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DENISE TAFFARELLO

Segurança hídrica e adaptação baseada em ecossistemas nas bacias de cabeceira do Sistema Cantareira, Brasil

CORRECTED VERSION
Sao Carlos
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Doctoral thesis presented at São Carlos School of Engineering, University of São Paulo, in partial fulfillment of the requirements for obtaining the Degree of Doctor in Science: Hydraulics and Sanitary Engineering.

Advisor:
Full Professor Maria do Carmo Calijuri

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*To my husband **Eduardo Mario Mendiondo** and our beloved son **Theo Taffarello-Mendiondo**, the Little Prince. For all the unconditional love, encouragement, patience, emotional support and smiles. I love live to make you both happier.*

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"Know all theories, master all the techniques, but when you touch a human soul, be just another human soul."

Carl Gustav Jung (1875-1961)

ABSTRACT

Taffarello, D. (2016) **Water security and ecosystem-based adaptation in the headwaters of Cantareira Water Supply System, Brazil.** Doctoral Thesis, Sao Carlos School of Engineering, University of Sao Paulo, Sao Carlos.

Water quantity, availability and, particularly, quality of Brazilian freshwater is under progessive degradation due to Anthropocene's environmental changing conditions. Strategies of Ecosystem-based Adaptation (EbA) are essential to mitigate these impacts. This Ph.D. thesis proposes a new model of water resources management, thereby integrating self-purification and ecohydrologic processes to evaluate ecosystem services from watershed under change. In **Chapter 2**, this thesis examinates the payment for hydrologic ecosystem services (Water-PES) in Brazilian Atlantic Forest and points ecohydrologic variables useful for assessing and further valuing hydrologic services. In **Chapter 3**, this thesis discusses proposals for freshwater monitoring plan which integrate quali-quantitative aspects for EbA and Water-PES projects. Therefore, in **Chapter 4** experimental quali-quantative freshwater data from *in-situ* field observations are investigated according land-use/land-cover (LULC) in headwaters of water supply systems. In **Chapter 5**, through simulated impacts on freshwater yield from scenarios of LULC change, the grey water footprint (greyWF) is assessed, as well as environmental sustainability of sub-basins is depicted from a new ecohydrologic index for assessing hydrologic services. The methodology is performed using through field sampling and lab-analysing of physico-chemical, biologic and hydraulic variables in nested sub-basins draining to the Cantareira Water Supply System, in Sao Paulo and Minas Gerais states, Brazil. These areas participate in the Water-PES projects *Water Producer/PCJ* and *Water Conservator* at headwaters of Piracicaba watershed, during recent severe drought conditions between years 2013-15. The greyWF is estimated from outputs of time series simulated through ecohydrologic model Soil and Water Assessment Tool (SWAT). Under assumption of continuity of Water-PES projects, and using the same series of hydrometorological records for a common period (2008-2014), freshwater quali-quantitative impacts are performed through three LULC scenarios: past situation "S1" (year 1990), current situation "S2" (year 2010) and future situation "S2+EbA" (year 2035). From these scenarios, flow and load duration curves, mean water yields, greyWF and seasonal variabilities, were simulated. Through this research, continuous-monitoring Data Collecting Stations were installed in public-private partnership encompassing EESC/USP, ANA, CPRM, CEMADEN, SMA, TNC, WWF and local mayors. This continuous monitoring is addressed to increase the system resilience, based on better decision-making for water security, in strategic headwaters not only for water supply, but also for environmental conservation. This doctoral thesis brings contributions to a better comprehension of anthropic impacts on water resources and for strategies of EbA in front of progressive rates of losses of ecosystem services. This PhD. thesis was part of three research initiatives which partly granted activities: (1) Thematic Project FAPESP 2008/58161-1 "*Assessment of Impacts and Vulnerability to Climate Change in Brazil and Strategies for Adaptation Options*; (2) *"INCLINE - INterdisciplinary CLimate INvEstigation Center"* (NapMC/USP – Núcleo de Apoio às Pesquisas em Mudanças Climáticas) and (3) "Água Brasil" Project, Banco do Brasil Foundation, WWF Brazil, ANA & FIPAI/EESC-USP.

Keywords: Hydrologic ecosystem services. Land-use/land-cover change. Water security. Ecosystem-based adaptation. Freshwater monitoring. Ecohydrologic modeling. Water footprint. Integrated water resources management. Cantareira Water Supply System. Water Producer.

RESUMO

Taffarello, D. (2016). **Segurança hídrica e adaptação baseada em ecossistemas nas bacias de cabeceira do Sistema Cantareira, Brasil.** Tese de Doutorado, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos.

A quantidade, a disponibilidade e, em particular, a qualidade da água doce está em degradação progressiva devido às mudanças ambientais no Antropoceno. Estratégias de adaptação baseadas em ecossistemas (EbA) são essenciais para reduzir estes impactos. Propõe-se um novo modelo de gerenciamento de recursos hídricos que integre a pegada hídrica cinza e processos ecohidrológicos para avaliação dos serviços hidrológicos em bacias hidrográficas sob mudanças. As etapas da pesquisa são: **Capítulo 2** - análise dos projetos de pagamentos por serviços ambientais de proteção às bacias hidrográficas na Mata Atlântica brasileira e, no contexto de EbA, indicação de variáveis ecohidrológicas úteis na quantificação e futura valoração dos serviços hidrológicos; **Capítulo 3** – desenvolvimento de plano de monitoramento ecohidrológico que integra aspectos qualitativos e quantitativos dos recursos hídricos para projetos de EbA; **Capítulo 4** – provisão de dados experimentais de qualidade e quantidade da água, além de observações *in-situ,* para investigação das influências das mudanças de uso e ocupação do solo nas cabeceiras de mananciais, estratégicos para o abastecimento público e a conservação ambiental; **Capítulo 5** - estimativas da pegada hídrica cinza para nitrato, fósforo total e sedimentos a partir do monitoramento de variáveis quali-quantitativas em bacias com diferentes condições de uso e ocupação de solo. Foi realizada a instalação de três Plataformas de Coleta de Dados, por meio de parceria entre EESC, ANA, CPRM, CEMADEN, SMA, TNC e WWF, visando aumentar a resiliência do sistema, decorrente de futuro aprimoramento da gestão, para a segurança hídrica. A metodologia incluiu coletas em seis diferentes períodos, durante dois anos, e análises das variáveis condutividade elétrica, cor, DQO, $DBO_{5,20}$, nitrato, nitrito, nitrogênio amoniacal, fosfato, pH, turbidez, sólidos totais, coliformes termotolerantes, *Escherichia coli*, medidas de vazões e velocidades médias em seções transversais. O método foi aplicado em microbacias participantes dos projetos *Produtor de Água/PCJ* e *Conservador das Águas*, dentre outras, com áreas de drenagem entre 7 e 1.000 km^2, que contribuem para a bacia do rio Piracicaba (12.530 km^2). Dados primários, medidos em recente período de severa estiagem no Sistema Cantareira (2013-14), foram integrados aos bancos de dados de órgãos gestores federais e estaduais. A produção de água foi maior em sub-bacias menos florestadas. Foi possível aprimorar a regionalização de cargas poluidoras por área de drenagem na região do Cantareira. A pegada hídrica cinza (WF) foi estimada a partir de simulações no modelo ecohidrológico *Soil and Water Assessment Tool* (SWAT). Curvas de permanência de vazões e carga poluidora por área de drenagem foram elaboradas. Supondo-se a continuidade dos projetos "Produtor de Água/PCJ" e "Conservador das Águas", foram investigados os impactos de cenário futuro de uso do solo. Finalmente, foi desenvolvido novo índice ecohidrológico para quantificação dos serviços hidrológicos e avaliação a sustentabilidade das sub-bacias, a partir da pegada hídrica cinza composta. Assim, usando ferramentas de vanguarda tecnológica (SWAT e WF), a tese fornece subsídios para uma melhor compreensão dos impactos antropogênicos sobre os recursos hídricos e novas estratégias de adaptação baseada em ecossistemas, frente às progressivas taxas de perda de serviços ambientais. Esta tese esteve vinculada a três projetos de pesquisa, dos quais obteve apoio financeiro: (1) Projeto Temático FAPESP 2008/58161-1 "*Assessment of Impacts and Vulnerability to Climate Change in Brazil & Strategies for Adaptation Options*"; (2) "*INCLINE - INterdisciplinary CLimate INvEstigation Center*" (NapMC/USP) e (3) Projeto "Água Brasil", Fundação Banco do Brasil, WWF Brasil, ANA e FIPAI/EESC-USP.

Palavras-chave: Serviços ambientais hidrológicos. Mudanças de uso e ocupação do solo. Segurança hídrica. Adaptação baseada em ecossistemas. Monitoramento de água doce. Modelagem ecohidrológica. Pegada Hídrica. Gerenciamento integrado de recursos hídricos. Sistema Cantareira. Produtor de Água.

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ANA National Water Agency / Agência Nacional de Águas

ATI Atibainha

BMP Best Management Practices

BOD Biochemical Oxygen Demand

CAC Cachoeira

CEMADEN Brazilian Center of Monitoring and Early-Warning of Natural Disasters

CETESB Environmental Agency of Sao Paulo State / Companhia Ambiental do Estado de São Paulo

CIIAGRO Integrated Center for Agrometeorology Information

CNSP National Council of Private Insurance / Conselho Nacional de Seguros Privados

COD Chemical Oxygen Demand

CPRM Brazilian Geologic Service / Serviço Geológico do Brasil

CPTEC Center for Weather Forecasting and Climate Studies / Centro de Previsão de Tempo e Estudos Climáticos

DAEE Sao Paulo State Water and Electricity Department / Departamento de Águas e Energia Elétrica do Estado de São Paulo

DEM Digital Elevation Model

EbA Ecosystem-based Adaptation

EESC Sao Carlos School of Engineering

EMBRAPA Brazilian Corporation of Agricultural Research

ES Ecosystem Services

FAO Food and Agriculture Organization of the United Nations

FDC Flow Duration Curve

FMP Freshwater Monitoring Plan

GDP Gross Domestic Product

HRU Hydrologic Response Units

JAG Jaguari

HSI Hydrologic Services Index

IAHS International Association of Hydrologic Sciences

IBGE Brazilian Institute for Geography and Statistics

IGAM Minas Gerais Water Management Institute / Instituto Mineiro de Águas

INMET National Institute of Meteorology / Instituto Nacional de Meteorologia

INPE	National Institute for Space Research / Instituto Nacional de Pesquisas Espaciais
INVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IVA	Impact, Vulnerability and Adaptation
LAI	Leaf Area Index
LDC	Load Duration Curve
LULC	Land-Use/Land-Cover
MEA	Millenium Ecosystem Assessment
NCE	Nested Catchment Experiment
NGO	Non-Governmental Organization
NIBH	Integrated Group of River Basins / Núcleo Integrado de Bacias Hidrográficas
NO_3	Nitrate
NO_2	Nitrite
NSE	Nash-Sutcliffe Efficiency Index
PCJ	Piracicaba, Capivari and Jundiaí
PES	Payments for Ecosystem Services
PNQA	National Plan of Water Quality
PNRH	National Water Resources Policy / Política Nacional de Recursos Hídricos
SPMR	Sao Paulo Metropolitan Region / Região Metropolitana de São Paulo
SUFI-2	Sequential Uncertainty Fitting
SWAT	Soil & Water Assessment Tool
SWAT-CUP	Calibration and Uncertainty Programs
TNC	The Nature Conservancy
TP	Total Phosphorous
TS	Total Solids
UGRHI	Water Resources Management Unit / Unidade de Gerenciamento de Recursos Hídricos
UNFCCC	United Nations Framework Convention on Climate Change
USP	University of Sao Paulo
Water-PES	Payments for Hydrologic Ecosystem Services
WF	Water Footprint
WHO	World Health Organization
WPL	Water Pollution Loads
WWF	World Wide Fund for Nature

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CHAPTER 1

GENERAL INTRODUCTION

1.1. Research Context

Life depends on water. Before humans have learnt how to write, they have been hunters and food gatherers. Agricultural revolution becomes possible to live in permanent villages. Thus, early state civilizations have been developed along the rivers. They built hydraulic structures, such as cisterns, dams, dikes and aqueducts in Tigris-Euphrates, Nile and Indus valleys around 4,000 b.C., i.e., from the late Holocene. In Latin America, the Mayas and Incas also developed ancient water systems. These advances in water supplies and distribution were interrupted around the fall of the Roman Empire.

Urban civilizations have replaced those small villages by cities. Agriculture has progressively replaced the forests. As populations have growth, concerns have arisen in dealing with the multiple uses of water resources, i.e., irrigation, flood protection and wastewater drainage. On the one hand, the hydraulic innovations were needed for human supply. On the other hand, these technologies and deforestation become ecosystems even more vulnerable as a result of anthropogenic impacts.

Since the mid-XXth century, the rapid human population growth, sophisticated technological development and increased consumption of resources have accelerated the water pollution and scarcity. FAO (2016) estimates that there will be need an increase in 60% of global food production to feed more than nine billion people forecasted to live on planet by 2050. This persistent human impact on Earth seems reflect on a new epoch in the geological time scale: the so called Anthropocene (Crutzen, 2002). Waters et al. (2016) summarized the key markers of anthropogenic changes which are indicative of the Anthropocene. For example, the biotic change, which encompass species invasions and accelerating extinction. Furthermore, human-induced stressors are reshaping marine, freshwater and terrestrial ecosystems in unprecedented ways (Magurran, 2016).

The water cycle connects the abiotic environment (lito- and atmosphere) with the bio- and anthropospheres, thereby leading the distribution of life on Earth (Ehret et al., 2014). In turn, freshwater ecosystems have been recognized as among the most threatened ecosystems in the world since 20 years ago (Postel; Daily & Ehrlich, 1996, Brauman et al., 2007; Dodds et al., 2013; Brauman 2015). Estimates point that at least 10,000–20,000 freshwater species are extinct or at risk, with loss rates comparable to those of previous succession Pleistocene-Holocene. It has been showed that 65% of Earth's river discharge and habitats associated are moderately to highly threatened (Vörösmarty et al., 2010).

In his pioneering work, A.G. Tansley (1935) proposed the term "ecosystem", encompassing abiotic and biotic factors, as well as their functional and structural relationships. Moreover, terrestrial ecosystems influence freshwater by moving and modifying flows in ecohydrologic processes. The relationships among ecohydrologic processes are strongly non-linear (see Rodriguez-Iturbe, 2000; Zalewski&Robartz, 2003; Olden., Kennard & Pusey, 2012; Jørgensen, 2016; also called geo-bio-hydrologic processes by Kobiyama; Genz & Mendiondo, 1998). This ecohydrologic processes in both aquatic and terrestrial ecosystems provide benefits for humans, i.e. ecosystem services (Daily, 1997; MEA, 2005). This term was first used in literature by the couple Erlich (Erlich & Erlich, 1981), both biologists from Stanford University.

In water resources, three classes of ecosystem services, provisioning, regulating and supporting and their links, are of relevance. Provisioning services involve the production of renewable resources (for example, freshwater). Regulating services are those that indicate benefits arising from regulation of ecological processes and hence lessen environmental change (for example, climate regulation, water purification, disease control, attenuation of hydrologic extremes like floods and droughts; Cardinale et al., 2012). Supporting services are cycles of transformation of energy and mass at ecosystems and they are the basis for providing other ecosystem services (such as water and nutrients cycles, soil development; MEA, 2005). All types of ecosystem services have been progressively damaged by anthropogenic pressures. Despite the increasing number of studies on ecosystems services in last years, interactions among land-use management, ecohydrologic processes and ecosystem services delivery are still not fully understood (De Groot et al., 2010).

Land-use/land-cover (LULC) changes are the main threats which induce unbalanced water flows, biodiversity losses and interruption of nitrogen, phosphorous and other biogeochemical cycles, depleting ecosystem services in large scales (Daily et al., 1997). Ecosystem services generated in consequence of water and soil conservation within the scale of watershed, catchments or river basins are defined as hydrologic services, i.e., when we consider the human well-being as a result of the multiple uses of water resources (Brauman, 2015; Dodds et al., 2013; Brauman et al., 2007). There are diverse links between hydrologic services and ecohydrologic processes (**Figure 1.1**). According to Vörösmarty, Pahl-Wostl & Bhaduri (2013), *"Humans are changing the global water system in a globally-significant way without adequate knowledge of the system and thus its response to change."* Thus, the hydrologic ecosystem services concept can be related to their capacity to help solving water problems, to identify and mitigate trade offs between management options.

In face of these significant changes, we need to understand how the ecohydrologic processes work, if we want to develop better policies on watershed management (Ricklefs, 2015). For building this knowledge, we need to understand the complex and dynamic interactions throughout diversities of phenomena in different scales, since catchments are complex dynamical systems. First, it is needed to study the continental hydrologic cycle and the linked energy and mass transfers into the ecosystems. In this cycle, the water flows can be divided into two: blue water (superficial and groundwater runoff) and green water (evapotranspiration and subsuperficial runoff) (**Figure 1.1**), in a way to become easier the water resources management into a catchment. Second, the geobiochemical cycles are also important at the catchment scale. Thus, the potential provisioning of hydrologic services depends on the water balance, e.g. the relationships between water availability and water demand, both from natural variabilities and human-driven activities.

