}_v$ are covered in Table AI.1. The value of the conditions corresponds to the aims of Ecuador's National Plan for a Good Living (Plan Nacional del Buen Vivir).

The results of the desirability check are not aggregated into a single indicator of desirability. This step could only be done by giving a certain weight to each of the indicators and that will depend on the priorities of the Government of Ecuador or the local communities. Rather, the results within MuSIASEM have the look of the multi-indicator characterization showed in Figure AI.1.

Table AI.1. Indicators of the population and housing census used to assess the desirability.

Indicator	Conditions	Unique Value
Sewage	Connected to the public sewage system	6
	Connected to septic tank	5
	Connected to cesspit	3
	Untreated return to surface water masses	2
	Latrine	4
	None	1
Toilet	Individual use	3
	Shared use	2
	None	1
Shower	Individual use	3
	Shared use	2
	None	1
Origin	Public network	5
	Well	3
	River, or other surface streams	2
	Delivery truck	4
	Other (rainfall collection)	1
Connection	Pipe within house	4
	Pipe within building / house group	3
	Pipe within lot	2
	No pipe	1

Figure AI.1. Desirability of three parroquias characterized with five indicators



The importance of the participative approach

Public participation is a key role of the desirability check, not only in the weighting of indicators, but also in the value of the conditions. The values given in

Table AI.1 are equal for all parroquias but this might not be the case. In order to test the influence of public participation in the valuation of the conditions, a survey was organized about the different perceptions of the conditions. Since the time extend of the project did not allow fieldwork, around 40 colleagues of the SENPLADES where used as stakeholders proxies. The survey asked their views about how each of the indicator's components should be valuated within the eastern part of the country (the Amazon region).

The results of the comparison are shown in Figure AI.2. The left series shows the desirability for each of the indicators when the valuation of the conditions is not participative. From top to bottom the desirability of the connection, sewage, origin, toilet and shower are shown. The right side shows the changes observed in the desirability when the valuation of the conditions changes for each of the parroquias of the Amazon region. White color indicates that the desirability remains more or less equal.

Figure AI.2. Geographical distribution of the desirability components when the values of the options are equal (left) and variation in the Amazon region when a participative approach is used (right). Darker colors (left) and positive values (right) indicate more desirable options.

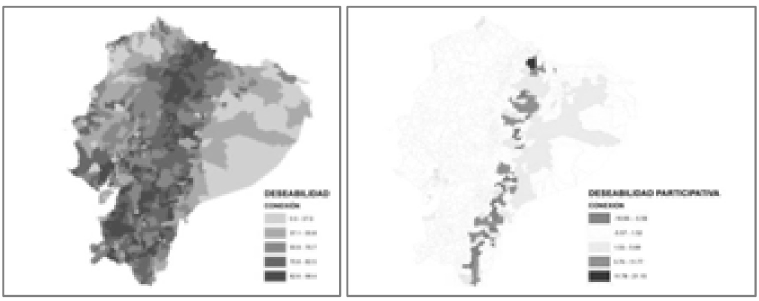
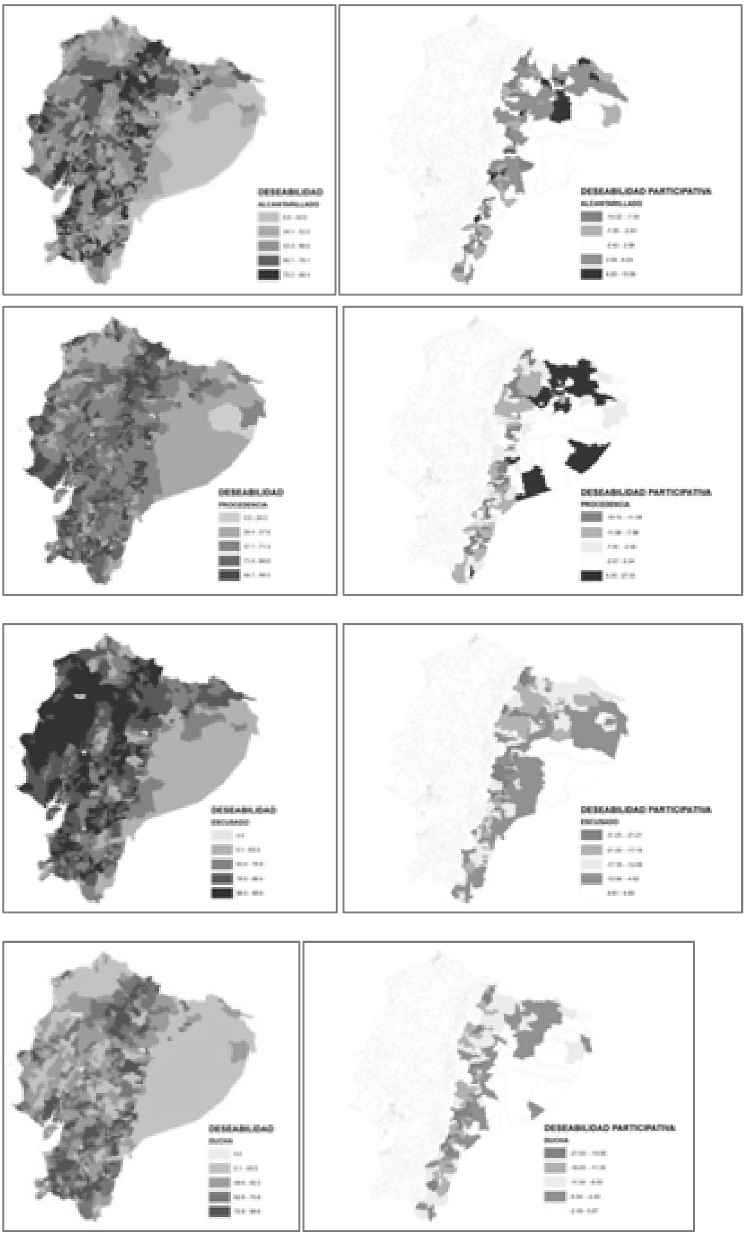


Figure AI.2. (Cont)



Annex II . Estimations of water flows in Andalusia

Crops included in the analysis and estimation of CWR (mm) per province.

	ALMERIA	CADIZ	CORDOBA	GRANADA	HUELVA	JAEN	MALAGA	SEVILLA
Avocado	2250	750	1500	1500	1200	1500	750	1500
Garlic	2881	1586	1773	2038	1824	1544	2167	1867
Apricot	2250	750	1500	1500	1200	1500	750	1500
Artichoke	8950	5912	7795	6654	7090	5707	8004	7371
Almonds	2250	750	1500	1500	1200	1500	750	1500
Egg plant	4890	2297	2303	2883	2808	1930	2609	1445
Zucchini	1943	1002	980	1418	1231	532	1067	525
Onion	5428	4298	5077	4882	4493	4398	1468	4626
Cherry	3000	1500	1500	2000	1200	1500	1800	1500
Plum	1500	750	750	750	1500	750	750	1500
Cabbage	3734	3006	3700	3708	3463	3375	2932	3404
Cauliflower	5399	4400	5908	5738	5797	5679	4560	5612
Asparagus	5317	4065	5711	5599	6152	5281	4682	5664
Strawberry	5288	4482	4860	4392	6000	4230	4824	4330
Peas	3886	2943	3295	3185	2762	2685	2967	2860
Broad beans	1872	1510	1240	1743	1373	1633	1664	1840
Green beans	3886	2943	3295	3185	2762	2685	2967	2860
Lettuce	1068	760	447	480	171	650	536	432
Lemon	3000	1500	2250	1500	1800	2250	2250	2250
Mandarin	3000	1500	1500	2000	1800	1500	1800	1500
Apple	3000	1500	2250	1500	2160	2250	2250	2250
Peach	3000	1500	2250	2250	2160	2250	2250	2250
Melon	3481	2069	2502	2703	2666	2136	2324	2196
Orange	3000	1500	2250	1500	2160	2250	2250	2250
Nectarine	1500	750	750	750	1200	750	750	750
Cucumber	2391	1123	1126	1410	1450	943	1276	706
Pear	3000	1500	2250	1500	2160	2250	2250	2250
Pepper	2897	2168	2117	2432	2132	7028	2287	2138
Water melon	3481	2069	2502	2703	2666	2136	2324	2196
Tomato	4922	3508	5812	3721	3288	2790	3224	3051
Carrot	5373	4254	5536	4939	4850	4552	4361	4684

Water exchange as direct use and extraction per crop, irrigation practice and infrastructure (10^3 m^3).