Regarding policies on water resources, the basin plan comprises the primary management tool for sustainable use of water resources in both spatial and temporal scales. However, to date, adaptive management alternatives have seldom been incorporated in the Brazilian basin plans, such as Ecosystem-based Adaptation (EbA). Neither integrated quali-quantitative analysis, nor combined indicators of human-ecosystem appropriation of freshwater resources have been established in basin plans. Among these quantitative indicators, I should highlight the water footprint - WF (Mekonnen & Hoekstra, 2015; Hoekstra et al., 2011; Hoekstra, 2003), because it encompasses grey, blue and green portions of water into a unique indicator for evaluating the sustainability arising from water resources pollution and consumption. For sustainable water allocation planning, the river plans must be elaborated based on accurate data on actual water availability per basin, taking into account: (i) water needs for humans; (ii) environmental water requirements and (iii) the basin's ability to assimilate pollution (Mekonnen et al., 2015).

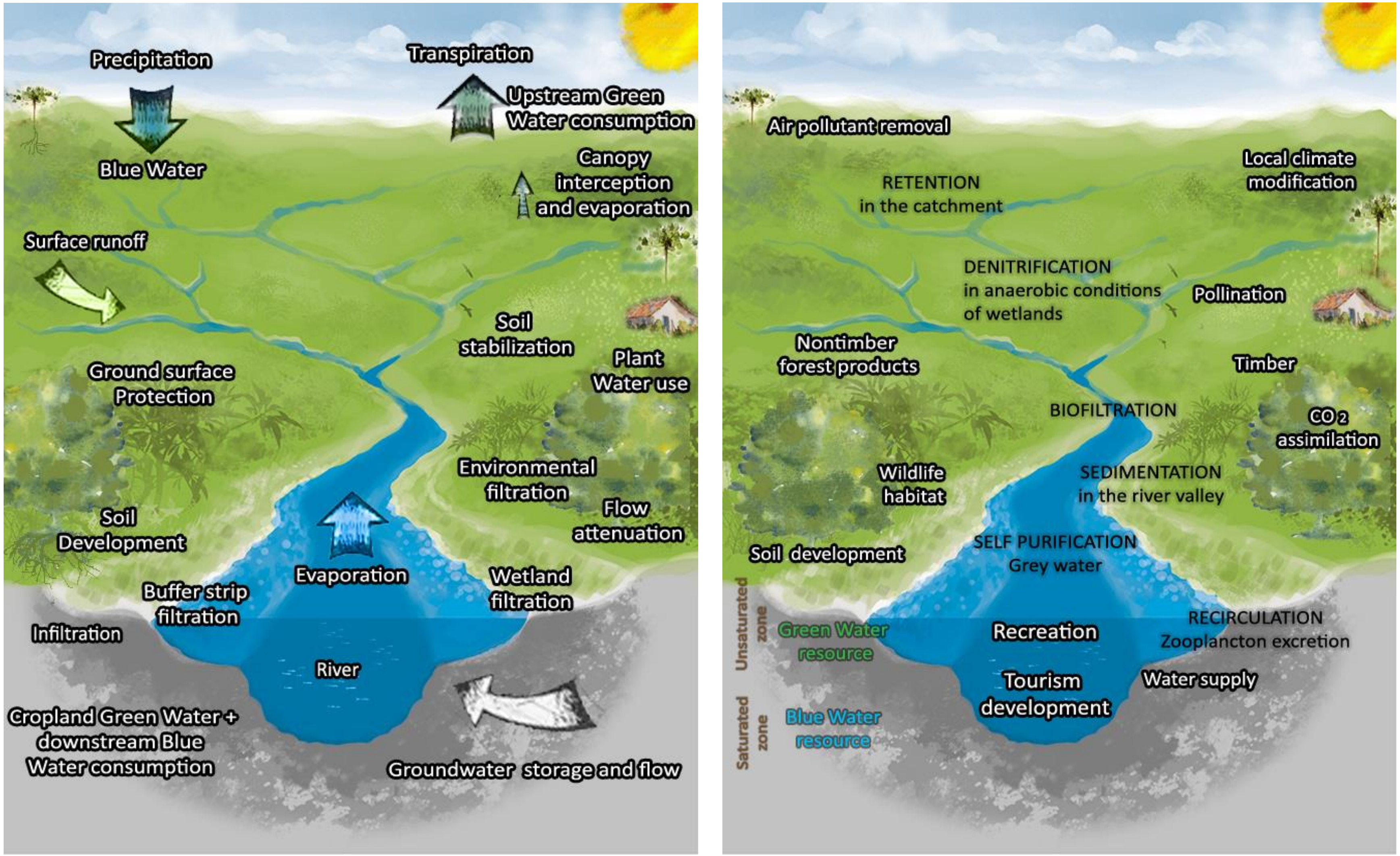

Figure 1.1. Ecohydrologic flows and ecosystem services into a catchment. Left side: Conceptual diagram highlighting three main flows (precipitation, evapotranspiration and surface runoff) in the hydrological cycle. Right side: hydrologic services framework showing how ecohydrologic flows impact the ways people can use water at the catchment scale. Adapted from Brauman (2015), Ellison et al. (2012), Gordon, Peterson & Bennett (2008), Zalewski & Robarts (2003).

Some countries have used the WF concept as an auxiliary tool for better water resources planning and management. For example, Spain enacted a regulation to use the water footprintin watershed plans (Velázquez et al., 2011; Aldaya et al., 2010). In Brazil, the watershed plans estimate the water demand by surface water and groundwater abstractions. However, a recent rule from the Brazilian National Water Agency recommends the inclusion of the WF indicator among other indicators to characterize the technical reports (ANA, 2015).

According to Hoekstra et al. (2011), WF measures both the direct and indirect "water use" within a river basin. The term "water use" includes *water withdrawal*: the consumptive use of rainwater (the green water footprint) and of surface/groundwater (the blue water footprint), and *water pollution*, i.e., the volume of water used to assimilate the pollutant loads (the grey water footprint, greyWF). The water footprint standards encompass four phases: (1) Setting goals, (2) Accounting, (3) Sustainability assessment, and (4) Response formulation. WF studies can be restricted to one specific activity of these phases or be related to more than one phase. In this research, I address phases 2, 3 and 4 of an overall investigation of WF proposed by Hoekstra et al. (2011).

1.2. Research Motivation

As a Biologist, I have worked on water resources management at Sao Paulo Environmental Secretariat in 2008-2014. I was introduced to the Water Footprint after the 5th. World Water Forum, Turkey, 2009. The WF appeared as an indicator of (regulating) ecosystem services with potential application in Sao Paulo watersheds, especially in the scope of Payment for Ecosystem Services (PES) projects. In 2011, I co-organized a Workshop on PES with 500 participants and a reference book on PES (Pagiola; von Glehn & Taffarello, 2013). Among the pioneering Brazilian PES initiatives, I highlight the "Water Producer/PCJ" project and its possible nexus with WF. Throughout this context, I gave speeches outside Brazil in Mexico (Taffarello & Mendiondo, 2011; Taffarello et al., 2011) and in Dominican Republic (*Aligning Water Fund Investment Prioritization in Latin America* Workshop). Also, I have completed the *1º Water Footprint Training Course in Brazil* (TNC/WWF/USP/Univ.Twente), when I have met Prof. A. Hoekstra and Prof. E. M. Mendiondo, who used to work on ecohydrology (Mendiondo, 2008). Prof. Mendiondo and I have noticed that a conceptual rationale was lacking to link PES, ecohydrologic processes and WF at changing watersheds.

I was intrigued because even with the evolution of those projects, some water related questions have persisted, such as: 1) How would hydrological monitoring be for PES projects? 2) What conditions and criteria about their linebases or benchmark for comparing PES schemes? 3) How to build partnerships among stakeholders responsible for these monitoring in long term, since decades are needed to notice water quality variations from possible PES results at the catchment scale? 4) What kind of ecohydrologic issues are needed to promote proper valuation of PES projects at the catchment scale?

To address these knowledge gaps, the current research was carried out using complementary inductive and deductive methods (Pathirage et al., 2008), encompassing experimental investigations and ecohydrologic modelling. Using as case study strategic headwaters of South-East Brazil, this Ph.D. research purposes a new conceptual model for water resources management, integrating ecohydrologic aspects and the greyWF for hydro-services assessment at different catchments scales. Besides the geographical and socio-economic relevance of the study area, climate change and poor water resources management added temporal relevance. Sao Paulo almost experienced a collapse on water supply during the years of this research (Nobre et al., 2016; Escobar, 2015; Manca, Falconi, Zuffo & Dalfré Filho, 2014).

1.3. Hypothesis

The current research assumptions are, mainly, related to hydrologic services as regulating ecosystem services, as proposed by Brauman (2015). In this context, identifying the hydrologic services of interest can help define which ecohydrologic processes to monitor for improve water resources management. For this reason, Ecosytem-based Adaptation (EbA) is here addressed with selected variables. Among the ecohydrologic variables, I highlight the grey water footprint (greyWF) as a robust and relatively straight forward for dealing with nutrient loads upstream to downstream at different scales of watersheds. Thus, based on Zhang et al. (2010), the greyWF can reveal the hydrologic regulating services throughout the use of rivers capability of autodepuration. From this background, the assumptions of this doctoral thesis are:

- First, the interactions between the hydrological cycle and the sustainability of the ecosystems can be linked to ecohydrologic processes and variables. Identifying specific ecohydrologic processes can be an adequated method for verifying the delivery of hydrological services in spatial and temporal scales in which the targeted service is generated. Especially, because the use of this method is still not explicitly incorporated into Brazilian mechanisms of Payment for Environmental Services (PES) for watershed protection.

- Second, because riparian forests contribute with autodepuration in streams and rivers, I expect to find better relationships between river water quality and forested land use types, which can be shown by lower greyWF for nutrients, such as nitrate and total phosphorous;

- Third, the correlation between greyWF for nutrients and water yield from catchment runoff I here postulate as a new indicator for assessment of hydrologic services. Therefore, studying this relationship through comparing scenarios with and without EbA allow us maintaining the ecosystem services of the river-catchment system for the long term.

1.4. Objectives

The main objective of this thesis is to create a multidisciplinary and new framework which integrates ecohydrologic aspects and the grey water footprint for the assessment of ecosystem services for protection of changing watersheds. This assignment, applied into the drainage watersheds of the Cantareira Water Supply System can contribute for the improvement of the water resources management in the context of catchments revitalization. I used literature review, planned a freshwater monitoring and field investigations through quali-quantitative freshwater sampling, integrated into three scenarios performed by an ecohydrologic model to investigate an inter-related range of specific objectives (**Figure 1.2**):

(i) In the context of Ecosystem-based Adaptation (EbA), evaluate the payment for hydrologic ecosystem services in the Brazilian Atlantic Forest and elucidate ecohydrologic variables useful for hydrologic services assessments and further valuation;

(ii) Develop a hydrologic monitoring plan for Ecosystem-based Adaptation (EbA) projects;

(iii) Provide new experimental data sets, integrating water quality and quantity samples from *in-situ* field observations, to study the role of land-use/land-cover (LULC) change at headwaters of water supply systems;

(iv) Assess the hydrologic services based on grey water footprint sustainability in catchments under LULC change, encompassing best management practices as EbA option.

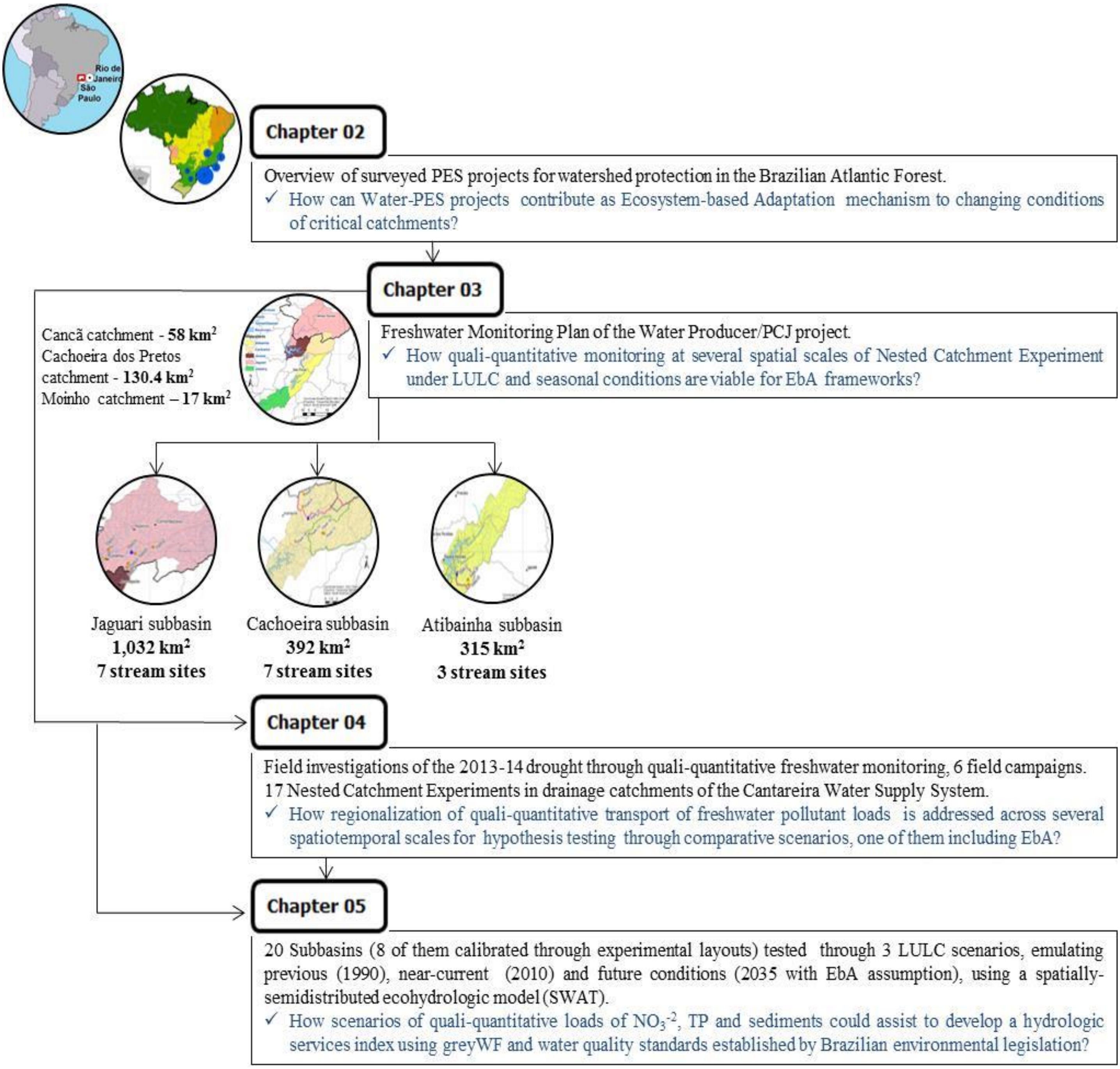

Figure 1.2. Methodological framework of the doctoral thesis and links among four chapters.

1.5. Thesis Structure

A methodological framework for this research and links between chapters is displayed in **Figure 1.2**. I organized this thesis into four chapters, modified versions of manuscripts, which address a set of my progressive knowledge on ecohydrologic processes and their interactions with ecosystem functioning and human needs. This is essential for a proper hydrologic services evaluation at catchment scale.

The thesis is structured as follows: after this introduction (**Chapter 1**), I begin with some ecohidrologic general definitions and an overview of water-related PES projects (Water – PES) in Brazilian Atlantic Forest. Then, I build a conceptual framework from ecohydrologic variables for integrated water resources management and provide some insights on how Water-PES may contribute as an Ecosystem-based Adaptation (EbA) option to face the changing conditions of catchments in the Atlantic Forest biome (**Chapter 2**).

The next step is to envision a viable freshwater monitoring plan, which integrates quantitative and qualitative aspects of water resources, for the selected study catchments: the micro catchments eligible to participate in the Water Producer/PCJ project (**Chapter 3**): Cancã (58 km^2) and Moinho (17 km^2). By planning and discussing conditions for efficiency in its implementation, this third chapter represents a conceptual link for the next.

Then, I present results from a multi-site, nested catchment experiment, carried out during a dry period (September 2013 – May 2014) within the Cantareira Water Supply System (hereafter referred as the Cantareira System), linking quali-quantitative freshwater monitoring to land-use/land-cover change evaluated by satellite images (**Chapter 4**). A quali-quantitative analysis of 17 catchments shows regional variabilities and trends for nitrate loads *versus* drainage areas (0.66 to 925 km^2). The field experimental method is resultant from the baseline of a monitoring that can allow the evaluation of maintenance of ecohydrologic health of streams in long term. In brief, the primary data brought by these field investigations outline a scale sensitive behavior, offering a useful tool for proactive management. Besides, these field data were used to calibrate the ecohydrologic model and compare the model performance regarding discharge and loads in the next chapter.

Although hydrological models provide hypothesis testing of complex dynamics occurring at river basin scales, freshwater quality modeling is still incipient at many Brazilian river catchments. In **Chapter 5**, I compare freshwater quality scenarios under different LULC, one of them related to Ecosystem-based Adaptation option. Using the spatially semi-distributed SWAT (Soil and Water Assessment Tool) model, nitrate and total phosphorous loads were modeled across Brazilian subtropical catchments with drainage areas ranging from 7.2 to 1037 km^2. Part of these catchments are eligible areas of the Brazilian PES-programs *Water Producer* and *Water Conservator* in the Cantareira System, which until the drought in 2013-14 supplied water to 9 million people in the Sao Paulo Metropolitan Region. On the one hand, simulations of nitrate and total phosphorous allowed the regionalization of grey water footprint (greyWF) at different spatial scales under LULC change. On the other hand, conservation practices simulated envisage not only viable best management practices, but also preventive decision making at the headwaters of water supply systems.

In **Chapter 6**, I summarize and conclude my doctoral thesis with a discussion of how the ecohydrologic processes are crucial for a comprehensive hydrologic services evaluation. According to Cunha & Calijuri (2012), we should make the best or most effective use of natural resources, minimizing the impacts and look for the best solutions. In this context, when the reduction of the greyWF is not possible, I purpose the compensating of the greyWF through implementation of EbA strategies. This can be a techno-scientific viable solution, economically advantage (because the “water provider” receive financial incentives for maintenance of health forests and freshwater ecosystems) and politically feasible, in accordance with a river basin focus on the integrated water resources management for the sustainable development.

Thus, the chapters of this thesis are timely and relevant on water security, with a specific focus on water quality. Here, I would like to acknowledge the inspiring cooperation of my co-authors, which makes my work possible. All four chapters are published or under review in peer-reviewed international journals: Science of the Total Environment (Chapter 2), Journal of Environmental Protection (Chapter 3), Water International (Chapter 4) and Water Resources Research (Chapter 5). Besides four international articles/manuscripts which are the chapters of this doctoral thesis, some of other outcomes are listed in **Appendix A**.

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CHAPTER 2

HYDROLOGIC SERVICES IN THE ATLANTIC FOREST, BRAZIL: AN ECOSYSTEM-BASED ADAPTATION OPTION THROUGH ECOHYDROLOGIC MONITORING*

* A modified version of this chapter has been submitted as **Taffarello, D**., Calijuri, M.C., Viani, R.A.G., Marengo Orsini, J.A., and Mendiondo, E.M. (2016). Hydrologic Services in the Atlantic Forest, Brazil: An Ecosystem-Based Adaptation Option through Ecohydrologic Monitoring. *Ecosystem Services: Science, Policy and Practice*. Journal Impact Factor 4.31.

Abstract

Payment for ecosystem services (PES) [1] is being widely proposed as a strategy for water resources conservation. Similarly, Ecosystem-based Adaptation (EbA) has been globally encouraged as an option to climate and land-use change. Our objective was to review information on Water-PES initiatives in the Brazilian Atlantic Forest, a hotspot for biodiversity conservation where several water-PES projects have been stablished. We found 16 ongoing Water-PES in the Brazilian Atlantic Forest. The first initiative was launched in 2005, and since then water-PES projects have rapidly grown. In spite of the success of many of these initiatives and their real advances, they seldom have hydrological baseline data and an implemented strategy for ecohydrological monitoring. Thus, we discuss how Water-PES projects could be more effective by implementing hydrological monitoring based on ecohydrology concepts, and how an integrated hydrological services valuation in water-PES projects would contribute as Ecosystem-based Adaptation options to climate and land-use changes.

Keywords - hydrologic ecosystem services; Ecosystem-based Adaptation; ecohydrology; Atlantic Forest; Brazil.

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[1] PES: Payment for Ecosystem Services, EbA: Ecosystem-based Adaptation, ES: Ecosystem Services, InVEST: Integrated Valuation Ecosystem Services and Tradeoffs, RIOS: Resource Investment Optimization System, SWAT: Soil and Water Assessment Tool.

Highlights

- Since 2005, many water-PES initiatives have been launched in the Brazilian Atlantic Forest.

- Water-PES schemes lack for hydrologic monitoring and options to cope with challenges under change.

- Hydrologic ecosystem services assessments are not integrated in the Water-PES schemes.

- An ecohydrologic framework for ecosystem services assessments is proposed.

- This framework is a tool for integrated water resources management and ecosystem-based adaptation.

2.1. Introduction

The Payment for Ecosystem Services (PES) through incentive strategies to conserve (Buckley &Pegas, 2014; Joly et al., 2014) or to restore (Banks-Leite et al., 2014; Palmer & Filoso, 2009) ecosystems represents possible solutions to prevent the degradation of water resources and related ecosystem services. This procedure can be instrumental not only to reduce the risks of inadequate land use, but also to manage and adapt to climate change and megadroughts (Underwood, 2015; Seppelt et al., 2011). In Latin America, particularly in Brazil, climate change adaptation options have been widely encouraged (Escobar, 2015; Marengo et al., 2015; Phillips et al., 2009).

The outcome of RIO + 20 provided a view that if development is to be truly sustainable; we need to value nature (Munang et al., 2013; Thiaw & Munang, 2012). This goal is based on the context of new scientific and policy awareness about climate change over the past 20 years (Tanner et al., 2015). Also, the concept of ecosystem-based adaptation (EbA), as ‘the use of biodiversity and ES to help people adapt to the adverse effects of climate change’, was defined by the Convention on Biological Diversity 10th Conference of the Parties (CoP) (CBD, 2010). According to EbA, protecting environmental services is required to help people and ecosystems to reduce their vulnerability and increase their resilience to climate change impacts (Marengo et al., 2014).

Scientists worldwide look for quantification and integrated methods to measure the value of hydrological ES (Brauman, 2015, Brauman et al., 2007, Broadbent et al., 2015, Duku et al., 2015, Naeem et al., 2015) to enable the effectiveness of PES initiatives. A pioneer technique, based on a benefits transfer approach, found that the economic value of 17 ES for 16 biomes averaged US$ 33 trillion per year and was 1.8 times higher than the global gross national product of 1995 (Constanza et al., 1997). This value was recently updated to a range between US$ 125 and US$ 145 trillion/year (Costanza et al., 2014).

Another study assessed the global human impact on the potential value of six freshwater ecosystem services (water quality, water availability, greenhouse gases, biodiversity, commodities and disturbance regulation) based on composite indexes (Dodds et al., 2013).

Ecohydrology is the interaction between biota and hydrology (Zalewski & Robarts, 2003), and the incorporation of its concepts can help to fill the gap between environmental scientists and engineers for achieving sustainable and integrated water resources management (Zalewski, 2014, 2015). Ecohydrology therefore provides the tools to address the current environmental challenges, such as the imbalance between water demand and available water resources. This subject has become more visible internationally with the *Agenda Post-2015 for sustainable development* (UN-Water, 2014) and in Brazil with the expected discussions in the next *8th World Water Forum*, which will be held in Brasília, Brazil, in 2018.

Despite the advances and increasing number of PES studies, some questions remain (Naeem et al., 2015; Pagiola et al., 2013), such as: how can the efficiency of the Water-PES projects, built through partnership between governments and stakeholders, be evaluated in the context of watershed under change? In what manner could the private companies or government provide better incentives for the participation of new stakeholders, e.g. water users and river basin committees, into PES markets? What methodological strategies of ecohydrology can be used to achieve faster advances in PES schemes under comparative EbA frameworks? And, what are the lessons learned from ongoing Brazilian Water-PES projects in the context of risk-based or EbA assessments?

This study aims to address PES in the Atlantic Forest, Brazil, as a climate change adaptation option. First, we systemize information about PES projects implemented in the Brazil's Atlantic Forest. Then, we present the development of ecohydrology and EbA concepts, and discuss how Water-PES projects can become more effective and reduce the vulnerability to climate change impacts, in an example of EbA option.

2.2. Water-PES projects in the Brazilian Atlantic Forest

We compile information about PES in the Brazilian Atlantic Forest using previous information provided by Guedes & Seehusen (2011), only considering actual PES cases, and Pagiola et al. (2013). Then, we expanded and detailed the list of PES initiatives by consulting specific published documents. We prioritized peer-reviewed articles but also considered publications in grey literature, thesis and dissertations, and the professional experience of the author in the projects. In addition, a questionnaire was sent to PES project managers to obtain supplementary information.

It was possible to acquire information on more than 60 Brazilian PES projects, classified in four types of ES: (a) protection of river basins (Water-PES); (b) carbon sink; (c) biodiversity protection; and (d) scenic beauty protection. From this sample, we selected only on the ground Water-PES and found 16 initiatives in Brazil's Atlantic Forests, created since the last decade (**Table 2.1**). Although we selected only the implemented projects, there are twice as many water-PES initiatives in articulation or development in different Brazilian states.

The first Atlantic Forest (and Brazilian) PES scheme, the "Projeto Conservador das Águas" at Extrema-MG, started in 2005 (Richards et al., 2015). Since then, Water-PES initiatives have rapidly expanded in the Atlantic Forest, and, on average, 1.5 new Water-PES projects have been initiated per year. The Atlantic Forest occurs in 17 Brazilian states, but we found Water-PES projects only in six states of South and South-East Brazil (**Fig. 2.1**), indicating Water-PES projects are not equally distributed through this vast and populous biome. Sao Paulo state, which is the most populous and richest (highest gross national product) state in Brazil, concentrated 40% of the implemented water-PES initiatives in the Brazilian Atlantic Forest.

Despite Water-PES projects in the Atlantic Forest vary on their area of abrangency and number of beneficiaries, only three of 16 initiatives ("Mina D'Água", "Bolsa Verde" and "Programa Reflorestar") are state programs occurring at a regional scale (Table 1). Most of the initiatives occur at local scale, in important catchments for urban water supply. For example, "Conservador das Águas" and "Produtor de Água/PCJ" are within the Cantareira Water Supply System, while "Oásis São Paulo" are around Guarapiranga and Billings reservoirs, in both cases, systems that supply water for the 20 million people of São Paulo metropolitan area.

Table 2.1. General information about Water-PES initiatives implemented in the Atlantic Forest, Brazil. Eligible actions for PES: FC – forest conservation, FO - forest restoration, OA - organic agriculture, SC – soil conservation practices.

Initiative name (starting year)[a]	**Location (scale)**	**Area (km^2)**	**Potential beneficiaries (nº of inhabitants)**	**Arrangement/funding (pilot institution in bold)**	**Legal instrument to guarantee funding or project**	**Eligible actions for PES**	**Duration of PES contracts (years)**	**Who implement/pay costs of eligible actions?**
1 - Conservador das Águas (2005) [b]	Extrema-MG (local)	60 (Posses and Salto catchments)	8,8 million (metropolitan area of São Paulo and PCJ River basin)	**Public (municipal**, state and federal), private, NGO, private foundation, watershed committee (PCJ water user fees)	Yes (municipal law and decree)	FC, FO, SC	5 (renewable)	Extrema municipality with resources from partners. No costs for landowners.
2 - Oásis-São Paulo (2006)	São Paulo-SP (local)	820	3,7 million (metropolitan area of São Paulo)	**Private foundation**, private	No	FC	5 (renewable)	Boticário Foundation
3 – Produtor de Água / Comitês Lagos São João (2007)	Rio de Janeiro: São João, Bacaxá and Capivari watersheds (local)	3825	250,000	**Watershed committee, FUNBOAS (Lagos São João water user fees)**	Yes (watershed committee resolutions)	FC, FO,OA, SC, rural sanitation	2 (renewable)	Project through direct execution or contracting third parties. No costs for landowners.
4 - Oásis-Apucarana (2009) [b]	Apucarana-PR; SPMR (local)	2687	400,000	**Public (municipal),** private foundation State water supply and sanitation company.	Yes (1% of sanitation company revenue at the municipality guaranteed by municipal law	FC, FO, OA, SC	4 (renewable)	Landowner execute through resources obtained from sanitation company
5 - Bolsa Verde (2008)	Minas Gerais state (regional)	32.3 (municipalities at Minas Gerais state)	7,6 million	**Public (state** - resources from a specific fund and from fines applied by the state forestry institute)	Yes (state law and decree)	FC, FO	5 (renewable)	When necessary, the landowner execute through resources obtained from project, apart from PES
6 – Produtor de Água – PCJ (2009) [b]	Nazaré Paulista-SP and Joanópolis-SP (local)	42.1 (Cancan and Moinho catchments)	8.8 million (metropolitan area of São Paulo and PCJ River basin)	**NGO**, public (municipal, state and federal), watershed committee (PCJ water user fees)	No	FC, FO, SC	3	Project through direct execution or contracting third parties. No costs for landowners.

Table 2.1. General information about Water-PES initiatives implemented in the Atlantic Forest, Brazil. Eligible actions for PES: FC – forest conservation, FO - forest restoration, OA - organic agriculture, SC – soil conservation practices **(cont.)**

Initiative name (starting year)[a]	**Location (scale)**	**Area (km^2)**	**Potential beneficiaries (nº of inhabitants)**	**Arrangement/funding (pilot institution in bold)**	**Legal instrument to guarantee funding or project**	**Eligible actions for PES**	**Duration of PES contracts (years)**	**Who implement/pay costs of eligible actions?**
7 – Produtores de Água e Floresta (2009) [b]	Rio das Pedras-RJ (local)	278 (Upper Piraí basin)	8 million (metropolitan area of Rio de Janeiro)	**Watershed committee (Guandu water user fees)**, ONG, public (municipal, state, federal)	Yes (watershed committee resolutions)	FC, FO, rural sanitation	1 (renewable by 1 year)	Project. No costs for landowners.
8-9 - Programa Reflorestar (2009, Florestas para vida and ProdutorES de Água)[b,c]	Espirito Santo State (regional)	6,222 (São José, Guandu and Benevente basins, and Vitoria Metropolitan Region (VMR))	1,900,000 (VMR population)	**Public (state), FUNDÁGUA**	Yes (state law)	FC, FO, SC	3 (renewable)	Inputs provided by project but execution is by the landowner.
10 – Camboriú (2009, but project implementation started in 2013) [b]	Camboriu-SC (local)	17,196	170,000 (fixed population) and 800,000 (tourists in South Summer)	**Municipal Enterprise of Water and Sanitation**, NGO, public (municipal, stare, federal), water committee, private	Yes (municipal law guarantee a % of water company revenue)	FC, FO, SC	--	Project. No costs for landowners
11 – Mina d'Água (2010)	São Paulo state (regional)	8,844 (22 watersheds in municipalities at São Paulo state)	874,486	**Public,** through the state fund FECOP and partnership among municipalities.	Yes (state law, decree and resolution)	FC, FO	2-5	Project. No costs for landowners
12 – Corredores do Vale (2010)	Paraíba River valley (local)	1,580	--	**Public** and **private**, with participation of private companies	--	Sanitary measures[d]	--	--
13 – Produtor de Água – Guaratinguetá (2011) [b]	Guaratinguetá-SP (local)*	105 (Guaratinguetá	112,091	**Public (municipal**, federal), private, NGO	Yes (municipal law and decree)	FC, FO, SC	3-10	Project. No costs for landowners
14 – Produtor de Água do Rio Vermelho (2011)	São Bento do Sul-SC (local)	230 (Rio Vermelho basin)	75,000	**Public (municipal),** Municipal water supply and sanitation company, private foundation	Yes (municipal law)	FC, FO	2 – 10 (renewable)	Inputs are provided by project but execution is by the landowner.

Initiative name (starting year)[a]	Location (scale)	Area (km^2)	Potential beneficiaries (nº of inhabitants)	Arrangement/funding (pilot institution in bold)	Legal instrument to guarantee funding or project	Eligible actions for PES	Duration of PES contracts (years)	Who implement/pay costs of eligible actions?
15 – Vinhedo (2012)	Vinhedo-SP (local)	82	63,685	Public	Yes (municipal law)	FC, FO	5	Project. No costs for landowners
16 – Produtor de Água – São Francisco Xavier (2014)[b]	São José dos Campos-SP (local)	7.5	2,867	Public	Yes (municipal law)	FC, FO	2	Project. No costs for landowners

a Main sources of information: Agueda et al. (2013), Bremer et al. (2016), EMASA (2016), Henrique (2009), Klemz et al. (2013), Klemz et al (2016), Nunes et al. (2013), Padovezi et al. (2013), Prefeitura São Bento do Sul & Samae (2010), Prefeitura Municipal de São José dos Campos (2015), Prefeitura Municipal de Vinhedo (2013), Richards et al. (2015), Silva et al. (2013), Sossai et al. (2013), Viani & Bracale (2015), von Glehn et al. (2013), Young & Bakker (2014). Information was also collect through direct contact with project managers.

b Initiatives linked to the “Water Producer Program” from the Brazilian Water Agency (ANA).

c We presented the general information from “Programa Reflorestar”. However, we counted two water-PES initiatives here because “Programa Reflorestar” is a state program created based on two previous pilot projects: “Florestas para a Vida - 2009” and “ProdutorES de Água - 2009”.

d Examples are septic tanks and individual domestic sewage treatment systems.