2004	*Total EXT*	Pipe	Canal	Acequia	*Total DU*	Flood	Sprinkler	Drip
Avocado	*23,467*	14,784	4,224	4,459	*14,802*	3,256	0	11,397
Garlic	*9,126*	7,484	1,278	365	*6,549*	2,227	1,506	2,751
Apricot	*466*	177	107	182	*294*	115	3	178
Artichoke	*30,350*	24,887	4,249	1,214	*21,779*	7,405	5,009	9,147
Almonds	*14,129*	5,369	3,250	5,510	*5,041*	1,971	50	3,065
Egg plant	*14,923*	12,237	2,089	597	*10,709*	3,641	2,463	4,498
Zucchini	*11,448*	9,388	1,603	458	*8,215*	2,793	1,890	3,450
Onion	*25,486*	20,898	3,568	1,019	*18,289*	6,218	4,206	7,681
Cherry	*5,747*	2,184	1,322	2,241	*3,628*	1,419	36	2,206
Plum	*6,137*	2,332	1,412	2,394	*3,930*	1,537	39	2,390
Cabbage	*5,121*	4,199	717	205	*3,675*	1,249	845	1,543
Cauliflower	*12,544*	10,286	1,756	502	*9,002*	3,061	2,070	3,781
Asparagus	*50,002*	41,002	7,000	2,000	*35,881*	12,200	8,253	15,070
Strawberry	*18,936*	18,936	0	0	*16,463*	16	0	16,446
Peas	*3,403*	2,791	476	136	*2,483*	844	571	1,043
Broad beans	*7,587*	6,221	1,062	303	*5,444*	1,851	1,252	2,287
Green beans	*52,319*	42,902	7,325	2,093	*38,546*	13,106	8,866	16,189
Lettuce	*11,016*	9,253	661	1,102	*8,854*	53	9	8,792
Lemon	*5,493*	5,493	0	0	*4,718*	5	0	4,713
Mandarine	*15,425*	15,425	0	0	*13,415*	13	0	13,402
Apple	*1,386*	527	319	541	*888*	347	9	540
Peach	*35,744*	13,583	8,221	13,940	*22,890*	8,950	229	13,917
Melon	*44,075*	16,748	10,137	17,189	*28,224*	11,036	282	17,160
Orange	*74,419*	74,419	0	0	*72,590*	73	0	72,517
Nectarine	*3,365*	2,120	606	639	*2,155*	474	0	1,659
Cucumber	*18,995*	15,956	1,140	1,899	*15,268*	92	15	15,161
Pear	*30,487*	11,585	7,012	11,890	*19,523*	7,633	195	11,870
Avocado	*48,670*	40,883	2,920	4,867	*39,120*	235	39	38,846
Garlic	*37,299*	14,174	8,579	14,547	*23,885*	9,339	239	14,522
Apricot	*94,451*	79,339	5,667	9,445	*75,917*	456	76	75,386
Artichoke	*27,904*	22,881	3,907	1,116	*38,999*	13,260	8,970	16,379
TOTAL	*739,920*	548,461	90,606	100,853	*571,174*	114,873	47,123	407,988

2009	*Total EXT*	Pipe	Canal	Acequia	*Total DU*	Flood	Sprinkler	Drip
Avocado	*24,430*	5,375	0	18,811	*15,409*	3,390	0	11,865
Garlic	*11,385*	3,871	2,619	4,782	*8,170*	2,778	1,879	3,431
Apricot	*797*	311	8	484	*508*	199	5	309
Artichoke	*25,963*	8,827	5,971	10,904	*18,631*	6,335	4,285	7,825
Almonds	*98,056*	38,340	981	59,618	*39,603*	15,485	396	24,079
Egg plant	*19,330*	6,572	4,446	8,118	*13,871*	4,716	3,190	5,826
Zucchini	*13,920*	4,733	3,202	5,846	*9,989*	3,396	2,297	4,195
Onion	*22,511*	7,654	5,177	9,454	*16,154*	5,492	3,715	6,785
Cherry	*4,728*	1,849	47	2,875	*3,022*	1,181	30	1,837
Plum	*12,395*	4,846	124	7,536	*7,937*	3,104	79	4,826
Cabbage	*3,945*	1,341	907	1,657	*2,831*	962	651	1,189
Cauliflower	*12,407*	4,219	2,854	5,211	*8,904*	3,027	2,048	3,740
Asparagus	*57,479*	19,543	13,220	24,141	*41,247*	14,024	9,487	17,324
Strawberry	*17,309*	17	0	17,291	*15,053*	15	0	15,038
Peas	*8,164*	2,776	1,878	3,429	*5,883*	2,000	1,353	2,471
Broad beans	*16,587*	5,639	3,815	6,966	*11,903*	4,047	2,738	4,999
Green beans	*26,565*	9,032	6,110	11,157	*19,063*	6,481	4,384	8,006
Lettuce	*10,997*	66	11	10,920	*8,839*	53	9	8,777
Lemon	*37,491*	37	0	37,453	*32,488*	32	0	32,455
Mandarin	*19,300*	19	0	19,280	*16,784*	17	0	16,767
Apple	*1,465*	573	15	891	*938*	367	9	570
Peach	*15,217*	5,950	152	9,252	*9,745*	3,810	97	5,925
Melon	*41,019*	16,038	410	24,939	*26,267*	10,270	263	15,970
Orange	*82,742*	83	0	82,659	*84,516*	85	0	84,432
Nectarine	*17,312*	3,809	0	13,330	*11,086*	2,439	0	8,536
Cucumber	*20,802*	125	21	20,657	*16,720*	100	17	16,603
Pear	*1,803*	705	18	1,096	*1,155*	451	12	702
Pepper	*46,202*	277	46	45,879	*37,136*	223	37	36,876
Water melon	*42,391*	16,575	424	25,774	*27,146*	10,614	271	16,505
Tomato	*103,425*	621	103	102,701	*83,131*	499	83	82,549
Carrot	*22,777*	7,744	5,239	9,566	*32,691*	11,115	7,519	13,730
TOTAL	***838,912***	**177,567**	**57,798**	**602,681**	***626,819***	**116,708**	**44,856**	**464,143**

Virtual water tables (exports in rows, imports in columns)

VW trade as Direct Use (10^3 m^3)

2004	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	0	88,143	4	605	0	143
Cadiz	0	0	0	0	0	0	0	0	0	1,731	3	0	0	0
Cordoba	0	0	0	0	0	0	0	0	11	5,856	231	93	2	99
Huelva	0	0	0	0	0	0	0	0	0	15,713	27	1	0	11
Jaen	0	0	0	0	0	0	0	0	0	21,314	4	9	15	29
Granada	0	0	0	0	0	0	0	0	0	643	8	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	11,057	400	40	50	0
Seville	0	0	0	0	0	0	0	0	6	17,761	185	34	96	47
Central America	0	30	0	0	0	0	0	4	0	0	0	0	0	0
Europe	219	485	556	359	262	1	2,408	6,900	0	0	0	0	0	0
Africa	1,399	440	15	24	9	0	153	347	0	0	0	0	0	0
North America	586	0	3,128	14	14	0	76	35	0	0	0	0	0	0
Asia	29	5	161	2	0	0	19	13	0	0	0	0	0	0
South America	56	46	390	255	3	0	568	384	0	0	0	0	0	0

2009	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	119	94,195	845	268	124	0
Cadiz	0	0	0	0	0	0	0	0	0	1,184	975	3	0	0
Cordoba	0	0	0	0	0	0	0	0	0	3,225	29	5	9	94
Huelva	0	0	0	0	0	0	0	0	0	13,466	18	1	0	0
Jaen	0	0	0	0	0	0	0	0	3	18,922	24	12	60	22
Granada	0	0	0	0	0	0	0	0	0	354	2	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	8,932	565	1	5	0
Seville	0	0	0	0	0	0	0	0	45	19,653	246	114	85	162
Central America	19	0	0	0	0	0	0	0	0	0	0	0	0	0
Europe	1,328	169	814	216	24	29	1,327	5,867	0	0	0	0	0	0
Africa	3,762	26	129	1,832	13	0	512	2,164	0	0	0	0	0	0
North America	4,463	0	2,358	80	0	0	373	188	0	0	0	0	0	0
Asia	140	0	85	28	0	0	8	28	0	0	0	0	0	0
South America	26	301	295	2,270	16	0	2,887	234	0	0	0	0	0	0