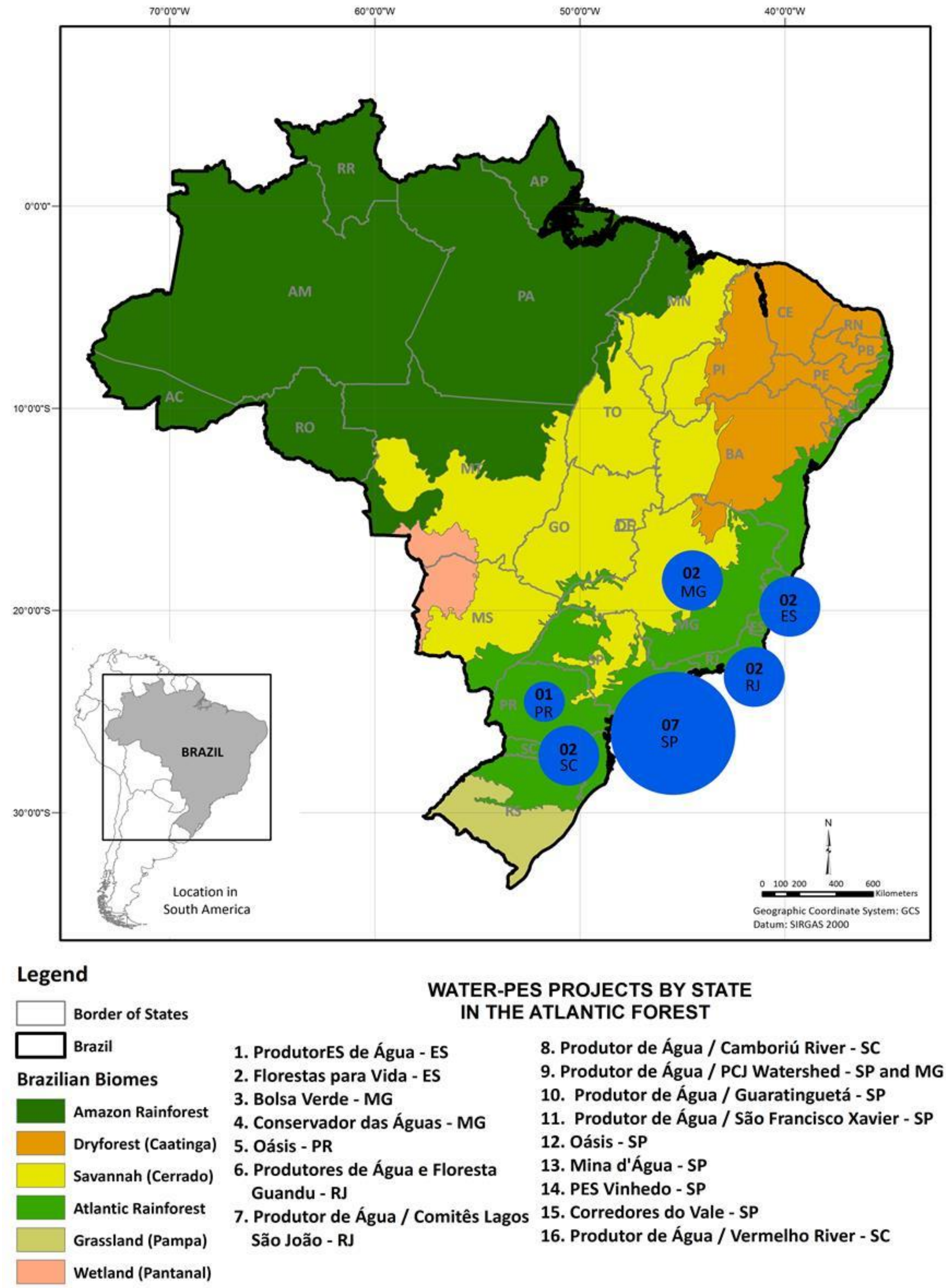

Figure 2.1. Brazilian Water-PES Projects per state in the Atlantic Forest biome.

All the on the ground Water-PES projects found in the Atlantic Forest pay for rural landowners, often through legal agreements (PES contracts varying in years of duration), which is not always the case for other Latin America countries (Bremer et al., 2016). Moreover, most of them (12) have already established legal instruments to secure the project and the flux of resources through time. Finally, all the initiatives have the conservation of forest remnants an eligible action for PES while forest restoration, soil conservation, organic agriculture and adoption of rural sanitary measures (for example, installation of septic tanks or sewage treatment) are considered for some of them.

Forest restoration, when considered as an eligible action, is focused on riparian areas called APP or "Permanent Protection Areas" according to the Brazilian forest law (Soares-Filho et al., 2014). Restoration of degraded APP is mandatory for landowners. Thus, our results show that Water-PES initiatives at Atlantic Forest often pay for actions in legally protected areas. Furthermore, most of the Water-PES initiatives provide other benefits to participants beyond the PES, paying part or integrally the costs for land management actions that generate the PES (**Table 2.1**). Thus, some Water-PES projects constitute an opportunity to landowner to receive PES as well as to comply with Brazilian forest law, with no costs.

We found public (federal, state, and municipal initiatives), private (companies and foundations) and non-profit organizations working with PES for the protection of watersheds (**Table 2.1**). Arrangements are diverse and involve multiple stakeholders, mixing public, private and non-governmental organizations, corroborating the idea that, for PES, one size does not fit all (Bremer et al., 2016). Having the local government leading the PES project is the most common situation in the Atlantic Forest. One rare case is the Oasis Project at São Paulo, where the leading institution is a private foundation (**Tabela 2.1**). Interesting cases arise from "Produtor de Água/PCJ", "Produtores de Água e Floresta" and "Conservador das Águas", located in watersheds that charge water users (**Tabela 2.1**). In these initiatives, PES for landowners is made integrally or partly, directly by the River Basin Committee, using the resources obtained through charging for water use. This scheme fits the polluter-payer and provider-recipient concepts (Taffarello et al., 2016b, Viani & Bracale, 2015). Other frequent and similar arrangement is the direct involvement of water supply and sanitation institutions. In some initiatives, as the "Camboriu River" and "Oásis-Apucarana" the legal arrangements were already established to guarantee part of the revenue of these companies for the project (**Table 2.1**).

Finally, six projects are linked to the “Water Producer” program, a concept that was introduced in the country by the National Water Agency, with the objective of supporting Water-PES projects that focus on improving water quality, increasing water supply and flow regulation (ANA, 2012). In spite of being all linked to the Water Producer Program, each of these six initiatives has your own local functioning, diverging with regard to scale of action, institutional arrangement, and amount of resources invested for implementation and maintenance of the project (**Table 2.2**).

Besides the 16 Water-PES projects summarized in **Table 2.1**, we highlight more two Water-PES programs due to its national importance: “Cutivando Água Boa” and “Olhos d’Água”. First, “Cutivando Água Boa”, is a program from binational Itaipu and partners which aims the headwaters and riparian forests conservation, and sustainable methods of farming. Second, “Olhos d’Água”, is a Water-PES program accomplished by the NGO “Instituto Terra”, founded by the famous Brazilian photographer Sebastião Salgado. The project is sponsored by Vale and supported by *(i)* EMATER-MG (technical rural assistance) and *(ii)* the Manhuaçu river basin committee. The Manhuaçu river basin is totally inserted in the Minas Gerais state, “Zona da Mata” and Doce river valley, with drainage area of 9,189 km^2. The investments in headwaters conservation have been increased by the “Olhos d’Água” program, since 2013. At least US$ 630,000[a] were performed by the program between 2013 and mid-2015 (http://www.institutoterra.org/projetos/VALE/).

More than 1.900 landowners have already signed Water-PES contracts in the Atlantic Forest, resulting in more than 48,000 ha of land managed for water resources conservation (Table 2). By far, the most common land management originating Water-PES is conservation of the remaining forest patches (**Table 2.2**). Atlantic Forest remnants are protected by a specific law (“Lei da Mata Atlântica”) and their legal suppression for other land uses is very restricted. Thus, PES for forest conservation is more acceptable by landowners than actions that directly affect their agricultural lands (Viani & Bracale, 2015). Payment values for landowners vary from US$ 8-891 (Table 2), reflecting differences for resource available for the project, methods of ES valuation and opportunity costs.

[a] 1 US$ = R$ 3.3 in July 2016.

Table 2.2. Results of the implemented Water-PES initiatives in the Atlantic Forest, Brazil. Sources of information are described in **Table 2.1**.

Initiative name	Investment* (thousand US$)	Number of PES contracts/agreements with landowners	Payment value[a] (US$/ha/year)	Area of land management (ha)
1 - Conservador das Águas (2005)	930 (only for PES)	210	71	3,638 (2,456 of soil conservation, 342 of forest reforestation; 840 of forest conservation;
2 - Oásis-São Paulo (2006)	---	14	up to 112	748 (forest conservation)
3 - Produtor de Água / Comitê Lagos São João (2007)	18	---	---	---
4 - Oásis-Apucarana (2009)	---	133	280 – 2098 per property/year (not per ha)	3,199 (800 of forest conservation and 2,399 with other practices)
5 - Bolsa Verde (2008)	1,690	980	61	32,338
6 – Produtor de Água/PCJ (2009)	770 (50 for PES and 720 for diagnosis, execution of eligible actions and divulgation)	41	8 - 38	489 (99 of soil conservation, 68 of forest restoration and 391 of forest conservation)
7 – Produtores de Água e Floresta (2009)	1,400 (only for PES)	62	18 - 30	3,587 (3095 of forest conservation and 492 of forest restoration)
8-9 – Programa Reflorestar (2009 - Florestas para vida and ProdutorES de Água)	---	459	340 - 402	4,317 (360 of forest restoration and 3957 of forest conservation)
10 – Camboriú (2009)	Implementation cost: 267; Maintenance costs per year: at least	12	97	360 (320 of forest conservation

Initiative name	**Investment* (thousand US$)**	**Number of PES contracts/agreements with landowners**	**Payment value[a] (US$/ha/year)**	**Area of land management (ha)**
	88			and 40 of forest restoration)
11 – Mina d'Água (2010)	1,060 for 5 years of project	---	22-91 per headwater/year	Up to 150 headwaters per city
12 – Corredores do Vale (2010)	3.8	--	--	--
13 – Produtor de Água – Guaratinguetá (2011)	372 (3.3% for PES and 96.7% for diagnosis, execution of eligible actions and divulgation)	50 contracts up to 2013	64-129	10528
14 – Produtor de Água do Rio Vermelho (2011)	---	18	up to 138	---
15 – Vinhedo (2012)	---	---	up to 891	---
16 – Produtor de Água – São Francisco Xavier (2014)	Up to 394	---	49-101	---

[a] 1 US$ = R$ 3.3 in July 2016.

Most of the Atlantic Forest Water-PES projects have clear hydrological services objectives and defined their area of occurrence base on the relevance of them for hydrological services generation or conservation (**Table 3.3**). In addition, especially for forest restoration, they prioritize actions for riparian areas, critical areas for hydrological services. However, not all the projects have the PES values varying according to the amount and/or quality of the generated hydrological services, only few of them have already established hydrological monitoring and none of the initiatives condition the PES to direct measures of the hydrological services (**Table 3.3**). In fact, in all of the projects, payments to landowners are done assuming that implementation of eligible actions (forest restoration and conservation, soil conservation, etc.) guarantee the existence of the hydrological services. Thus, advances for hydrological services valuation and monitoring in Atlantic Forest Water-PES initiatives are needed.

2.3. Ecohydrology as a tool for valuation of hydrological services

River flow dynamics and the interaction of flow with landscape provide a large number of ES that can (i) improve water quality, (ii) create positive socioeconomic effects and (iii) regulate land use and water use. However, the conversion of natural land cover to human uses, henceforth called land-use/land-cover change (LULC), influences river water flows mainly by reducing the absorption and the filtration of water flows. In addition to the impacts of human activities, such as agriculture, urbanization, industry, rapid population growth, sub-urban development and building of dams, extensive research also shows the additional impact of climate change on ES (Ehret et al., 2014, Hallegatte et al., 2014, Marengo et al., 2014, Nelson et al., 2013, Palmer et al., 2009, Pedrono et al., 2016).

On the one hand, changes in precipitation, air temperature and wind regimes are the main consequences of extreme climate variability and climate change impacts on hydrologic services flow (Nickus et al., 2010). One recent example could be the drought of the megacity of Sao Paulo, where due to a drought during austral summer of 2013-14 the main reservoirs had reached storage levels of only 5% of their 1.3 billion m^3 capacity, generating a severe water crisis aggravated by a combination of lack of rainfall, higher temperatures, increasing population and water consumption (Escobar, 2015, Nobre et al. 2016, Taffarello et al., 2016a). On the other hand, at local and regional scales, ecosystem flows may be altered due to changes in the water cycle, changes in river flow regimes or changes in groundwater level and other factors. To quantify and integrate these hydrological and ecological processes, an ecohydrological framework can be applied (**Fig. 2.2**).

Table 2.3. Ecohydrological and Ecosystem-based adaptation considerations in Water-PES initiates in the Atlantic Forest, Brazil. Sources of information are described in **Table 2.1**.

Initiative name	**Project area and management lands selected based on hydrological services**	**Hydrological services in the objectives**	**PES values vary according to potential of hydrological services provided**	**Existence of hydrological services monitoring**	**PES linked to measures of hydrological services**	**Considers adaptive measures for long-term changes?**
1 - Conservador das Águas (2005)	Yes. The two selected watersheds are within Cantareira water supply system and forest restoration is focused on riparian areas.	Reduce erosion and sedimentation,	No	Yes. Quality and quantity of water, with partners (ANA, CPRM EESC/USP, IAG/USP, Esalq/USP, Lavras University).	No	Yes, through hydrological monitoring.
2 - Oásis-São Paulo (2006)	Yes. Watersheds were selected based on relevance for water production and contribution to Guarapiranga and Billings reservoirs, which supply water to São Paulo metropolitan area.	Increase water storage, Erosion control, improvement of water quality	Yes – multiple factors considered	No. Only vegetation and property monitoring	No	No
3 - Produtor de Água / Comitê Lagos São João (2007)	No	No	No	No	No	No
4 - Oásis-Apucarana (2009)	Yes. The projected started by the most important watershed for water supply in the region.	Increase water quality and quantity	Yes – multiple factors considered	No. Only vegetation and property monitoring	No	No
5 - Bolsa Verde (2008)	No	Regulation services in general. No clear hydrological services in the objective.	No	No	No	No
6 – Produtor de Água – PCJ (2009)	Yes. The two selected watersheds are within Cantareira water supply system and forest restoration is focused on riparian areas	Reduce erosion and sedimentation, increase water flow	Yes	Yes. See Taffarello et al., 2016	No	Yes
7 – Produtores de Água e Floresta (2009)	Yes. Project is within Guandu water supply system and forest restoration is focused on riparian areas	Water flow; sediment retention; water quality (multiple parameters)	Yes	Yes	No	Yes

Initiative name	Project area and management lands selected based on hydrological services	Hydrological services in the objectives	PES values vary according to potential of hydrological services provided	Existence of hydrological services monitoring	PES linked to measures of hydrological services	Considers adaptive measures for long-term changes?
8-9 – Programa Reflorestar (2009 - Florestas para vida and ProdutorES de Água)	No	No. The main objective is to gain forest cover.	No	No	No	No
10 – Camboriú (2009)	Yes. In area for urban water supply and with prioritization of management of riparian areas	Sediment reduction, Flow regulation;	Yes	Yes. Hydrological monitoring and geomorphologic analyses of the water bodies	No	Yes. See Klemz et al. (2016)
11 – Mina d'Água (2010)	Yes	Yes	Yes – multiple factors considered	Partially. Mina d'Água: monitoring plan was elaborated with support of the World Bank.	No	No
12 – Corredores do Vale (2010)	---	---	---	---	No	---
13 – Produtor de Agua – Guaratinguetá (2011)	---	---	Yes	---	No	---
14 – Produtor de Água do Rio Vermelho (2011)	Yes. The projected is along the river which supply water to the city and focus on restoration of riparian areas	Increase water quality and quantity	Yes – multiple factors considered	No	No	No
14 – Vinhedo (2012)	Yes. Implemented per sub-basin (first in Capivari sub-basin) in the priority areas for public supply.	No	No	No	No	No
15 – Produtor de Água – São Francisco Xavier (2014)	Yes, Implemented in Ribeirão das Couves and Peixe watersheds, headwaters of Jaguari reservoir, Paraíba do Sul river basin, i.e., in the priority areas for public supply.	---	---	No	No	No