2013	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	94	122,444	635	301	94	0
Cadiz	0	0	0	0	0	0	0	0	2	785	832	0	0	2
Cordoba	0	0	0	0	0	0	0	0	19	3,826	263	57	36	174
Huelva	0	0	0	0	0	0	0	0	0	18,855	116	0	4	0
Jaen	0	0	0	0	0	0	0	0	0	18,173	184	18	108	186
Granada	0	0	0	0	0	0	0	0	0	345	22	0	9	0
Malaga	0	0	0	0	0	0	0	0	4	12,276	867	107	11	0
Seville	0	0	0	0	0	0	0	0	24	15,139	160	149	244	400
Central America	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Europe	1,176	234	784	436	22	11	436	2,110	0	0	0	0	0	0
Africa	5,833	273	34	1,278	59	0	1,035	1,539	0	0	0	0	0	0
North America	2,550	41	3,816	553	0	0	250	94	0	0	0	0	0	0
Asia	18	2	44	9	0	0	13	0	0	0	0	0	0	0
South America	8	1,117	68	1,631	0	0	4,942	79	0	0	0	0	0	0

Water metabolic density with Direct use (m^3/ha)

2004	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	0	1,499	156	2,271	0	2,901
Cadiz	0	0	0	0	0	0	0	0	0	1,899	391	0	0	985
Cordoba	0	0	0	0	0	0	0	0	1,541	854	627	1,302	1,541	1,541
Huelva	0	0	0	0	0	0	0	0	0	2,763	1,639	3,987	0	1,313
Jaen	0	0	0	0	0	0	0	0	0	1,502	3,534	1,241	187	175
Granada	0	0	0	0	0	0	0	0	0	2,225	1,231	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seville	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	0	1,766	0	0	0	0	0	2,344	0	0	0	0	0	0
Europe	561	591	403	4,492	3,029	2,996	394	2,035	0	0	0	0	0	0
Africa	2,484	2,002	360	5,429	2,279	0	723	1,696	0	0	0	0	0	0
North America	413	0	344	10	6,152	0	187	643	0	0	0	0	0	0
Asia	2,881	114	1,381	1,666	0	0	2,243	1,469	0	0	0	0	0	0
South America	331	363	399	3,814	4,317	0	1,770	1,659	0	0	0	0	0	0

2009	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	2,304	2,196	2,412	3,056	590	0
Cadiz	0	0	0	0	0	0	0	0	0	594	124	649	649	0
Cordoba	0	0	0	0	0	0	0	0	0	505	1,025	180	186	1,927
Huelva	0	0	0	0	0	0	0	0	0	1,909	1,587	126	0	0
Jaen	0	0	0	0	0	0	0	0	3,288	2,295	2,779	1,033	1,952	2,933
Granada	0	0	0	0	0	0	0	0	0	2,590	2,402	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	1,321	1,598	293	1,573	0
Seville	0	0	0	0	0	0	0	0	1,922	2,082	1,708	1,494	1,546	1,856
Central America	2,816	0	0	2,070	0	0	0	1,198	0	0	0	0	0	0
Europe	539	228	216	1,220	2,015	3,938	2,211	1,547	0	0	0	0	0	0
Africa	3,399	2,371	5,408	5,676	2,564	0	1,518	1,995	0	0	0	0	0	0
North America	271	0	188	90	0	0	438	457	0	0	0	0	0	0
Asia	2,304	0	1,946	1,355	0	0	1,518	1,672	0	0	0	0	0	0
South America	2,304	83	353	1,774	8,359	0	1,555	1,007	0	0	0	0	0	0

2013	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	2,304	2,112	1,286	968	722	0
Cadiz	0	0	0	0	0	0	0	0	1,137	220	59	0	649	633
Cordoba	0	0	0	0	0	0	0	0	1,927	380	607	177	319	1,906
Huelva	0	0	0	0	0	0	0	0	0	808	1,924	7	2,096	0
Jaen	0	0	0	0	0	0	0	0	2,288	2,283	2,657	1,035	1,764	2,520
Granada	0	0	0	0	0	0	0	0	0	1,959	1,432	0	865	0
Malaga	0	0	0	0	0	0	0	0	293	1,242	1,525	297	659	0
Seville	0	0	0	0	0	0	0	0	2,093	1,842	1,781	1,496	1,564	1,794
Central America	0	3,643	0	0	0	0	2,383	2,174	0	0	0	0	0	0
Europe	598	1,587	248	1,327	2,027	3,897	1,672	1,640	0	0	0	0	0	0
Africa	3,505	412	5,253	5,405	2,326	0	1,788	1,612	0	0	0	0	0	0
North America	271	649	186	759	0	0	1,165	457	0	0	0	0	0	0
Asia	2,316	2,108	1,902	1,799	0	0	1,716	1,672	0	0	0	0	0	0
South America	2,335	298	2,087	4,361	0	0	1,518	869	0	0	0	0	0	0

VW trade as Extraction (10^3 m^3)

2004	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	0	305,790	5	2,971	0	200
Cadiz	0	0	0	0	0	0	0	0	0	4,265	3	0	0	2
Cordoba	0	0	0	0	0	0	0	0	14	11,238	271	117	3	125
Huelva	0	0	0	0	0	0	0	0	0	26,656	31	4	0	15
Jaen	0	0	0	0	0	0	0	0	0	460,362	5	12	21	42
Granada	0	0	0	0	0	0	0	0	0	593	12	0	0	0
Malaga	0	0	0	0	0	0	0	0	1	15,713	525	33	64	0
Seville	0	0	0	0	0	0	0	0	4	19,821	195	35	107	58
Central America	0	119	0	0	0	0	0	9	0	0	0	0	0	0
Europe	493	1,036	694	268	358	0	4,598	13,803	0	0	0	0	0	0
Africa	1,664	362	135	15	346	0	279	1,363	0	0	0	0	0	0
North America	718	0	4,210	3	4	0	95	38	0	0	0	0	0	0
Asia	41	1	161	7	0	0	11	17	0	0	0	0	0	0
South America	69	28	509	97	19	0	752	503	0	0	0	0	0	0

2009	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	166	404,497	2,497	2,159	155	0
Cadiz	0	0	0	0	0	0	0	0	0	2,153	714	5	0	0
Cordoba	0	0	0	0	0	0	0	0	0	11,920	40	11	14	131
Huelva	0	0	0	0	0	0	0	0	0	32,104	30	3	0	0
Jaen	0	0	0	0	0	0	0	0	4	420,221	30	16	147	38
Granada	0	0	0	0	0	0	0	0	0	262	0	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	14,796	803	2	8	0
Seville	0	0	0	0	0	0	0	0	56	27,484	282	185	133	188
Central America	30	0	0	0	0	0	0	0	0	0	0	0	0	0
Europe	3,835	26	1,642	348	316	14	2,810	9,974	0	0	0	0	0	0
Africa	4,825	38	43	1,532	363	0	812	2,892	0	0	0	0	0	0
North America	6,970	0	3,678	20	0	0	587	293	0	0	0	0	0	0
Asia	195	0	113	43	0	0	13	39	0	0	0	0	0	0
South America	36	315	437	1,036	4	0	4,562	329	0	0	0	0	0	0

2013	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	131	514,737	534	2,684	496	0
Cadiz	0	0	0	0	0	0	0	0	3	1,406	376	0	0	8
Cordoba	0	0	0	0	0	0	0	0	26	15,183	376	147	76	245
Huelva	0	0	0	0	0	0	0	0	0	35,532	181	2	7	0
Jaen	0	0	0	0	0	0	0	0	3	477,890	1,209	26	300	106
Granada	0	0	0	0	0	0	0	0	0	345	31	0	15	0
Malaga	0	0	0	0	0	0	0	0	6	20,102	1,366	167	45	0
Seville	0	0	0	0	0	0	0	0	29	23,345	200	234	414	687
Central America	0	0	0	0	0	0	1	5	0	0	0	0	0	0
Europe	2,392	271	1,207	699	395	5	653	2,622	0	0	0	0	0	0
Africa	8,497	373	16	2,145	1,847	0	1,732	2,815	0	0	0	0	0	0
North America	3,982	63	5,959	140	0	0	396	147	0	0	0	0	0	0
Asia	27	4	62	16	0	0	3	1	0	0	0	0	0	0
South America	11	2,853	82	601	0	0	7,847	113	0	0	0	0	0	0

Water metabolic density from extraction (m^3/ha)

2004	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	0	6,407	246	15,057	0	4,043
Cadiz	0	0	0	0	0	0	0	0	0	4,617	506	0	0	5,099
Cordoba	0	0	0	0	0	0	0	0	2,148	1,947	831	1,824	2,148	2,148
Huelva	0	0	0	0	0	0	0	0	0	5,897	2,540	20,032	0	1,829
Jaen	0	0	0	0	0	0	0	0	0	32,552	5,487	1,612	352	337
Granada	0	0	0	0	0	0	0	0	0	2,057	1,715	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Seville	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Central America	0	7,084	0	0	0	0	0	5,623	0	0	0	0	0	0
Europe	1,259	1,262	503	3,360	4,138	1,193	753	4,071	0	0	0	0	0	0
Africa	2,956	1,647	3,210	3,478	84,081	0	1,316	6,658	0	0	0	0	0	0
North America	507	0	463	2	1,829	0	234	709	0	0	0	0	0	0
Asia	4,02	21	1,37	4,48	0	0	1,23	1,89	0	0	0	0	0	0

2004	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
	9		9	2			3	6						
South America	408	222	520	1,452	25,736	0	2,341	2,170	0	0	0	0	0	0

2009	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	3,211	9,428	7,132	24,643	739	0
Cadiz	0	0	0	0	0	0	0	0	0	1,080	91	1,014	1,014	0
Cordoba	0	0	0	0	0	0	0	0	0	1,866	1,445	400	291	2,685
Huelva	0	0	0	0	0	0	0	0	0	4,551	2,624	300	0	0
Jaen	0	0	0	0	0	0	0	0	5,105	50,973	3,484	1,342	4,817	5,046
Granada	0	0	0	0	0	0	0	0	0	1,916	726	0	0	0
Malaga	0	0	0	0	0	0	0	0	0	2,188	2,273	458	2,566	0
Seville	0	0	0	0	0	0	0	0	2,428	2,911	1,956	2,433	2,419	2,147
Central America	4,465	0	0	3,282	0	0	0	1,899	0	0	0	0	0	0
Europe	1,556	35	436	1,964	26,401	1,906	4,683	2,631	0	0	0	0	0	0
Africa	4,360	3,441	1,805	4,746	70,203	0	2,407	2,667	0	0	0	0	0	0
North America	423	0	293	23	0	0	689	714	0	0	0	0	0	0
Asia	3,211	0	2,573	2,124	0	0	2,407	2,327	0	0	0	0	0	0
South America	3,211	87	523	810	2,250	0	2,457	1,415	0	0	0	0	0	0

2013	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
Almeria	0	0	0	0	0	0	0	0	3,211	8,878	1,081	8,633	6,846	0
Cadiz	0	0	0	0	0	0	0	0	1,260	395	27	0	1,014	2,728
Cordoba	0	0	0	0	0	0	0	0	2,685	1,507	869	456	964	2,694
Huelva	0	0	0	0	0	0	0	0	0	1,523	2,987	35	3,35	0

2013	AL	Ca	Co	Hu	Ja	Gr	Ma	Se	CAm	Eu	Af	NAm	As	SAm
													3	
Jaen	0	0	0	0	0	0	0	0	84,082	60,049	17,459	1,464	6,506	1,435
Granada	0	0	0	0	0	0	0	0	0	1,958	1,995	0	3,022	0
Malaga	0	0	0	0	0	0	0	0	458	2,034	2,402	463	3,523	0
Seville	0	0	0	0	0	0	0	0	2,510	2,840	2,225	2,357	2,652	3,084
Central America	0	5,077	0	0	0	0	7,528	5,331	0	0	0	0	0	0
Europe	1,217	1,834	382	2,128	37,128	1,809	2,503	2,038	0	0	0	0	0	0
Africa	5,106	563	2,482	9,075	73,261	0	2,992	2,948	0	0	0	0	0	0
North America	423	1,014	291	192	0	0	1,844	714	0	0	0	0	0	0
Asia	3,558	2,992	2,695	3,240	0	0	350	2,330	0	0	0	0	0	0
South America	3,195	762	2,538	1,606	0	0	2,410	1,246	0	0	0	0	0	0

Example of the disaggregation levels for the flow assessment. VW exports (m^3).

Crop	Compartment	Central America	Europe	Africa	North America	Asia	South America	Total
Avocado	Almeria	-	112,997	-	-	-	-	112,997
	Cadiz	-	499	1,789	-	-	-	2,287
	Cordoba	-	-	39,832	-	-	-	39,832
	Huelva	-	2,016,547	22,089	-	-	-	2,038,636
	Jaen	-	312	-	-	-	-	312
	Granada	-	-	-	-	-	-	-
	Malaga	-	8,490,548	395,469	-	48,205	-	8,934,221
	Sevilla	-	-	146,486	-	-	-	146,486
	Andalusia	-	10,074,323	563,620	-	45,781	-	10,683,724
Garlic	Almeria	-	1,284,988	-	7,255	-	140,784	1,433,028
	Cadiz	-	10,993	-	-	-	-	10,993
	Cordoba	11,152	1,495,430	138,938	87,805	2,466	99,128	1,834,919
	Huelva	-	14,396	5,086	1	-	10,829	30,312
	Jaen	-	6,580		-		-	6,580

Crop	Compartment	Central America	Europe	Africa	North America	Asia	South America	Total
				-		-		
	Granada	-	189,297	7,671	-	-	-	196,968
	Malaga	-	30,167	108	-	-	-	30,276
	Sevilla	-	331,774	-	-	-	-	331,774
	Andalusia	14,564	3,535,819	197,454	118,729	3,221	221,455	4,091,242
Apricot	Almeria	-	283,678	-	-	-	-	283,678
	Cadiz	-	974	-	-	-	-	974
	Cordoba	-	-	-	-	-	-	-
	Huelva	-	-	-	-	-	-	-
	Jaen	-	17,138	-	-	-	-	17,138
	Granada	-	-	-	-	-	-	-
	Malaga	-	1,477	552	-	-	-	2,029
	Sevilla	-	72,113	-	-	-	-	72,113
	Andalusia	-	350,723	377	-	-	-	351,100

Annex III Support material for IO estimations in Spain

Standardization of sectors

Given the different origins of the data standardization is needed for a certain degree of comparability. Each regional IOT has a certain disaggregation of sectors while the water accounts provide information for 24 sectors only. Some assumptions are made for the transformation of the regional IOTs into the 24-sector IOTs that we need. Besides, the INE does not provide regional water data beyond 2001 and the numbers for 2005 have also been estimated.

The disaggregation levels vary for each of the regional IOTs and the industries are included in different groups, according to the resolution. Therefore a process of standardization was necessary for the sake of later comparability. The standardisation process has been done following Eq. A.III.1, mathematically proved by Ara (1959; see also Theil 1957) to be a suitable method for the aggregation of sectors as the total sum of each column's elements remains the same.

$$Z_{24}^{r} = G^{r}\, Z^{r}\ \ G^{r\prime} \qquad \text{Eq. A.III.1}$$

Here G^{r} is the aggregation matrix and Z^{r} is the original matrix of region *r*.

Another issue concerns the sectors, 75.12 and 90.01 (“Administrative services related to water” and “treatments of wastewater”), which were extracted from the larger groups of “public administration” and “waste treatment”. As the contribution of 75.12 and 90.01 to the total of the sectors vary for the Total, Internal and Imported IOT’s, three different aggregation matrixes are necessary for each region. The aggregation matrices for each region can be found in the annex.

The distribution of the sector from the original tables into de 24-sector table follows the CNAE-93 rev 1.

Equivalences between Z^r, Z_{24}^r and the end use functions and water dimensions Spain 2005. Note that the disaggregation of the end uses is marked by Z_{24}^r.