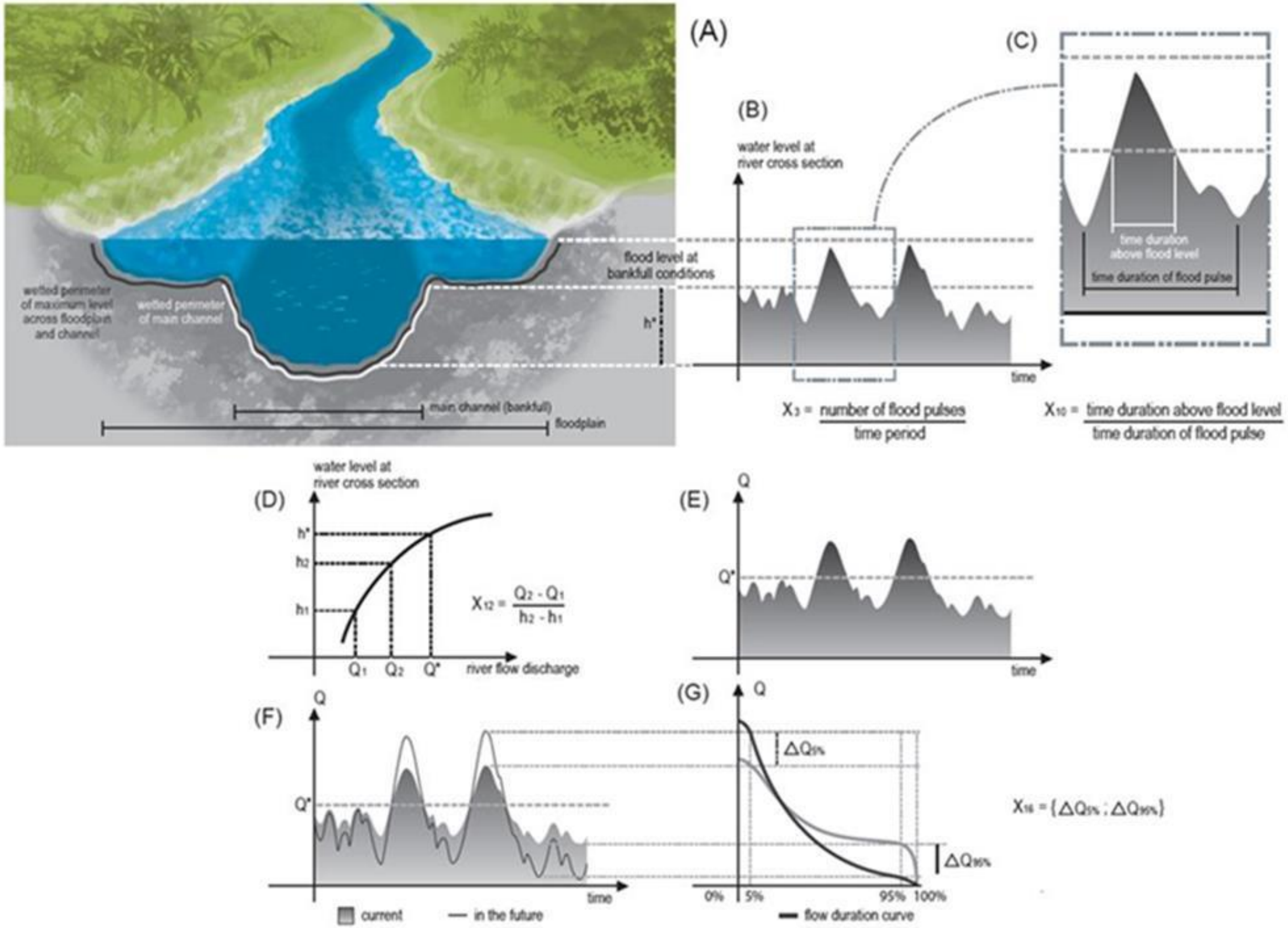

Figure 2.2. Conceptual terms used in this manuscript. A: river cross-section. B: time series of water level. C: a flood pulse during time. D: rating curve between water levels and discharges. E: time series of flow discharges. F: changes in time series of present and future flow regimes. G: changes in flow duration curves between present and future flow regimes.

In a typical river basin scheme (**Fig. 2.2-A**), there are several ecohydrological variables. The geo-hydrological processes (Kobiyama et al., 1998), also known as eco-hydrologic processes, interact in a non-linear way (Mendiondo, 2008, Zalewski, 2014, 2015). Such processes define the river regime, the ecosystem flow and ES, generated because of soil conservation and the (non)protection of water resources and biodiversity in watersheds.

A healthy river promotes responses to changes in the landscape and climate change. The natural sinuosity of the main channel across the floodplain produces flow characteristic and load discharges at the cross section. Thus, the main channel is defined up to the bankfull condition with water level at h* value. Flooding events above h* occupy the floodplain over a time series and define high flow regimes (h>h*) in the flow duration curves.

Each pulse flood over time (**Fig. 2.2-B**) can be characterized by frequency, intensity, amplitude and seasonality (Neiff et al., 2008, Richter et al., 1997). As a result, categories of sinuosity, continuity, diversity, dynamics, resilience and vulnerability constrained by 18 ecohydrological variables can express the conditions of river ecosystems (Mendiondo, 2008). For example, an ecohydrological variable can determine the frequency of pulses for the number of flood pulses per time period (X_3, **Fig. 2.2-B**). For a determined flood pulse (**Fig. 2.2-C**), the ecohydrological variable X_{10} defines the ratio of time duration above flood level and time duration of total flood pulse. The higher the X_{10}, the stronger is the river biodiversity. Both ecohydrological variables X_3 and X_{10} influence how pollutant loads can be lower or higher than that observed for flows at high water levels. Because water levels are related to river discharges, at non-linear relationships ($X_{12} = \Delta Q \div \Delta h$ in **Fig. 2.2-D**), time series of water levels h(t) can be converted into flow discharges Q(t) at the same cross sections (**Fig. 2.2-E**). Similarly, situations of Q(t)>Q* represent flood pulses.

From the above discussion, LULC changes can alter normal flow regimes (**Fig. 2.2-F**), intensifying flow extremes with higher floods or lower droughts. Flow duration curves, represented by the frequency of time permanency of flows, usually depicts a monotonically downward flow curve for all curves measured at the river cross-section. A new ecohydrological variable X_{16} of changing reference flows, i.e., at 5% ($\Delta Q_{5\%}$) and 95% ($\Delta Q_{95\%}$) could be assessed for non-stationary conditions of flow duration curves.

In summary, these new ecohydrological variables can help quantifying ES (in other words, assess how the landscape context influences the amount of hydrological services) in Water-PES schemes. From this interaction, the “water+climate” composition is the main sustainability element (Moss et al., 2010, Tucci & Mendes, 2006), directly influencing biodiversity. Since the potential of hydrological services depends on the equilibrium of the water balance (variable given the natural oscillations or induced by impacts from anthropic and/or climatic factors), besides the functional distribution of the ecosystems on the watersheds, we propose a framework to achieve integrated assessments of ES in water-PES initiates.

2.4. Impacts, Vulnerability and Adaptation linked to Water-PES Projects

Some countries have made efforts to adapt to climate change and variability, for example, through the conservation of key ecosystems, compensation for ES, and the use of early-warning systems and climate forecasts. However, global change is a strong stressor that threatens human water security and biodiversity (Vörösmarty et al., 2010). Besides, there are different climate change scenarios for Brazil up to the end of the twenty-first century (**Fig. 2.3**), indicating how unpredictable the impacts are. The 2013-14 drought in South-East Brazil, mentioned before, which led to a water crisis for 85 million people, is an example of these hard to predict scenarios, which impact both freshwater ecosystems and people.

The valuation of river health and associated ES involves several challenges regarding how to account for the vulnerabilities to land use and climate change impacts and uncertainties. Here we outline how an EbA contributes to reducing risks in three steps. First, we briefly introduce the impact-vulnerability-adaptation rationale (IVA). Second, we show the conditions that appear to fill the gap between the PES practices and on-hand opportunities from EbA to improve our knowledge on adaptation options. Finally, we discuss about expanding the classification of Water-PES projects, in an EbA approach, to enhance more efficient practices towards valuing ES.

The vulnerability of an ecosystem can be viewed in the changes in ecohydrological variables (**Figure 2.2**). The flood pulses across river cross-sections, floodplain and regime duration are seen in the quantitative percentile flows (or flow duration curve). Climatic extreme events increase the flow 5% of the time and decrease the outflow 95% of the observed time period, hence a higher (in the ordinate) and flatter (in the axis) duration curve is found (**Fig. 2-G**). Moreover, the higher water level (at the overflow height) can bring about a buffer effect of pollutants transported by the inadequate land-use.

An EbA approach could result firstly from the ecohydrological monitoring baseline of the Water-PES projects, which will allow assessing the maintenance of ecohydrological health of river systems. This proposal is flexible, applicable in other watersheds and offers a good cost-benefit relationship, besides being easily understood and desirable since the PES has been recognized as a measuring indicator for the EbA (BFN/GIZ, 2013).

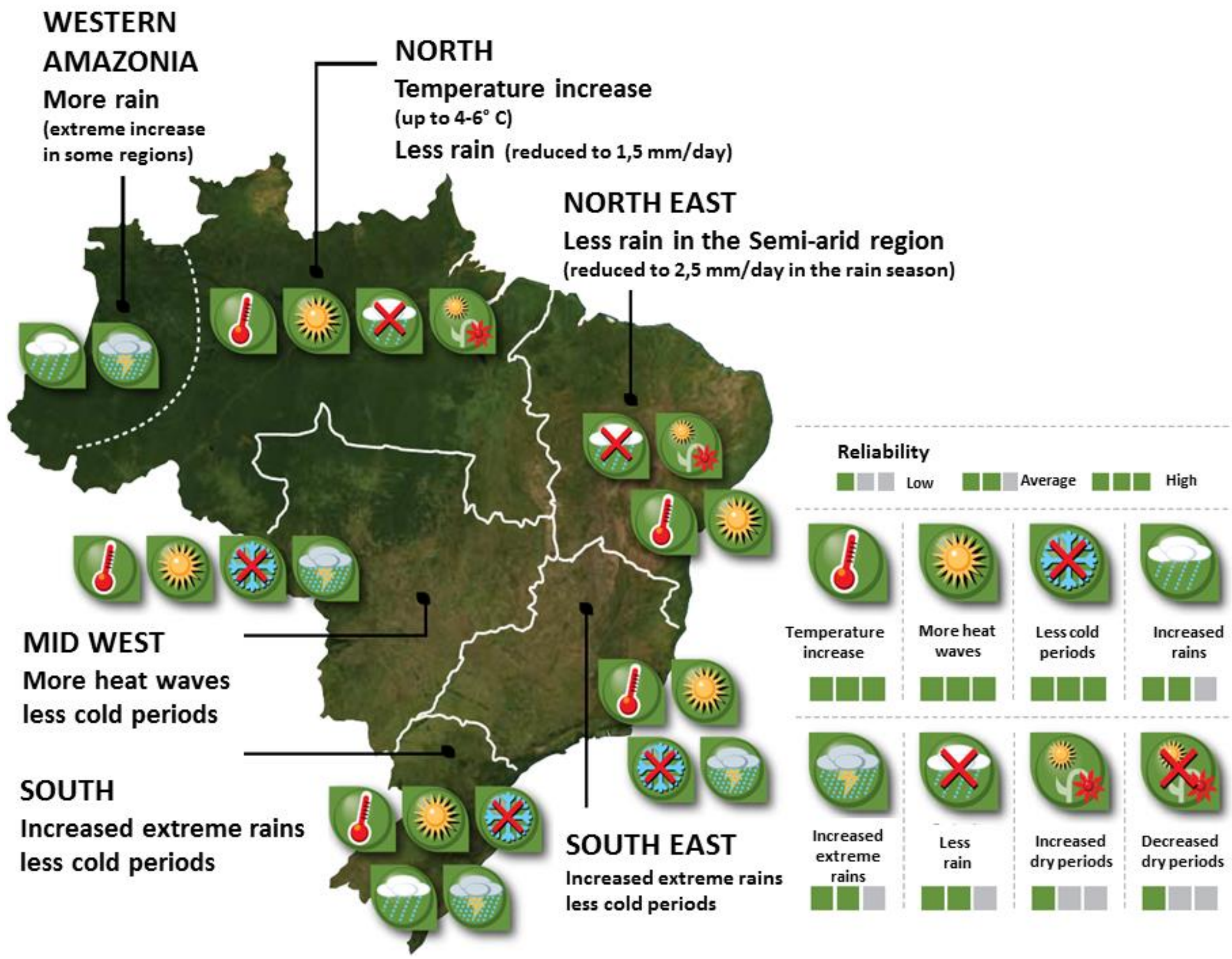

Figure 2.3. Brazilian regional scenaries of climate change projected by INPE climate models until the end of the twenty-first century. The symbols in the leaves (change indicators) are the same used in the IPCC AR5 (IPCC, 2014) and the degrees of reliability are evaluated according to the consistency between the projections of three regional INPE models and the IPCC AR5 global models.

2.4.1. Risk assessment and adaptation

The types of admissible risks in ES are manageable at the river basin scale have been discussed (Lin et al., 2013, Wunder, 2006). At least one previous study has emphasized the need for research incentives in the risk management area and adaptive management (AR-5 IPCC, 2014). Then, Naeem et al. (2015) found that of 118 USA-PES projects analyzed, most do not ensure scientific integrity in their environmental interventions, among other factors, because there are no metrics to assess the risks, as for instance, climate change. Aiming to fill part of this gap, we recommend that water risks of Water-PES projects be categorized in terms of vulnerability, impacts and adaptation strategies.

First, risk assessment is related to a specific combination of factors related to hazards, exposure and vulnerability, which can evolve to a disaster condition. Second, hazards are closely related to ecosystem variables at extreme behaviors across spatiotemporal scales where ecosystems develop their respective functions. These react to decision-making drivers and scenarios (MEA, 2005). However, the degree of susceptibility of the ecosystems to water hazards includes their characteristics with regard to vulnerability conditions, especially considering hydrological prediction in ungauged or poorly gauged basins.

Third, impacts are addressed in terms of comparing vulnerability characteristics with the support capacity of the environment to counterpart hazards (Montanari & Koutsoyiannis, 2014). The adaptation options are the types of non-structural or structural measures to help the ecosystem recover to the equilibrium conditions without the effects of risks (Palmer et al., 2009). This recovering capacity, included in the resilience concept (Baggio et al., 2015, Russell et al., 2012, Tanner et al., 2015), is scale-dependent and dependent on the type of risk condition (Mendiondo, 2010), which could be incorporated in the Water-PES projects in the long term (Mazzocato et al., 2013, Naeem et al., 2015, van de Sand, 2012, Wunder, 2006).

2.4.2. Water-PES initiatives & Ecohydrology

Linking ecohydrologic processes and human well-being is crucial in the ecosystem services framework (Brauman, 2015). To achieve better water quality by reducing eutrophication, some ecohydrological categories can be useful to address water challenges (Bunn & Arthington, 2002, Hannah et al., 2011, Vannote et al., 1980, Zalewski, 2015). All these categories are classified in accordance with principles of continuity, dynamics, resilience, vulnerability and diversity, which affect ecosystem interactions across the river basin scale (Richter et al., 1997). The delivery of hydrological services is measured (for example, measurement of flow, water quality variables or sediment levels) and/or simulated in ecohydrological models, such as SWAT (Bressiani et al., 2015; Francesconi et al., 2016), InVEST (Bremer et al., 2016, Guimarães, 2013, Tallis et al., 2011, 2012) or RIOS (Vogl et al., 2016). Besides, indirect methods to find this delivery can be quantifying water treatment costs to the end-users of hydrological services, as discussed by Osuna et al. (2014), or investigating the value of a protected park’s water contribution to end-user (Strobel et al., 2007). In any of these methodologies, assessments of ES through its quantification are needed. In this context, Water-PES projects would have to benefit of ecohydrology as a promising tool for includes metrics in interventions.

Table 2.3 shows that, with the exception of 1 initiative (Camboriu), there have not been ecohydrologic monitoring since before start of the interventions (to create the baseline). It is a challenge to build integrated monitoring guidelines which encompass actions before, during (to assess project performance and provide feedbacks) and after the end of Water-PES project actions.

Forward these guidelines, at least 4 ecohydrological categories are feasible to monitor in Water-PES projects, such as continuity, diversity, resilience and vulnerability (see Mendiondo, 2008, Table 5). Integrating hydrology and limnology in a holistic problem-solving strategy, ecohydrologic tools improve water quality for freshwater ecosystems and become easier watersheds restoration (Zalewski & Robarts, 2003).

In this context, both freshwater quality and quantity play a key role in network of provisioning and regulating ecosystem services interactions. Qualitative and quantitative freshwater monitoring should be performed in an integrated manner. From this perspective, we recommend the plan and accomplishment of freshwater monitoring in the long term. It is crucial to link the monitoring data to Water-PES project outcomes, revealing the quality and frequency of available data where benefits for ecosystem and landowners can be realized – this is scarce in Brazilian Atlantic Forest's Water-PES projects. If baseline and freshwater monitoring exist, the evaluation of project performance based on delivery of ES become easier. In turn, it provides reliability for ES buyer and allows comparison among Water-PES projects. Thus, a checklist of ecohydrological indicators, water quality variables and river morphology characteristics would help to delineate and classify the Water-PES projects. It is shown in **Table 2.4**.