NACE-rev2 Name	Z_{73}	CNAE-93 rev 1	Direct Use		End Use	Life / Citizenship
			Z_{24}	Z_{24} B		
Crop and animal production, hunting and related service activities	1	01	AA		FOOD	Life
Forestry and logging	2	02	AB			
Fishing and aquaculture	3	05	B			
Mining of coal and lignite	4	10	CA		ENERGY	Citizenship
Extraction of crude petroleum and natural gas, Uranium and Thorium	5	11-12				
Mining of metal ores	6	13	CB		CONSUMPTION	Citizenship
Mining of non-metal ores	7	14				
Manufacture of coke and refined petroleum products	8	23	DF		ENERGY	Citizenship
Electric power generation, transmission and distribution	9	401	E		ENERGY	Citizenship
Manufacture of gas; distribution of gaseous fuels through mains	10	402-403				
Water collection, Cleaning and distribution	11	41	41		WATER	Citizenship
Processing and preserving of meat and production of meat products	12	151	DA		FOOD	Life
Manufacture of dairy products	13	155				
Other food manufactures	14	152-154,156-158				
Manufacture of beverages	15	159				
Manufacture of tobacco products	16	16			CONSUMPTION	Citizenship
Manufacture of textiles	17	17	DB		DRESSING	Life
Manufacture of wearing apparel and articles of fur	18	18				
Manufacture of leather and Footwear	19	19	DC			
Manufacture of wood and of products of wood and cork	20	20	DD		MANUFACTURE	Citizenship
Manufacture of paper and paper products	21	21	DE			
Printing and reproduction of recorded media	22	22				
Manufacture of chemicals and chemical products	23	24	DG			
Manufacture of rubber and plastic products	24	25	DH			

NACE-rev2 Name	Z_{73}	CNAE-93 rev 1	Direct Use		End Use	Life / Citizenship
			Z_{24}	Z_{24} B		
Manufacture of cement, lime and plaster	25	265	DI			
Manufacture of glass and glass products	26	261				
Manufacture of refractory products	27	262-264				
Manufacture of other non-metallic mineral products	28	266-268				
Manufacture of basic metals	29	27	DJ			
Manufacture of fabricated metal products	30	28				
Manufacture of machinery and mechanical equipment	31	29	DK		PC	Citizenship
Manufacture of computers and office material	32	30	DL			
Manufacture of electrical equipment	33	31				
Manufacture of electronic products	34	32				
Manufacture of therapeutic and precision equipment	35	33			HEALTH	Citizenship
Manufacture of motor vehicles, trailers and semi-trailers	36	34	DM		TRANSPORT	Citizenship
Manufacture of other transport equipment	37	35				
Manufacture of furniture and other manufacturing	38	36	DN		HOUSING	Life
Recycling	39	37			CONSUMPTION	Citizenship
Construction	40	45	F		HOUSING	Life
Repair of motor vehicles and motorcycles and Retail sale of automotive fuel	41	50	R		TRANSPORT	Citizenship
Wholesale trade and intermediaries	42	51			CONSUMPTION	Citizenship
Retail sale; Repair of personal and household goods	43	52			HOUSING	Life
Accommodation	44	55.1-55.2			LEISURE	Citizenship
Food and beverage service activities	45	55.3-55.5				
Rail transport	46	601			TRANSPORT	Citizenship
Land transport and transport via pipelines	47	602-603				
Water transport	48	61				
Air transport	49	62				
Support activities for transportation	50	63.1-63.2 , 63.4				

NACE-rev2 Name	Z_{73}	CNAE-93 rev 1	Direct Use		End Use	Life / Citizenship
			Z_{24}	Z_{24} B		
Travel agency, tour operator and other reservation service and related activities	51	63.3			LEISURE	Citizenship
Postal and courier activities	52	64			SERVICES	Citizenship
Financial services	53	65			FINANCE	Citizenship
Insurance and pension funding	54	66				
Activities auxiliary to financial services	55	67				
Real estate activities	56	70			HOUSING	Life
Rental and leasing of personal and household goods	57	71				
Computer programming, consultancy and related activities	58	72			SERVICES	Citizenship
Scientific research and development	59	73			SCIENCE	Citizenship
Other entrepreneurial Activities	60	74			SERVICES	Citizenship
Education (market)	61	80(p)			EDUCATION	Citizenship
Human health and social services activities (Market)	62	85(p)			HEALTH	Citizenship
Waste collection, treatment and disposal activities (Market)	63	90(p)		90.01	SERVICES	Citizenship
Activities of membership organizations (Market)	64	91(p)			LEISURE	Citizenship
Sports activities and amusement and recreation activities (Market)	65	92(p)			SERVICES	Citizenship
Personal service activities	66	93			LEISURE	Citizenship
Public administration and defense	67	75		75.12	GOVERNMENT	Citizenship
Education (non-market)	68	80(p)			EDUCATION	Citizenship
Human health and social services activities (Non-Market)	69	85(p)			HEALTH	Citizenship
Waste collection, treatment and disposal activities (Non-Market)	70	90(p)		90.01	SERVICES	Citizenship
Activities of membership organizations (Non-Market)	71	91(p)			LEISURE	Citizenship
Amusement and recreation activities (Non-Market)	72	92(p)			SERVICES	Citizenship
Activities of households as employers of domestic personnel	73	95			HOUSING	Citizenship

Annex IV Library of formalizations

Formalizations of water dimensions

Water as a system (watershed)

Origin of the supply (top-down)

Ecosocial asset→System→Water cycle function→Supply→Precipitation

Ecosocial asset→System→Water cycle function→Supply→External inflow

Water as a fund (watershed)

Destination of the Supply (bottom-up)

Ecosocial asset→Fund→ Ecosystem function →Supply→Precipitation

Ecosocial asset→Fund→ Ecosystem function →Supply→External inflow

(Note that the dimensions of supply origin and destinations because the water cycle is the primary source of water)

Origin of the recharge (top-down)

Ecosocial asset→Fund→Ecosystem function→Recharge→Precipitation

Ecosocial asset→Fund→Ecosystem function→Recharge→ External inflow

Destination of the recharge (bottom-up)

Ecosocial asset→Fund→Water bodies→Recharge→ Surface

Ecosocial asset→Fund→Water bodies→Recharge→ Groundwater

Ecosocial asset→Fund→Water bodies→Recharge→ Soil

Origin of the appropriation (e) / extraction (s) (top-down)

Ecosocial asset→Fund→Water bodies→ Appropriation/extraction → Surface

Ecosocial asset→Fund→Water bodies→ Appropriation/extraction → Groundwater

Ecosocial asset→Fund→Water bodies→ Appropriation/extraction → Soil

Water as a flow (problemshed)

Destination of the extraction (s) (bottom-up)

Ecosocial asset→Flow→Society→ Extraction → Distributed

Ecosocial asset→Flow→Society→ Extraction →Non-distributed

Origin of the Direct use (top-down)

Ecosocial asset→Flow→Society→ Direct use → Distributed

Ecosocial asset→Flow→Society→ Direct use →Non-distributed

Destination of the Direct use (I) (bottom-up)

Ecosocial asset→Flow→Societal Function→ Direct use → Agriculture and fishing

Ecosocial asset→Flow→ Societal Function → Direct use →Manufacturing

Ecosocial asset→Flow→ Societal Function → Direct use →Services and Government

Destination of the Direct use (II) (bottom-up)

Ecosocial asset→Flow→Societal Function→ Direct use → Life

Ecosocial asset→Flow→ Societal Function → Direct use → Citizenship

Ecosocial asset→Flow→ Societal Function → Direct use → Economy

Origin of the end use (top-down)

Ecosocial asset→Flow→Societal Function→ End use → Agriculture and fishing

Ecosocial asset→Flow→ Societal Function → End use →Manufacturing

Ecosocial asset→Flow→ Societal Function → End use →Services and Government

Destination of the end use (bottom-up)

Ecosocial asset→Flow→Societal Function→ End use → Life

Ecosocial asset→Flow→ Societal Function → End use →Citizenship

Ecosocial asset→Flow→ Societal Function → End use →Economy

Annex V Curriculum Vitae (10/2014)

Academic Education

Institute of Environmental Science and Technology (ICTA) Autonomous University of Barcelona, Spain.

PhD Ecological Economics and Environmental Management. Viva November 2014.

Thesis: *The water metabolism of socio-ecosystems: Epistemology, methods and applications.*

MSc (DEA) Economic History and Economic Institutions. 2007.

Thesis: *Moisturizing Socioeconomic Metabolism: Virtual Water Flows and the Water Metabolism. (In Spanish).*

Institute of Education Sciences. Autonomous University of Barcelona, Spain.

Postgraduate Studies. Pedagogy for natural science teaching. 2007.

Department of Applied Economics. Autonomous University of Barcelona, Spain.

Postgraduate Diploma. International Comparative Rural Policy Studies. 2007.

Universidad Pablo de Olavide. Seville, Spain.

BSc + MSc (5-year "Licenciatura"). Environmental Sciences. 2004.

Thesis: *Virtual Water: A new concept for old issues. Application of the concept of Virtual Water to the Andalusian exports of tomato. (In Spanish).*

Complementary education

European Society for Ecological Economics. (ESEE). *Marie Curie Summer School series in Emerging Theories and Methods in Sustainability Research.*

Event IV. Integrated analysis of complex, adaptive systems. Brighton, UK. 2009.

Event III. Methods and tools for environmental appraisal and policy formulation themes. Lisbon, Portugal. 2008.

Event II. Institutional analysis of sustainability problems. Vysoké Tatry, Slovakia. 2007.

International Institute for Geo- Information Science and Earth Observation. Enschede, The Netherlands.

Participatory GIS, mapping and visualization in local-level spatial planning. 2006.

University of Almeria, University of Texas.

GIS for water resources. 2005.

Liphe 4 Scientific Society.

Procedures and toolkits for integrated and participatory analyses of sustainability. Murcia, Spain. 2005.

Academic Appointments

Senior Researcher. Liphe4 Scientific Society. 2013.

FPU Doctoral Research Associate. Department of Applied Economics. Autonomous University of Barcelona. 2007-2011.

Associate Researcher. Institute of Environmental Science and Technology (ICTA). Autonomous University of Barcelona. 2005- 2007.

Visiting stays

Instituto de Altos Estudios Nacionales. Quito. Ecuador. With Jesús Ramos Martín. Jun-Jul 2014

King's College London. With Professor Tony Allan. Sept-Dec 2009.

University of Twente. The Netherlands. With Professor Arjen Hoekstra. Oct 2007-May 2008.

Research projects

IANEX: Integrated Assessment of the water-energy Nexus: the water metabolism of hydraulic fracturing. Marie Curie International Outgoing Fellowship. 2014-2017.

Desarrollo de metodologías para el estudio biofísico en política prospectiva. SENPLADES. Gobierno de Ecuador. 2014.

The Water-Human activity-Food-Land-Energy Nexus. Coordinated by FAO, funded by the German Cooperation Department (GIZ). Water Assessment and Punjab Case study Coordinator. 2012-2013.

Citrus-ProPlanet. Coordinated by Global 2000, funded by REWE supermarket. Participatory workshop coordinator. 2013-2014.

EU COST action Euro-Agriwat (ES1106). Invited expert in Group 3 (Water use Sustainability). 2012-2016.

Fortalecimiento académico-investigativo del Grupo de Desarrollo Institucional y Gestión Comunitaria en Recursos Hídricos y Ambiente, del Instituto Cinara de la Universidad del Valle, Colombia. (Funded by the Spanish Cooperation Agency, AECI). 2012.

S*haring Water and Environmental Values: Peace Construction efforts in Cyprus* (Funded by the Catalan Peace Institute). 2011-2012.

Economic Uses of Water in Catalonia. (Funded by the Catalan statistic Institute). 2010-2011.

CREPE: Cooperative Research on Environmental Problems in Europe. (EU FP7 Funded: SiS-CT-2008-217647). 2008-2010.

Emission Satellite Accounting in Catalonia. (Funded by the Catalan Statistical Service). 2007.

MATISSE: methods and tools for integrated sustainability assessment (EU FP6 Funded: 004059 GOCE). 2005-2006.

Environmental Costs of Water use in Menorca, Balearic Islands (Part of AQUAMED: Les eaux de la Méditerranée. EU INTERREG BIII funded). 2005-2006.

LIFE water agenda (Funded by the EU, LIFE04/ENV/GR/000099). 2005.

HarmoniCOP: Harmonizing collaborative planning (EU FP5 Funded: EESD-ENV-2000-02-57). 2005.

Publications

Peer Reviewed Articles

Madrid-Lopez C & Giampietro M (in press). The water metabolism of socio-ecological systems: Reflections and a conceptual framework. *Journal of Industrial Ecology.*

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

Madrid C, Cabello V, Giampietro M (2013). *Water-use Sustainability in Socio-Ecological Systems: a Multi-scale Integrated Approach*. *Bioscience*. 63(1):14-24.

Velázquez E, **Madrid C** and Beltrán MJ (2011). *Rethinking the Concepts of Virtual Water and Water Footprint in Relation to the Production-Consumption Binomial and the Water-Energy Nexus. Water resources Management*, 25: 2. 743-761.

Madrid C and Velázquez E (2008). *El metabolismo hídrico y los flujos de agua virtual. Una aplicación al sector hortofrutícola de Andalusia (España).* (The water metabolism and the virtual water flows: an application to the fruit and vegetable sector in Andalusia, Spain). *Revibec* Vol. 8: 29-47.

Tabara JD, Roca E, **Madrid C**, Valkering P, Wallman P & Weaver P (2008) *Participatory Integrated Sustainability Assessment of Water Systems. Lessons from the Ebro River Basin. International Journal on Innovation and Sustainable Development* 3:1. 48-69.

Submitted or in preparation

Navarro F & **Madrid-Lopez C**. Water Debt and Scarcity: A Multiregional Input Output analysis of water use in Andalusia.

(with A Scheidel) Global Trade and water grabbing: the Italian olive oil.

Water metabolism and the economic activity. An application to the Andalusian agrarian case.

(with V Alcántara) Multiregional Physical Backward and Forward Linkages of water use in Spain.

Book chapters

In: Giampietro M, Aspinall R, Ramos Martín J and Bukkens S (ed) (2014). *Resource Accounting in Sustainability Assessments: Exploring the nexus between land, water, food, energy, wealth and population.* Routledge.

Madrid-Lopez C & Giampietro M (2014). The water grammar. Chapter 9.

Madrid-Lopez C, Cadillo Benalcazar J, Diaz Maurin F, Kovacic Z, Serrano Tovar T, Giampietro M, Aspinall R, Ramos-Martin J, (2014). Punjab State: India's Grain Basket. Chapter 13.

Serrano Tovar T, Cadillo Benalcazar J, Diaz Maurin F, Kovacic Z, **Madrid-Lopez C**, Giampietro M, Aspinall R, Ramos-Martin J (2014). Mauritius: The Idyllic Sugarcane Island. Chapter 12.

Diaz Maurin F, Cadillo Benalcazar J, Kovacic Z, **Madrid-Lopez C**, Serrano Tovar T, Giampietro M, Aspinall R, Ramos-Martin J (2014). South Africa's Emerging Economy. Chapter 14.

Santos A, **Madrid C**, Barbas Baptista G & Kök I (2007) Cross-level institutional dynamics and ecological conflicts: a history of the eucalyptus expansion in Portugal. In Kluvánková-Oravská et al, eds. *Institutional analysis of sustainability problems: emerging theories and methods in sustainability research*. Prague: Nakladatelství a vydavatelství litomyšlského semináře.

Other relevant publications

Navarro F & **Madrid C** (2012). *Análisis de los balances de agua virtual entre Andalusia y el Resto de España mediante un análisis MRIO.* (Analysis of the Spanish-Andalusian virtual water balance using Multi Regional Input Output). Departamento de Economía Aplicada. Working paper series 3/12.

Madrid C and Cabello V (2011). *Re-opening the black box in Societal Metabolism: the application of MuSIASEM to water.* Working Papers on Environmental Sciences.

Tabara JD, Roca E & **Madrid C** (2006) *Developing new methods and tools for the Integrated Sustainability Assessment of water. The MATISSE project and the Ebro River Basin*. Matisse Working papers, 8.

Tabara JD, Elmqvist B, Ilhan A, **Madrid C**, Olson L, Schilperoord M, Valkering P, Wallman P & Weaver P (2006) *Participatory Modelling for the Integrated Sustainability Assessment of Water: the World Cellular Model and the MATISSE Project.* Matisse Working papers, 9.

Boada M, Canto S, Cazorla-Clariso X, Costeja M, Domene E, Domenech L, Gomez FJ, Lopez F, **Madrid C**, Mayo S, Meerganz G, Miro N, Muñiz S, Roca E, Sauri D, Tabara JD & von

Igel W (2005). *Sustainable water management in Spain according Water Framework Directive and Agenda 21. Keys of internal basins of Catalonia.* LIFE Survey Report.

Most relevant conference presentations

An integrated assessment of Spanish strawberry production and its impacts (oral communication). European Geographical Union General Assembly. Wien. May 2014.

El metabolismo hídrico de los Socio-ecosistemas: raíces teóricas y metodológicas. VI Congreso Iberoamericano de Desarrollo y Ambiente. FLACSO Quito. Dec 2013.

The incoherence between agriculture and water policies in Andalusia. A societal metabolism perspective. IV EUGEO Congress: Europe, what's next? Changing geographies and geographies of change. Rome. Sep 2013.

Analyzing water metabolism in Socio-Ecological Systems: A Multi-Scale Integrated Approach. EGU Leonardo Topical Conference Series on the hydrological cycle. Hydrology and Society: Connections between Hydrology and Population dynamics, Policy making and Power generation. Turin. Nov 2012.