In spite of the expansion of Water-PES projects in Atlantic Forest Brazil, they have not fully implemented hydrological monitoring (**Table 2.3**). Besides, there are inconsistencies or the absence of standards, definitions and methodologies for the hydrological monitoring in Water-PES projects. Nested Catchment Experiments (NCE), comparing freshwater monitoring from headwaters to downstream river (Mendiondo et al., 2007, Zaffani et al., 2015), are suitable to study Water-PES under flood pulse approach (**Fig. 2 A-C**). NCE are flexible in terms of river characterization (Rosgen, 1994), geomorphologic river networks (Rodrigues-Iturbe, 2000) and "the river active area" methodology (Smith et al., 2008). Pollution loads across nested scales show how ecosystem diversity is affected by human-driven occupation of the basin, and also nested scales can show the possible further effects of river restoration through Water-PES.

Table 2.4. Recommendations of the ecohydrological variables that should be measured and used to standardize, compare and select areas for new Water-PES projects.

Level of Applicability	Variables	References
Identification of the Project (Phase of Articulation)	**Biomatic features**: Annual precipitation Evapotranspiration Slope Temperature Order of the watershed Area of the watershed Class of soil uses	HORTON (1945) SANCHEZ-CANALES et al. (2012)
Comparison & Selection of PES Projects (Phase of Development)	**River Morphology**: Substrate of the river bed Longitudinal Slope Sinuosity Width/Depth-Relation of the river Floodplain Area/River Width-Relation	VANNOTE et al. (1980) ROSGEN (1994) SMITH et al. (2008) WILDHABER et al. (2014)
	River Water Quality: Polluting Load (COD, $BOD_{5,20}$), nitrate, total phosphorous, Residence Curve Thermotolerant coliforms	ZALEWSKI & ROBARTS (2003) MENDIONDO (2008) CUNHA et al. (2012) CUNHA et al. (2011) MACHADO et al. (2016)
	Ecohydrological indicators related to flood pulses and monitoring: Frequency: see X_3 (Fig. 2-B); Inundation time: see X_{10} (Fig. 2-C) Rating Curves: see X_{12} (Fig. 2-D), Changes in reference flows due to LULC or climate changes: see X_{16} (Fig. 2-F and Fig. 2-G; i.e., $\Delta Q_{5\%}$ and $\Delta Q_{95\%}$)	Adapted from: MENDIONDO (2008) SINGER et al. (2016) BRUDER et al. (2016) BENISTON & STOFFEL (2013)

Another opportunity could be implementing integrated load and flow duration curves (Cunha et al., 2012) for hydrological ES assessment. For example, (i) *in-situ* observations of water bodies could elucidate the role played by LULC at upstream catchments involved in PES (Taffarello et al., 2016a) and (ii) for the improvement of a semi-distributed model with experimental data. To date, we have observed a good relationship between phosphate and nitrate loads versus drainage area (0.66 to 925 km^2) and have demonstrated the actual need for ecohydrological monitoring to test the PES benefit assumptions and to improve scientific frameworks including tools, metrics and methods for Water-PES projects selection.

Monthly quality data are limited and the planning and execution of field campaigns are costly and time consuming in Brazil. Thus, ecohydrological models are necessary to construct the load duration curves. Regarding available data sources for applying ecohydrological models in Brazil, Bressiani et al. (2015), in a review on Brazilian SWAT applications, list an extensive array of data sources and include on-line locations for many of the data sources in an Appendix. Recently, SWAT has been used as a methodological framework for quantifying ES to support decision-making (see review of Francesconi et al. 2016). Besides SWAT, other agricultural watershed models can help in facing this challenge (Alvarenga et al., 2016, Cuartas et al., 2012, De Mello et al., 2016).

Using quality and quantity data for the same period of time, collected preferably at the same sites (or selecting as the nearest stations) enable ecosystem functions evaluation by applying qualitative and quantitative permanence curves. Future scenarios of climate and land-use changes can be evaluated by these curves, as shown schematically (**Fig. 2 F-G**).

Moreover, by using the grey water footprint (amount of freshwater required to assimilate pollutants) related to nitrogen and phosphorous inputs (Hoekstra & Chapagain, 2008, Hoekstra et al., 2011, Mekonnen et al., 2015), qualitative and quantitative permanence curves could be used to quantify the ES, which could be measured as the volume of freshwater needed to dilute the pollutant loads (Zhang et al., 2010), i.e., the water required for the self-depuration capacity of rivers. Concerning the needs for adaptation actions, we suggest evaluating the grey water footprint for nitrate, since nitrogen is one of the most mobile element. Both point and diffuse nitrogen source impacts on freshwater can be investigated with ecohydrological models. Then we could assess: (i) how polluting loads are produced under different land use in the current climate and in the future, and (ii) the impacts of best management practices (BMP), such as EbA (**Fig. 2.4**).

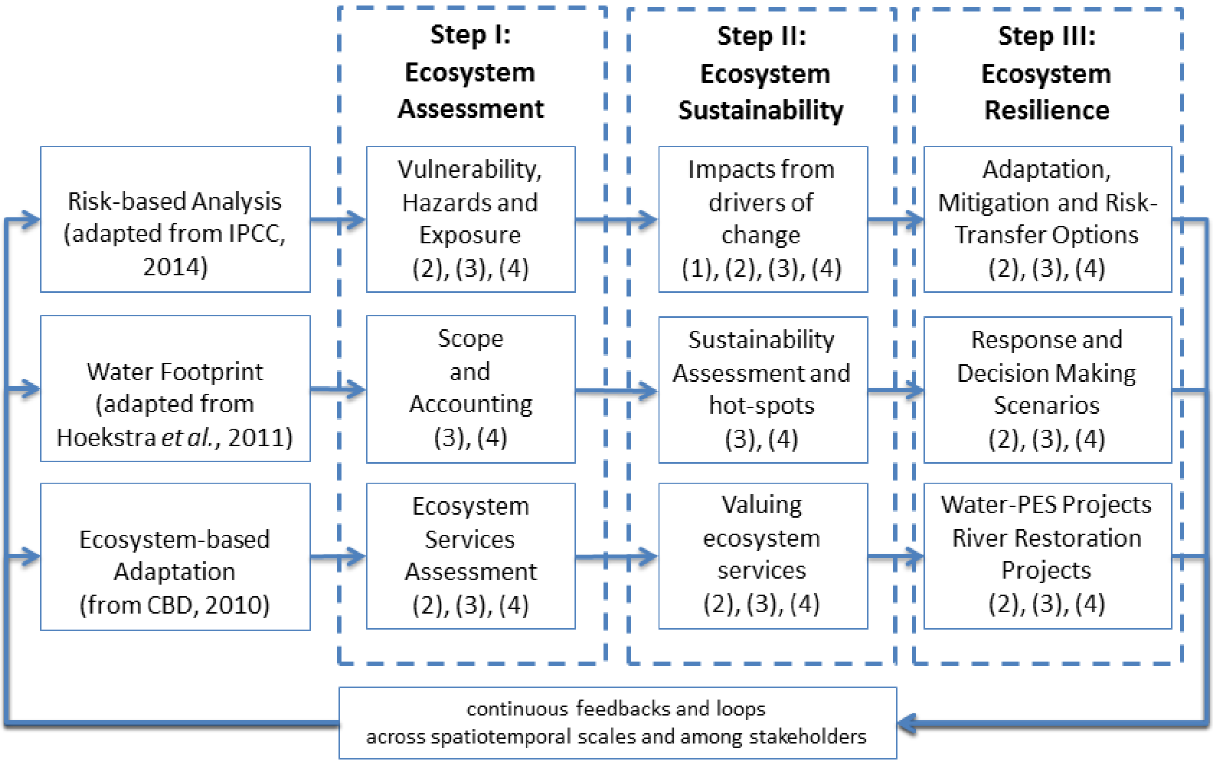

Figure 2.4 Illustrative interlinkages among methodologies of Ecosystem-based Adaptation, Risk-based Analysis, and Water Footprint. Legends (1): drivers of change: i.e. population growth, land-use and land-use change (LULC), climate change, consumption habits, institutional governance evolution, (2): ecohydrological monitoring, (3) field investigation and data mining, (4) modeling, calibration, validation and uncertainty analysis.

Based on Naeem et al. (2015), we propose that Water-PES projects should use ecohydrological variables (Fig. 2) for delineation, monitoring and comparison of Water-PES projects. This facilitates the access to public and private investments, which in turn will strengthen and enhance the EbA in Brazil.

In essence, the full efficiency of an EbA mechanism could be measured across the basin and compared to other initiatives in the same basin. Ultimately, Water-PES tradeoffs could be relatively different depending on the scale used to analyze and the variables incorporated in the assessment and valuation of hydrological ES. This comparison, through hierarchy metrics and analysis of the selected ecohydrological categories, enables to reflect on how the EbA methodologies, specifically Water-PES projects, can minimize the vulnerability to the impact of climate chang

2.5. Water-PES as ecosystem-based adaptation to climate change

Ecosystem-based Adaptation addresses the links between climate change, water cycle, biodiversity and sustainable resources management. Ecohydrological approaches, by preserving and enhancing ecosystems, allow to measure and evaluate these interactions. It is essential that EbA strategies contribute to the resilience of ecosystems (Fiering, 1982, Tanner et al., 2015,), protect livelihoods and mitigate poverty (Engel et al., 2008, Hallegatte et al., 2014, Pagiola et al., 2010).

Considering the EbA approach, Water-PES should be spatially implemented in river basins, preferably in heterogeneous landscapes, and with efficient technical support to the farmers. Studies show that carefully implementing these programs can bring significant water quality (Keeler et al., 2012) and biodiversity benefits (Whittingham, 2011). However, the potential of PES in climate change adaptation has been little realized (van de Sand et al., 2014).

Major risks and uncertainties surround the extent to which climate variability, climate change and other changes could modify the water cycle in relevant regions for the implementation of PES projects such as the EbA type. For example, changing rainfall, snow and ice melt patterns could affect how water transfers through soils and ecosystems and hence river flows and groundwater recharge. These changes present potential risks and benefits to society. Increased water security for developing countries occurs in integrated systems for ecosystem sustainability under climate change (Ambrizzi et al., 2007, Liu et al., 2015, Marengo et al., 2011). This means it is vital to ensure sufficient quality, quantity and distribution of water for productive use, ecosystems, through environmental flows (Arthington et al., 2006, 2010, Arthington, 2015), human health and to minimize water-related risks to people, environments and economies.

While there are many Water-PES programs in Brazilian Atlantic Forest (**Fig. 2.1**, **Table 2.1**), it is still hard to put a price on some other valuable hydrologic services provided by Amazonian forests, such as the recycling of atmospheric moisture and its transport to regions outside, such as the Atlantic Forest.

Key questions still should be solved to achieve ecosystem sustainability services. For example, should the states in central and southern Brazil pay the Amazonian states because the rain that falls in their fertile lands comes from the Amazon region?; How much does one cubic meter of water costs? And how much water moves from Amazonia to central-southern Brazil? One thing we know is that changes in forest coverage and the services offered by the forest may affect the moisture provision from Amazonia to central-southern Brazil. The provision of these services may be a determinant for vulnerability that is enhanced by climate change. Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ES provided, including moisture recycling.

2.6. Conclusions

Water-PES initiatives have rapidly expanded and advanced in the Atlantic Forest in Brazil. However, most of them still lack ecohydrological monitoring strategies, which would provide the baseline for the standardization, comparison and hierarchization of projects. We argue this is essential to validate implemented land management actions as generators of hydrological services and, consequently, to prove effectiveness of PES projects in providing hydrologic ES. Moreover, this approach could in turn increase public and private awareness and investments in Water-PES initiatives.

Concerning the multiple uses of water, the balance for maintaining the services that watersheds provide is only achieved through equitable water governance and ES management. We highlight that any adaptive management cannot be achieved without ecohydrological monitoring. Thus, integrated assessment and valuation of ES should use ecohydrology variables as tools.

Finally, ecohydrological monitoring is crucial to reduce EbA uncertainties, contribute to consolidate water resources information system, improve ecohydrological modelling and integrated water resources management. Future work remains to be done to link the hydrological services to dynamic and integrated assessment models to better understand how the complex processes of land use and climate changes affect the environment.

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CHAPTER 3

FRESHWATER MONITORING PLAN OF THE BRAZILIAN WATER PRODUCER/PCJ PROJECT*

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Abstract

Both Ecosystem-based Adaptation (EbA) and Payment for Ecosystem Services (PES) have a wide range of definitions that include many economic instruments for nature conservation. Although the generation and maintenance of payment for hydrologic ecosystem services (Water-PES) is expanding in Brazil, there are difficulties in the implementation of projects. Due to the complexity and non-linearity of the geomorphological processes, also affecting both EbA and Water-PES goals, monitoring quali-quantitative aspects of streams have been here addressed as a useful management tool. This study presents the Freshwater Monitoring Plan (FMP) of the Water Producer/PCJ project, operating since 2009, in order to: i) evaluate the impact of project actions under quali-quantitative aspects; and ii) promote the incorporation of FMP's elements in water resources management. FMP of the Water Producer/PCJ project has been implemented following the conditions for efficiency (baseline, long-term scale compatible with the actions of the project, in the experimental and reference watersheds). Spatial and temporally, FMP is being implemented from upstream to downstream in catchments with areas ranging from 17 to 130 km . This new proposal favors the quantification and valuation of hydrologic services that could be assessed by ecohydrologic monitoring (Chapter 4 of this Thesis) and modeling (Chapter 5 of this Thesis). Thus, we look forward to the consolidation of the Brazilian information system of water resources, the reduction of modeling uncertainties and integrated assessment of the consequences of land-use/land-cover change that strongly impact goals of EbA and Water-PES initiatives.

Keywords – freshwater monitoring; Brazilian Water Producer/PCJ project; hydrologic services; quali-quantitative aspects of water resources

3.1. Introduction

The hydrologic ecosystem services, hereafter referred as hydrologic services, are the ecohydrologic natural processes arising from river flow dynamics and flow/riparian areas interaction which benefit people. These processes can, for example, improve water quality, regulate flood risks, increase recreational opportunities and create positive socioeconomic effects. Hydrologic services are quantified by quali-quantitative river monitoring. The Active River Area assessment (Smith et al., 2008; Palmer et al., 2009) methods can also be applied in the monitoring, as it considers the hydrologic connectivity and natural variability of riparian areas from the headwaters downstream to the catchment's outlet. Several authors have proposed definitions of payments for ecosystem services (PES) for the water resources or biodiversity protection, and carbon sequestration. Costanza et al. (1997) define them as compensation for the benefits people obtain from ecosystems. They are considered voluntary transactions in which a determined ecosystem service is purchased from a provider under the condition of securing the service provision (Wunder, 2006). Pagiola & Platais (2007) added generating positive externalities to this concept. Balvanera et al. (2012) define them as the availability (or utility) of ecosystems for human needs. Furthermore, Muradian & Rival (2012) relate PES with policy prospects and partnerships to align decision-making on land use. The definition of PES is sufficiently broad to encompass various economic instruments for environmental conservation (Pagiola, von Glehn & Taffarello, 2013). On the one hand, ecohydrological processes (i.e. Zalewski, 2010; Mendiondo, 2008, among other authors) interact nonlinearly. These processes affect biodiversity and primary production, and define the river regime, environmental flows and hydrologic ecosystem services (Taffarello & Mendiondo, 2013). Specifically for Water-PES, the potential provision of these services depends on the water-balance equilibrium of flows and pollution loads (Cunha, Calijuri & Mendiondo, 2012). On the other hand, Water-PES are dependant on the relationship between availability and demand, variable according to both (i) natural fluctuations or induced by the impacts of human activities, and (ii) functional and distribution conditions of the ecosystems in the watersheds. In this interaction, the "water + climate" composition is the main sustainability element for water security. Moreover, the insignificant water uses defined by river basin committee based on Brazilian and Sao Paulo state water resources laws (n. 9433/1997 and n. 7663/1991, respectively) add a recognized stress on water security. The "insignificant uses" demand a detailed study on water withdrawal and wastewater disposal of small rural properties to ensure seasonal safe drinking water in these critical subbasins, strategic for public supply and for ecosystem services delivery. The objective of the Water

Producer/PCJ project freshwater monitoring is to evaluate the PES economic instrument to stimulate the use of voluntary conservation practices for soil conservation, forest restoration in Permanent Preservation Areas (APP), and conservation of remaining forest fragments. It is a pioneering pilot project in Sao Paulo state which includes public-private partnerships (Mazzocato, Taffarello & Mendiondo, 2013), with the aim of providing support for larger scale projects (Padovezi et al., 2013). The objectives of the FMP of Water-PES projects are:

- Characterize the natural freshwater quality of the catchments covered by the project to consolidate the respective PCJ/ River Basin Plan.

- Determine the baseline of the project based on land-use/land-cover information, questionnaires with information on environmental and socioeconomic perception;

- Assess trends and hydrologic conditions, concentrations of monitored pollutants and the expected limits for the re-systematization of water bodies;

- Identify areas with potential water quality changes;

- Promote mitigating actions for the prevention and control of soil and water pollution;

- Assess the effectiveness of project actions and long-term adaptation strategies;

- Provide consistent information to assess the maintenance and future expansion of the project or its replication in other Brazilian regions through new PES public policies;

- Encourage the creation and maintenance of real-time monitoring database, which are able to issue environmental alerts, reducing the vulnerability[2] of the watersheds and productive sectors inserted there.