Assessment of virtual water embedded in trade between Andalusia and the rest of Spain with a Multi regional Input-Output model *(MRIO)*. IV Conference on Input Output Analysis. Madrid. Sep 2011.

Multi Scale Integrated assessment of Socio-ecological metabolism of water. ESEE 2011: Advancing ecological economics: theory and practice. Istanbul, Turkey. Jun 2011.

An assessment of Almeria's virtual water flows by agricultural products exported to United Kingdom and its implications for the water management. ISEE 2010: Advancing sustainability in a time of crisis. Oldenburg, Germany. Aug 2010.

Virtual Water, Water footprint and other indicators of water sustainability. A necessary conceptual and methodological revision. ESEE 2009: Transformation, innovation and adaptation for sustainability. Ljubljana, Slovenia. Jul 2009.

The water metabolism of the society: Global forces with local consequences. ISEE 2008: Applying ecological economics for social and environmental sustainability. Nairobi, Kenya. Aug 2008.

Virtual Water in the Economy. The Case of Fruit and Vegetable Production in Andalusia, Spain. ISEE 2006: Ecological sustainability and human well being". New Delhi, India. Dec 2006.

Participatory Modeling of Water System Sustainability. The World Cellular Model and The Matisse Project. International conference on sustainability measurement and modeling. Barcelona. Nov 2006.

Methods and tools for integrated sustainability assessment. Possible applications for the economic evaluation of the integration and participatory provisions of European Water Framework Directive (WFD). International workshop on hydro economic modeling and tools for implementation of the European water framework directive. Valencia, Spain. Jan 2006.

Invited talks

Desarrollo de gramáticas MuSIASEM para el studio del agua. Seminario de presentación de la metodología MuSIASEm. SEPLADES. Gobierno de Ecuador. Quito, Febrero 2014.

MuSIASEM for Water. Workshop on Water Metabolism. Universidad Pablo de Olavide. Seville, May 2012.

The Water Metabolism of the Society: a set of global forces with local consequences. Environmental Sciences Master Program Seminar Series. Autonomous University of Barcelona. Feb 2010.

A study of the Water Metabolism of the fruit and vegetable production and trade in Andalusia, Spain. Project WU0120 meeting. UK Department of Environment, Food and Rural Affairs (DEFRA), London, Nov. 2009.

El Metabolismo Hídrico de la Economía. Project meeting: the water footprint of Spain. Spanish Ministry of Environment, Madrid, March 2009.

Teaching activities

Integrated Assessment of water issues. Liphe4 Scientific Society Summer school series. (2012,2013)

Workshop on water metabolism. MSc in in Ecological Economics. Autonomous University of Barcelona (2010); PhD in Environmental Studies. University of “El Valle” Colombia (2012).

Introduction to Economics and Environmental Economics. BSc in Environmental Sciences. Autonomous University of Barcelona. (2006/2007; 2008/2009; 2009/2010; 2010/2011).

Outreach activities

Workshop on water and international trade. Science Week. Miquel Crusafont high school. November 2013

Topic 3 Virtual Water and the Water Footprint. Open Systems Project, bridging art and science for high school students. April 2013

Research prizes

(Shared with Navarro, F.) 2011 Emilio Fontela Prize for Young researchers. Hispan American Society of Input-Output Analysis.

Service

Research

Coordination of ICTA_AQUA: The informal interdisciplinary group of researchers dedicated to water topics at the Institute of Environmental Science and Technology. Autonomous University of Barcelona. 2011-present.

Peer-reviewed journals

Revista Iberoamericana de Economía Ecológica.

Journal of Cleaner Production.

Journal of Industrial Ecology.

Water Resources Research.

Conference organization

I Conference of the Spanish association of ecological economics. Barcelona. June. 2011.

Biannual conference of the International Society for Ecological Economics. Applying ecological economics for social and environmental sustainability. Nairobi, Kenya. Aug 2008.

University service

Researchers Representative:

PhD researchers. Institute of Environmental Science and Technology. Autonomous University of Barcelona. 2011- present.

Junior Associates. Department of Applied Economics. Autonomous University of Barcelona. 2010-2011.

Student Representative:

Undergraduate students. Universidad Pablo de Olavide. Seville. 2000-2004.

Other Jobs

Practicum: *Junior environmental consultant*. Design of a template for ISO 14001 adapted data gathering and processing. Contributions to fund raising. Jan-Jun 2004.

Student job: *Conference organization staff*. Management of conferences up to 2000 participants including protocol transfers, registration and session assistance. 2000-2004.

Languages

Spanish: Mother tongue *English*: Proficient user *French*: Basic user

German: Independent user *Catalan*: Independent user

Annex VI Dissertation-related publications

Revista Iberoamericana de Economía Ecológica (2008)

URL: http://www.redibec.org/IVO/rev8_03.pdf
Madrid & Velázquez 2008. Revista Iberoamericana de Economía Ecológica Vol. 8: 29-47

El metabolismo hídrico y los flujos de agua virtual. Una aplicación al sector hortofrutícola de Andalucía (España)

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Resumen

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Palabras clave: [illegible]

Abstract

[illegible]

Key words: [illegible]

Water Resources Management (2011)

Water Resour Manage (2011) 25:743–761
DOI 10.1007/s11269-010-9724-7

Rethinking the Concepts of Virtual Water and Water Footprint in Relation to the Production–Consumption Binomial and the Water–Energy Nexus

Esther Velázquez · Cristina Madrid · María J. Beltrán

Received: 21 December 2009 / Accepted: 6 October 2010 /
Published online: 28 October 2010

Abstract In the field of Ecological Economics, the need of using physical indicators to analyse economic processes, at the same time they serve as tools in decision making, has been lately highlighted. Virtual Water (VW) and Water Footprint (WF) are two useful indicators in achieving this objective, the first one from the perspective of production, the second one from that of consumption. This difference between them is interesting inasmuch as it allows to identify the subjects who are responsible for water consumption, whether producers or consumers, and proves both indicators' potential when designing water management policies. In this work, we consider a hypothesis according to which there is a clear difference between the two concepts—Virtual Water and Water Footprint—and this difference, although evident in their respective conceptualizations, is not reflected in their estimations and applications. This is true to the point that the two concepts are often used as synonyms, thus wasting the enormous potential associated to their difference. Starting from this hypothesis, our objective is, first of all, to highlight this evident but ignored difference between VW and WF through a deep and thorough literature review of the conceptual definitions and contributions, the methodologies developed and the applications made regarding the two concepts. Second, we intend to make a conceptual and methodological proposition aimed at underlining the differences already mentioned and to identify responsibilities in water consumption. We do it by

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M. J. Beltrán
Institute for Environmental Sciences and Technologies (ICTA),
Autonomous University of Barcelona, ICTA-University of Barcelona,
08193 Bellaterra (Barcelona), Spain

BioScience (2013)

Water-Use Sustainability in Socioecological Systems: A Multiscale Integrated Approach

CRISTINA MADRID, VIOLETA CABELLO, AND MARIO GIAMPIETRO

Human societies and ecosystems use water in different ways and at different scales, which complicates the study of water-use sustainability in socioecological systems. We present a multiscale integrated assessment of societal and ecosystem metabolism, an innovative approach to the quantitative analysis of water use that addresses the problem of multiple scales. It builds on the concept of metabolic pattern *and the flow–fund model of Georgescu-Roegen. We show how to define water resources and water use (expressed in hourly rates) for socioeconomic systems in relation to the identities of relevant fund elements (relevant categories of human activity or land use) over a time span of 1 year. Similarly, we define the limits on the human appropriation of water (aggregate withdrawal or dumping per year) on the basis of the structural and functional stability of ecological funds (defined over a much longer time scale) and the related land-use pattern.*

Keywords: water metabolism, water-use sustainability, multiscale assessment, socioecosystems, MuSIASEM

Water scarcity is a socially driven phenomenon, fed by what Allan (2011) called a "deep social delusion" about water that manifests itself as a mismatch between physical water availability and societal water use. A clear example of this is the location of intensive-irrigation agricultural land or human settlements in deserts. The physical availability of water is determined by broadscale natural dynamics, whereas its use is determined by societal dynamics operating at a much narrower scale. Governance of water resources also has consequences at various scales (Laborte et al. 2007). As a result, quantitative analyses based on the consideration of only a single scale are unlikely to provide an input for the management of water resources that is adequate for both natural and social systems.