3.2. Scope of this work

Thus, the objectives of this work are: (i) assess the impact of conservation actions in the Water Producer/PCJ project through the freshwater monitoring plan (FMP) with key integration to EbA and Water-PES projecs; and (ii) support the incorporation of FMP elements through water resources management tools, such as: information systems, river basin plan, freshwater quality standards, water rights concessions and charging for water resources uses according to the current norms (Brazilian Water Law 9.433/97, Sao Paulo State Water Law No.7.663/91, No12.183/05 and Decree 50.667/06).

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[2]Vulnerability is the state of a system exposed to risks, controlled by biophysical and socio-cultural factors at different temporal and spatial scales, combined with its responsiveness (INCLINE/USP, 2013).

3.3. Material and Methods

3.3.1. Study area

The study area includes watersheds that contribute to the Piracicaba, Capivari and Jundiaí (PCJ) river basins, covering 15.304 km^2. In the Sao Paulo portion of the PCJ river basin, the Water Resources Management Unit No. 5 (UGRHI-5) has 14.178 km^2 (92.6% of the basin area), and the rest of the UGRHI-5 territory of the PCJ basins (7.4%) is located in Minas Gerais state. The PCJ basins have higher economic development and per capita income in Brazil. However, due to the high population density (301 hab/km^2) compared to other Brazilian river basins, the use of this water is conflicting and eutrophication of the water sources is at an advanced stage (Cobrape, 2011). Because of it, in the last decade, the headwaters of the sub-basin of the Atibainha and Jaguari rivers become of strategic interest. The implementation of charging for the use of water resources in the PCJ Committees in 2007 allowed that part of the funds of water charging could be applied in the Water Producer/PCJ project. In mid-2013 the project area covered 252 hectares in Joanópolis/Nazaré Paulista cities, state of Sao Paulo. After three years of contracts between landowners and the financial borrower from PCJ Committees (2011-2014), the project area was 489 hectares, being 99 hectares of soil conservation, 68 hectares of forest restoration and the major part of forest conservation, i. e., 391 hectares (Taffarello et al., submitted).On account of the prior information and the scarcity of native vegetation, the catchments being part of the FMP are previously selected: Cancã (97 km^2) and Cachoeira dos Pretos (130.4 km^2), in Joanópolis, and Moinho (17.6 km^2) in Nazaré Paulista (**Figure 3.1**).

3.3.2. Methods

Regarding the self-purification[3] process of rivers and streams, freshwater monitoring is critical for understanding the changes of pollutant concentrations in different seasons (Bottino, 2008; Mendiondo, 2008). To assess self-purification characteristics, quali-quantitative parameters were included into the FMP of the headwaters of the main tributary rivers to Sistema Cantareira: Jaguari (1.000 km^2), Cachoeira (392 km^2) and Atibainha (315 km^2) to find possible seasonal changes of pollutants or macronutrients (see **Table 3.1**).

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[3]Self-purification is the restoration of the water quality after the changes induced by the discharge of effluents. The main parameters changed due to self-purification are the dissolved oxygen concentrations, biochemical oxygen demand (BOD) and pathogenic microorganisms, river contaminants (von Sperling, 2005).

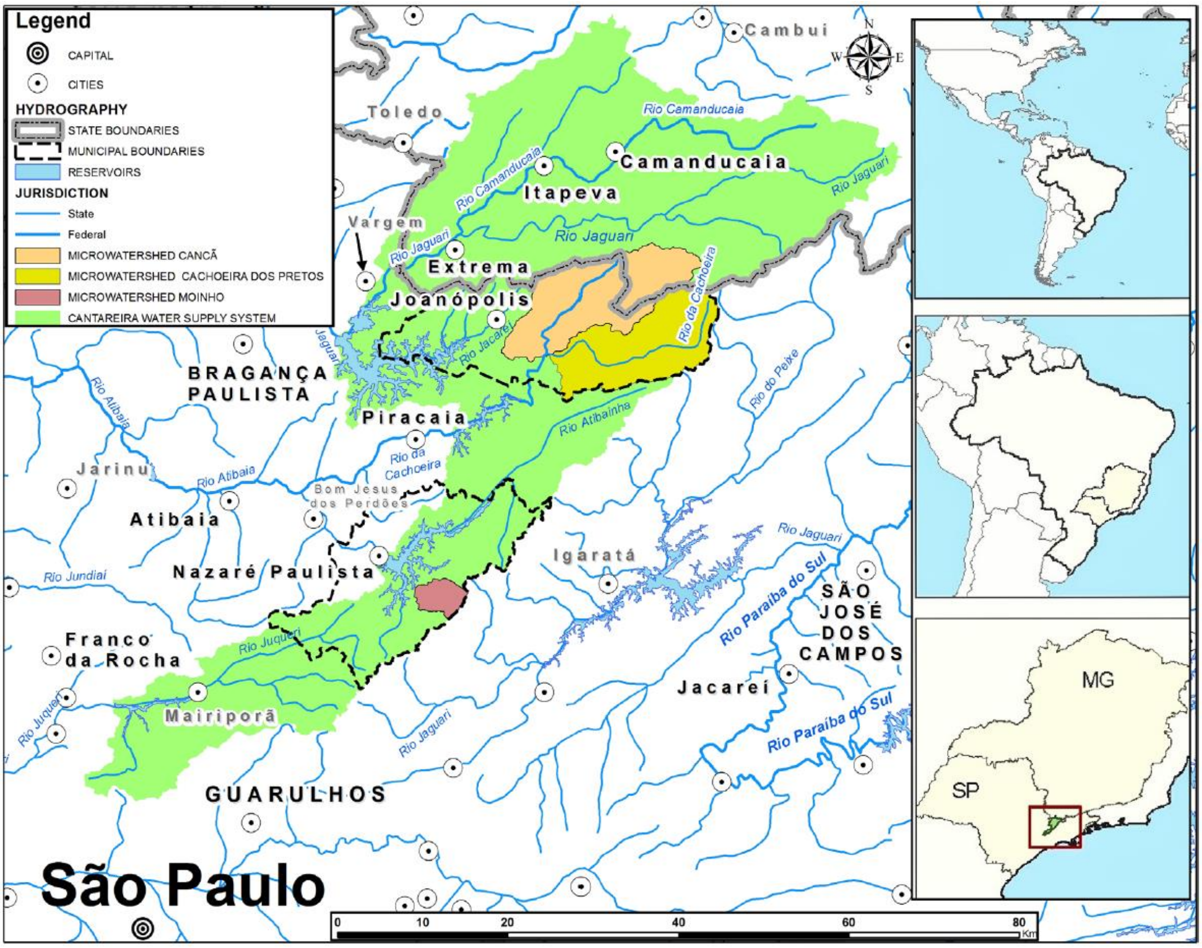

Figure 3.1. Catchments of the Water Producer/PCJ pilot project.

Land-use/land-cover (LULC) change impact ecosystems and the services they provide in diverse scales. Regarding hydrologic services, LULC change is one of the most significant anthropogenic pressures which change water flows and modify regulating hydrological services (Brauman, 2015; Rounsevell et al., 2012; Daily et al., 1997). In addition, slope, topography, soil development and soil depth are also terrestrial characteristics of the watersheds which impact hydrologic services, as we have shown in **Figures 1.1** and **2.1** (Chapters 1 and 2, respectively of this thesis) and were reported by Koschke et al. (2014), Terrado et al. (2013), among others.

The land-use/land-cover (LULC) changes of microcatchments contributing to public drinking supply are crucial for the production of water in adequate quantities and quality conditions (Whately & Cunha, 2007). Also, these changes lead to risks of potential water crisis with impacts on vulnerable ecosystems and people (Tundisi & Tundisi, 2015; Gordon et al., 2008).

Table 3.1. Surface FPM methods with key variables for ecohydrological assessments of EbA and Water-PES projects. Source: adapted from Rice et al. (2012).

Method	Key variable	Method	Unit
Systematic monitoring	pH	40500 H^+-B- Electrometric method	--
	Electrical conductivity	2510 B- Laboratory method	$\mu mho.cm^{-1}$
	Turbidity	2130 B	NTU
	Water Temperature	2550 B- Field and laboratory method	º C
	Water level	Limnimetric scale	m
	Air temperature	--	º C
	Relative humidity	Vapor pressure - temperature relationship	% (Pa/Pa)
	Precipitation	Volumetric	mm
	Radiation	Net radiation	W
Episodic Monitoring (seasonal campaigns)	Flow rate	Bathymetry and propeller; ADCP-Doppler	$m^3.s^{-1}$
	Dissolved Oxygen (DO)	4500 OG – Electrode with membrane	$mgO_2.L^{-1}$
	Chemical Oxygen Demand (COD)	5220 D – Colorimetric closed reflection method	$mgO_2.L^{-1}$
	Biochemical Oxygen Demand (BOD)	5210 B – BOD test 5 days	$mgO_2.L^{-1}$
	Total Dissolved Solids (TDS)	2540 C - Porcelain capsule	$mg.L^{-1}$
	Total Suspended Solids (TSS)	2540 D - Membrane	$mg.L^{-1}$
	Total Nitrogen	4500 NB- Macro Kjeldahl	$mg.L^{-1}$
	Nitrate (NO_3)	4500 NO_3^--B – Spectrophotometric method	$mg.L^{-1}$
	Nitrite (NO_2)	4500 NO_2^--B – Colorimetric method	$mg.L^{-1}$
	Nitrogen Ammonia (NH_3)	4500 NH_3-C Titration method	$mg.L^{-1}$
	Total phosphorus	4500 P-E- Ascorbic acid	$mg.L^{-1}$
	Escherichia coli	9223 B – Enzyme-substrate test	$CFU/100mL^{-1}$

To verify how anthropic activities for one hand and Water-PES actions, on the other hand, can further influence environmental quality, FMP investigates the past conditions (year 2003) and near current conditions (year 2010) of LULC (**Figure 3.2**). This diagnosis helps understanding the current environmental quality of catchments for prospective EbA initiatives using this FMP. Also, FMP improves the monitoring of Water Producer/PCJ project, as auxiliary tool in planning and selecting quali-quantitative sampling sites under LULC change, regarding water yield, seasonal flow-with-load regimes and ecohydrological variables (see **Figure 2.1** of the thesis). After 6 GTM-Hydro meetings and several studies, we conclude that specific conditions are crucial for effectivity of the freshwater monitoring. See **3.4.1** Section.

Comparing LULC in years 2003 and 2010, regarding soil uses, **Figure 3.2** shows that the anthropic use is higher in Cancã catchment (66%) than in Moinho (around 50%) and Cachoeira do Pretos catchments (49% in 2003 and 38% in 2010). There is a trend to reduce agriculture areas in Cancã and Cachoeira dos Pretos catchments, which is not observed in Moinho catchment. Both in Cancã and in Cachoeira dos Pretos catchments part of agriculture has been replaced by reforestation. This issue is relevant for the recovery of ecosystem since both catchments are located in Cachoeira basin. Joanópolis municipality, where larger part of Cachoeira basin is located, has 80% of its protected area occupied by pasture, agriculture, and bare soil (Whately & Cunha, 2007). Then, current consumptive water use and intensive agriculture impact the blue and the green water availability in the Cachoeira basin (Rodrigues et al., 2014).

Although the Water Producer/PCJ project started in 2009, FMP is at an early implementation stage, which enhanced since 2013 onwards (see Taffarello et al., 2016). We believe that this FPM enables posing questions such as: Do Water-PES' actions of the Water Producer/PCJ project improve and conserve the water quality and water flow regulation in the headwaters under LULC changes of the Cantareira Water Supply System? To address answers through EbA methods, ecohydrologic experiments and modeling are needed. Using field campaigns (episodic monitoring) and official database (systematic monitoring) from agencies engaged in FMP at PCJ committees, i.e. CETESB, DAEE, SABESP, INMET, ANA, CODEAGRO, CEMADEN, human impacts on quali-quantitative freshwater regimes are verified (Taffarello et al., 2013a; Cunha, Calijuri & Mendiondo, 2012). Furthermore, possible positive impacts of Water-PES project's conservation actions are viable to screen explicitly through FMP. Further details about field evidences of episodic FMP and about ecohydrologic modeling with EbA scenarios are, respectively, in Chapter 4 and Chapter 5 of this thesis.

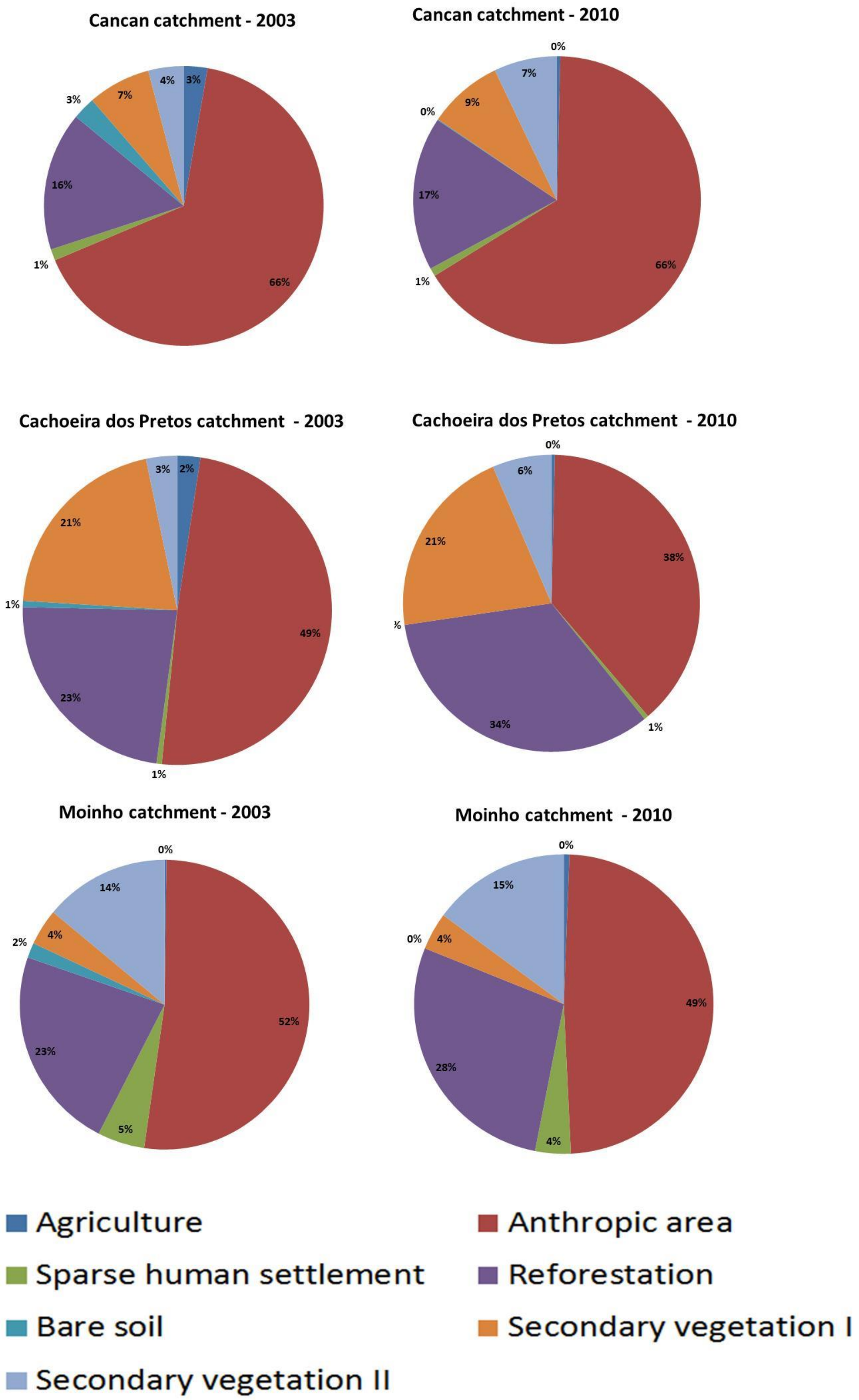

Figure 3.2. Past (2003) and near present (2010) soil cover in catchments located in headwaters of Cantareira Water Supply System, which drainage areas are involved in Water Producer/PCJ project (lines 1 and 2: Joanópolis- Sao Paulo state; line 3: NazaréPaulista-Sao Paulo state). Secondary vegetation I: old forests, with at least 30 years. Secondary vegetation II: forests with age below 30 years. Anthropic area encompasses pasture. Data source: Socioambiental Institute [ISA] (2003) and (2011).

3.4. Results and Discussion

From the EbA approach, the Integrated Group of River Basins (*Núcleo Integrado de Bacias Hidrográficas*, NIBH) of the Sao Carlos School of Engineering, University of Sao Paulo with support from The Nature Conservancy (TNC), drafted a FMP proposal for Water Producer/PCJ project based on the document "Water and Soil Monitoring Protocol – Water Producer Program" (Diederichsen et al., in press). This FMP is in accordance with the National Plan for Water Quality (PNQA) of Brazilian National Water Agency (ANA), and with part of the hydrological monitoring in Water Funds' case studies in Latin America, organized by Bremer, Vogl, de Bièvre & Petry (2016). The FMP was presented to Water Producer/PCJ project's partners in a Workshop held in May 2013 in Atibaia municipality, Sao Paulo state. Also, we fully presented a version of this FMP plan at the XX Brazilian Simposium of Water Resources, held 2013 in Bento Gonçalves, Rio Grande do Sul state (Taffarello et al., 2013b).