Several quantitative methods have been proposed to link societal water use to ecosystem impact. However, none of these methods explicitly addresses the issue of scale. The problem is twofold. First, these quantitative methods are deeply rooted in a reductionist approach to the definition of *water*. In fact, *water* has different meanings for different actors and scientists in different contexts and levels of analysis. Second, these methods do not bridge the results of the analyses at different levels.

An integrated assessment of water use should be able to address the shifting identity of a water mass perceived differently in different contexts. For example, a typical classification of *water* may define it as either blue or green, depending on its origin (evaporated from surface or groundwater or stored in the soil as moisture, respectively; Falkenmark 1995). However, it is doubtful that this characterization (1 cubic hectometer [hm^3] of blue water or 1 hm^3 of green water) will always be useful when moving across different contexts and levels of analysis. For example, if we need to check the number of jobs created in the paper sector per liter of water used, the origin of the water is usually not relevant. Yet, the origin of water is relevant for assessing the impact inflicted on the ecosystem. Water extracted from ecosystems can certainly be blue or green, but the potential usefulness of this classification will always depend on both the purpose of the analysis and the final use of this water. Given that social systems can control only (blue) freshwater, this has traditionally been the main indicator used to characterize water use within social systems, and there has been a systemic tendency to ignore green water.

The theoretical concept of *virtual water* (Allan 1998), beyond its operative characterization as the amount of water needed to produce a good or a service, is a step toward the adoption of a more flexible definition of *water* that is able to connect different perceptions referring to different systems. In fact, by adopting this concept, one can establish a water

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Journal of Industrial Ecology (in press)

Journal of Industrial Ecology Peer Review Proofs

Journal of Industrial Ecology

The water metabolism of socio-ecological systems: Reflections and a conceptual framework

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Complete List of Authors:	Madrid-Lopez, Cristina; Universitat Autonoma de Barcelona, Institut de Ciencia i Tecnologia Ambiental Giampietro, Mario; Catalan Institution for Research and Advanced Studies, Universitat Autonoma de Barcelona-Institut de Ciencia i Tecnologia Ambiental
Keywords:	scale, complexity
User-Supplied Keywords:	Water Accounting, Socio-Eco-Hydrology, MuSIASEM, Punjab
Abstract:	Water accounting is an unresolved issue in metabolism studies. Through epistemological analysis, we show that the problem resides in the conceptualization of social metabolism. Social metabolism has its origins in the analysis of societal energetics, which has led to an exclusive focus on society and a representation based on linear throughputs at a single scale. While fossil energy resources constitute a mere stock-flow for society, water constitutes a set of both funds and flows essential for the maintenance of the internal organization and stability of society and ecosystems. This means that societies and ecosystems need water for different reasons. Consequently, the analysis of water requires the simultaneous adoption of multiple narratives and scales. The development of hydrology towards a socio-eco-hydrology deals with this multidimensionality, but lacks a conceptualization of the coupled human-water system useful to integrate the assessment of water processes at different rates and scales. We propose a conceptual framework, based on the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) approach, that combines the perspectives of socio-eco-hydrology and social metabolism. This framework describes society and the embedding ecosystem as two distinct levels of the same hierarchical system, that is the socio-ecological system, expressing two distinct but tightly interconnected metabolic patterns (societal and ecosystem) at different spatiotemporal scales. Using food grain production in Punjab as an example, we show that this framework can accommodate the multiple interpretations of social metabolism found in different scientific fields.

Resource accounting for sustainability assessment (2014)

9 Water grammar

Cristina Madrid-Lopez and Mario Giampietro

Summary

The water grammar integrates the multiple societal and ecosystem dimensions of water metabolism into a coherent accounting method. It combines the distinct narratives for the analysis of ecosystem and societal metabolic pattern, including the different definitions of hierarchical levels of organization, functional compartments, and semantic accounting categories. Within the societal view, definitions are based on socio-economic criteria (water flows per hour of human activity and per hectare of land use), within the ecosystem view, on the role of water as a fund. We show how to check feasibility and viability of both water supply and water use. The grammar is implemented using practical examples.

9.1 The two non-equivalent narratives used in the water grammar

The metabolic patterns of water in societies and ecosystems are closely interwoven through biophysical and economic/societal processes. Connecting and combining them into a single quantitative representation has proven difficult, because this requires combining distinct scales of analysis and dimensions relevant for an integrated assessment (Madrid *et al.* 2013). Any given perception of water, such as production asset or rainfall, is tied to a specific disciplinary narrative used for its representation (specific scale, dimension of analysis, and set of causal relations – Giampietro *et al.* 2006). Therefore, any representation necessarily neglects other potentially useful perceptions focusing on other aspects of the metabolic pattern (e.g. sanitary aspects of drinking water, recreational aspects of a waterfall). The simultaneous existence and use of non-equivalent perceptions (and corresponding narratives) of different aspects of the metabolic pattern of water has resulted in a proliferation of analytical definitions of water that are mostly logically independent and incommensurable. For instance, water has been defined as a climatic phenomenon, a geological element, an ecosystem element, a human right, a production factor, a commodity, a chemical element and a public service, among others.

Hence, as is the case with the other nexus elements, what we need for a comprehensive accounting of water within MuSIASEM is a grammar that is able to

Resource accounting for sustainability assessment (2014)

13 Punjab state, India

Cristina Madrid-Lopez, Juan José Cadillo-Benalcazar, François Diaz-Maurin, Zora Kovacic, Tarik Serrano-Tovar, Tiziano Gomiero, Mario Giampietro, Richard J. Aspinall, Jesus Ramos-Martin and Sandra G.F. Bukkens

Summary

In this chapter we use MuSIASEM to explore the metabolic pattern of rural Punjab, with a special focus on the economic viability and ecological feasibility of the specialization of its economy in food grain production. We show how remittances from abroad and subsidies from the central government tied to the National Food Security Bill maintain a relatively high per capita income and keep the metabolic pattern of the rural economy of Punjab viable. Relating monetary flows to water and soil use patterns, we find that the present system of subsidies for electricity and the minimum support price programme regulated by the central government are responsible for the progressive overdraft of aquifers and soil degradation.

13.1 Punjab state: the granary of India

In this chapter we employ MuSIASEM to study the link between the socio-economic context of agricultural production in Punjab and the state of its environment. As illustrated in Part II of this book, MuSIASEM connects, in theoretical and quantitative terms, societal dynamics to their environmental impact across different levels of analysis. In the case of Punjab, four distinct levels are relevant: rural households, Punjab (state level), the Republic of India (national level) and the international markets. As regards the environmental impact, we focus on the overdraft of water for irrigation, which has been for years the most dominant environmental problem in the area (Dhawan 1993).

The broader *region* of Punjab is located within the Indus river basin. Its name is related to water abundance and literally means 'the five rivers'. In 1947, with the Partition of India, the region was split between India and Pakistan. In this case study, we exclusively focus on the Indian state, to which we refer from now on as simply 'Punjab'.

13.1.1 Socio-economic context of Punjab's agricultural production

Punjab, like the other Indian states, is subject to country-level regulations regarding resources management, energy subsidies, food distribution policies and

Credits

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Mequinensa Damm: http://upload.wikimedia.org/wikipedia/commons/f/f8/Presa_de_Mequinensa.jpg

Almeria greenhouses:
http://upload.wikimedia.org/wikipedia/commons/5/57/NASA_photo_of_plasticulture,_Campo_de_Dal%C3%ADas,_Spain.jpg

Precipitation: http://upload.wikimedia.org/wikipedia/commons/0/0c/FoggDam-NT.jpg

Old Irrigation: http://upload.wikimedia.org/wikipedia/commons/5/57/Irrigation_2.jpg

Tahoe Lake: http://i.huffpost.com/gen/938106/thumbs/o-LAKE-TAHOE-NORTH-SHORE-VERSUS-SOUTH-SHORE-facebook.jpg

Water Molecule: http://www.texample.net/media/tikz/examples/PNG/electric-dipole.png

Water Cristal: http://www.cloudman.com/snowflake/snowcrystal.jpg

Light Tunnel:
http://upload.wikimedia.org/wikipedia/commons/3/38/Light_at_the_end_of_tunnel_(633321722).jpg

Desert: http://www.nature.com/polopoly_fs/7.14610.1387814759!/image/1.14446_p11-Water-Scarcity-Panos-00041222.jpg_gen/derivatives/landscape_630/1.14446_p11-Water-Scarcity-Panos-00041222.jpg

Bottled water:

http://3.bp.blogspot.com/-LQmHTkM2nR8/T1QFozENECI/AAAAAAAAAPI/It9_p_c3sJ4/s1600/mineral+wtr.jpg

UAB