Metrics and indicators for evaluating PES effectivity are essential. Regarding the Water Producer/PCJ project, the HMP, especially **Figure 3.2**, seeks to help assessing the Water-PES implementation. Examples of these metrics or indicators can be: 1) PES project area/watershed area; 2) benefited population[4]/total watershed population; 3) applied financial resources related to benefits generated (lower water treatment costs and higher water yield, for example). Thus, this HMP can help obtaining short- and long-term Water-PES project performance, a scientific guideline for PES according to Naeem et al. (2015).

Then, to apply the quali-quantitative monitoring plan, which can further allow the assessment of PES implementation, some requirements are needed to monitoring sites selection. The first monitoring sites were determined based on scale compatible with Water-PES actions, aspects related to LULC changes and comparing EbA-reference catchments to catchments targeted of conservation actions of Water-PES in the scope of Water Producer/PCJ project (**Figure 3.3** and **Table 3.2**). Local LULC change allowed elucidating the complexity of soil uses verified from field *in loco* diagnosis of water yield at these headwaters. Field evidences showed LULC was as relevant on watersheds as used for public supply, because local modifications impacted water quantity and quality. Freshwater quality was jeopardizing because of agrochemicals used in conventional agriculture, and erosion

[4]Benefited population, also called PES beneficiaries, here means the number of inhabitants living in 1) the PES project areas, 2) downstream the PES project area, and/or 3) regions with flow transfers from PES project areas.

process due to urbanization. Also, urbanization and economic activities were performed at unappropriated areas, without planning, damaging water yield (as pointed by Whately & Cunha, 2007).

We found erosion field evidences in these subtropical Oxisols during *in loco* visits were expressive as previously related by Pereira & Teixeira Filho (2009) and PCJ (2011). Mendiondo et al. (2007) also related field evidences of surface flow water pathways related to erosion patterns in catchment laying on Oxisols with erosion rates of ca. 1 t/ha per year and variable concentration of suspended solids. This evaluation justifies the FPM monitoring of water flows and erosion on the watershed scale. In mid-2013, the monitoring includes two Data Collection Platforms (DCP), four fluviometric scales and two barologgers. Barometric readings are synchronized with the level readings. The equipment purchase, installation and maintenance are the responsibility of ANA, TNC, WWF and EESC/USP. The location of equipments installation was determined by the Hydrologic Monitoring Working Group (GTM-Hydro) of the Water Producer/PCJ project, shown in **Table 3.2** and **Figure 3.4**.

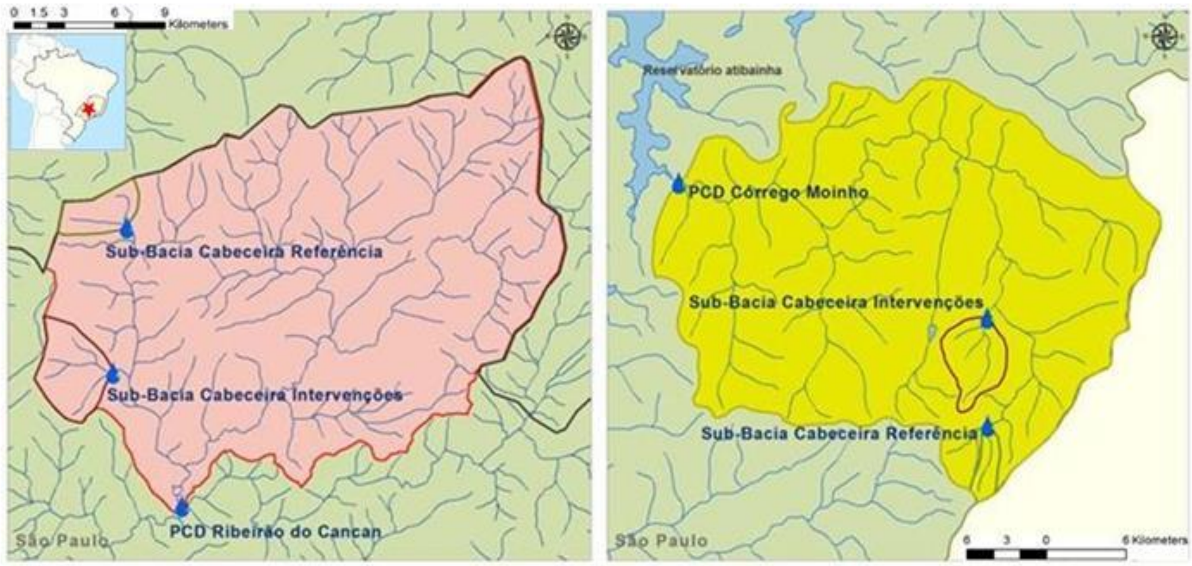

Figure 3.3. Selected Water-PES sites for the FMP of the Water Producer/ PCJ project. Left side: monitoring sites in the Cancã catchment, Joanópolis municipality, Sao Paulo state. Right side: monitoring sites in the Moinho catchment, Nazaré Paulista city, Sao Paulo state.

Table 3.2. Location of dataloggers installed in catchments of the Water Producer/PCJ project.

Freshwater monitoring sites	Location	Geographical Coordinates	Drainage area (km^2)	Monitoring
Sub-basin of intervention in the Cancã catchment	B. S. Silveira farm, Joanópolis, SP	46W 13' 29" , 22S 54' 42"	2.01	Water level sensor
Sub-basin of reference in the Cancã catchment	D. R. Queiroz farm, Joanópolis, SP	46W 13' 18" , 22S 53' 11"	1.26	Water level sensor
Cancã outlet	F30 site of SABESP Joanópolis, SP	46W 12' 42" , 22S 56' 06"	97.00	DCP (water level, pressure and temperature)
Sub-basin of intervention in the Moinho catchment	B. da Silva farm, Nazaré Paulista, SP	46W 19' 29" , 23S 13' 19"	3.10	Water level sensor
Sub-basin of reference in the Moinho catchment	R. Santalúciafarm, Nazaré Paulista, SP	46W 19' 29" , 23S 13' 58"	0.66	Water level sensor
Moinho outlet	property of SABESP, Nazaré Paulista, SP	46W 21' 33" , 23S 12' 29"	16.9	DCP (water level, pressure and temperature)

Figure 3.4. Selected locations for the freshwater monitoring of the Water Producer/PCJ project. Upper left photo: sampling in the Cancã reference catchment; Lower left photo: place selected for the limnimetric scale installation in Cachoeira dos Pretos catchment; Right side photo: Cancã outlet. Photo: Denise Taffarello, October 2013.

3.4.1. Effective Monitoring Conditions

a – Baseline conditions

Monitoring should be implemented preferably before start of LULC interventions. This is necessary to identify the baseline and to serve as a temporal analysis reference. The baseline can identify possible positive changes as a result of the expansion of ecosystem services promoted by the project, as well as ecohydrologic variables related, thereby encompassing the integration of quali-quantitative variables.

b - Long-term monitoring

The PES pilot projects should necessarily have long-term monitoring. Regarding both quali-quantitative aspects, “long-term” is understood as a horizon span ranging between 30 and 50 years, to consolidate legal and socio-economic elements as well as LULC change. An operational framework is required to document the changes for the regular storing and analysis of the field data collection.

c - Scale compatibility with project actions

It is crucial to have a significant geographic scope, integrating PES interventions at local scales, which will promote the maintenance and recovery of native soil vegetation in the river basin scale, because it is assumed that the monitoring data obtained will reflect the expected benefits from the actions through EbA. However, it is not easy to implement forest restoration and soil conservation activities in a significant portion of the basin and within a short period of time.

Thus, it is recommended to implement the monitoring structure in the catchment scales scale, when there is a sufficient range of land use changes, to enable perceiving in the short term the impacts on water quality and flow regime.

d – Reference and intervention catchments

The improvement and maintenance of the water quality conditions and hydrologic regime will be included in the monitoring of catchments where the forest cover has changed significantly, named as “intervention” catchment. A property located in the same catchment was selected (which has the same physiographic, climatic and environmental characteristics), but with no significant change in the original vegetation cover (minimum of 80% of native vegetation cover), named as “reference” catchment

3.4.2. Types of monitoring

Spatial monitoring (nested catchment experiment)

For the experimental catchments, monitoring quali-quantitative control sites of water yield is selected through Nested Catchment Experiment method (NCE, McDonnell et al., 2007; Mendiondo et al., 2007), as follows. Headwater reference catchments of 1st or 2nd order, with no forest restoration and soil conservation interventions are compared to headwater catchments with project interventions. Both inside the same basin of 3rd order.

Temporal monitoring

The variables have to be collected (i) systematically (quantitative), with time interval as a fraction of the observed time of concentrations, ie., the average response time of a rainfall-runoff process (Tucci, 1993; Tucci, 2008); and (ii) episodic (qualitative) based on seasonal campaigns (Bieroza et al., 2014; Abell, Hamilton & Rutherford, 2013; Chiwa et al., 2010). Specifically, in the Water Producer/PCJ project freshwater monitoring, we set uped the time-step of continuous monitoring variables of water level, pressure and temperature each 15 minutes. The seasonal field campaigns have choosen to be bimonthly, to investigate the seasonal dynamics of river regimes, as explained in **Figure 2.1** (Chapter 2 of this thesis).

We also suggest using flow-load duration curves in the monitoring of the Water Producer/PCJ project, to describe the pollution loads according to flow rates, facilitating to visualize the quali-quantitative natural behavior of freshwater resources (Chen et al., 2011; Cunha et al., 2012; Taffarello et al., 2013a). Flow and load duration curves demonstrate changes in land use or climate in the watersheds (Taffarello & Mendiondo, 2013). Studying flow-load duration curves under different scenarios, for example, including EbA or different rates of wastewater treatment, allows evaluating hydrologic services provided by Water-PES, addressing a more effective and reliable water security.

3.5. Conclusions & Recommendations

Regarding the Water Producer/PCJ project, the following actions can be envisaged with the freshwater monitoring here proposed: 1) complement the water resources information system in the PCJ Watersheds Committee; 2) Incorporate the information system in ANA's database (PNQA), CETESB and DAEE; 3) Estimate the detailed water balance in experimental watersheds; 4) Anticipate the frequency curves of flow and loads; 5) Assess water availability for water use permission; 6) Anticipate the balance of pollutant loads and the re-categorizing of water bodies; 7) Estimate the green, blue and gray water flows, and their water footprint (according to Hoekstra et al., 2011); 8) Identify and prioritize low-sustainability critical areas by comparing availabilities and demands within the PCJ watersheds; 9) Improve the information quality of user registration; 10) Support adaptation strategies for potential climate changes and mitigation measures for the medium and long term; 11) Identify possible changes in the quality and quantity of water resources resulting from the conservation actions of the Water Producer/PCJ project; 12) Strengthen institutional arrangements in PES projects undertaken in the River Basin Committee.

Our study consists of a new freshwater monitoring proposal with variables that can be quantified in the flow and load duration curves. Advancing the monitoring of Water-PES projects contributes toward consolidating the Brazilian information system on water resources, improving hydrologic models and updating the integrated environmental assessment. Besides, the hydrological monitoring here proposed can help obtaining short- and, if continuously applyied, long-term evidence of Water-PES project performance. Estimate project or program performance is a scientific guideline for Water-PES, linked to ecological sustainability principle for ensures project durability, according to Naeem et al. (2015). As a result, the real sustainability of ecosystem services can be better assessed and valued in the long term.

3.6. Acknowledgments

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CHAPTER 4

FIELD INVESTIGATIONS OF THE 2013-14 DROUGHT THROUGH QUALI-QUANTITATIVE FRESHWATER MONITORING AT THE HEADWATERS OF THE CANTAREIRA SYSTEM, BRAZIL*

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ABSTRACT

Integrating seasonal patterns of water availability and land-use/land-cover change is crucial in watershed planning. Often, these are not considered under hydrological extremes affecting decision making. This article presents results from a multi-site, nested catchment experiment carried out during a dry period in the Cantareira Water Supply System, South-East Brazil, linking quali-quantitative freshwater monitoring to land-use/land-cover change. Results from 17 catchments show regional behaviour for nitrate loads and drainage areas (0.66-925 km^2). An inverse correlation between forest cover and water yield was observed. Despite forest growth in spatial extent, nutrient loads showed potential hazards for water security.

Key words: Water availability, Freshwater monitoring, Drought, Land-use/land-cover change, Brazil

4.1 Introduction

Rivers provide goods and services linked to the flow dynamics and the interaction between flow and landscape. These sustain the integrity of the ecosystems. However, land-use changes such as urbanization, industrial development, deforestation and intensive agriculture with rapid population growth and climate change threaten the supply of safe drinking water and ecological integrity. These changes lead to risks of potential water crisis with impacts on vulnerable ecosystems and people (Tundisi & Tundisi, 2015; Gordon et al., 2008).

The International Hydrological Programme of UNESCO defined water security as the "capacity to guarantee drinking water access in acceptable conditions of quality and quantity, for sustaining human and ecosystem health" (UNESCO, 2012). Therefore, water security is an interdisciplinary and multidimensional concept to assess the tolerable level of water-related risks to society (Bakker, 2012). Water security encompasses a variety of multipurpose water resources (Pahl-Wostl, 2015; Sivapalan et al., 2014), for both consumptive and nonconsumptive uses, which affect sustainability (Vörösmarty et al., 2010) and water allocation (Hellegers & Leflaive, 2015; Hoekstra, 2013).

Water scarcity can impact these basic aspects of water security. Integrating quantitative, qualitative and seasonal aspects of water security is a crucial topic in river basin planning, especially concerning strategic water supply basins. For example, in Brazil the decreasing freshwater volumes in rivers, as well as increased water temperatures and elevated concentrations of nutrients, have caused frequent cyanobacteria blooms (Tundisi & Tundisi, 2015). In watersheds with marked land-use/land-cover (LULC) change, field monitoring of both the quantity and quality of freshwater also under drought conditions is an important input for decision making.

In large countries like Brazil, those uncertainties resulting from water monitoring are inherent to the biome diversity and territorial extension. For example, the Brazilian Policy on Water Resources (Law Nº. 9433; Brazil, 1997) determined water security by integrating river water quantity with quality and the decentralization of water resources management (Porto & Porto, 2002). The objectives of the Brazilian water law are to: (i) assess the evolution of water quality; (ii) identify critical areas of pollution; and (iii) assess the effectiveness of water resources management. However, there are still large gaps in the water quality, quantity and seasonal monitoring in Brazil related to ecosystem services (Libanio, 2015; Pagiola, von Glehn & Taffarello, 2013), especially under climate extremes (Nobre et al., 2016; Marengo et al., 2015; De Araújo et al. 2004).

4.1.2 Water Supply Programmes and Environmental Conservation

Water yield has been affected by land-use and climate changes, which in turn has strained the conservation or restoration of water resources management (Palmer & Filoso, 2009; Arthington et al., 2006). Conservation mechanisms have been recently implemented in Brazil. There are at least 20 Payment for Ecosystem Services (PES) programs in operation in Brazil (Richards et al., 2015; Pagiola, von Glehn, & Taffarello, 2013), most of them focusing on hydrological services, e.g., improving water quality (by filtering pollutants and/or reducing sediments) and regulating flow discharge, in the Atlantic Forest biome.

The watersheds in the Atlantic Forest are a rich source of available water in Brazil. This biome has an estimated 8000 endemic plants species and over 650 endemic vertebrates (Mittermeier et al., 2004) across 1.43 million km^2 (Buckley & Pegas, 2014). The headwaters of these watersheds supply the drinking water to more than a half of the Brazil's population - 122 million people (Rodrigues, Brancalion, & Isernhagen, 2009) - and produce 62% of Brazilian electricity (Joly, Metzger, & Tabarelli, 2014). The Brazilian Atlantic Forest has been protected by law since 2006, but less than 7% of its original coverage remains, which, added to secondary forests and fragments of less than 100 ha, results in 11.4% - 16% of cover (Ribeiro, Metzger, Martensen, Ponzoni & Hirota, 2009). The fragmentation has led to some regions of this forest's biodiversity being very threatened. One of them is the part of the Mantiqueira Mountains where the Cantareira Water Supply System (hereafter referred as the Cantareira System), the area of our study, is located. Despite the legal protection, more than 73% of protected areas in the Cantareira System are under anthropic occupations (Whately & Cunha, 2007). Social and economic conflicts have arisen among the different water users. Conservation programmes are necessary not only for water and biodiversity (Joly et al., 2014), but are also for the restoration of this unique biome (Rodrigues et al., 2009; Banks-Leite et al., 2014).

A pioneering Brazilian example of payment for watershed services is the Water Producer/PCJ (*Produtor de Água/Piracicaba, Capivari and Jundiaí*) project. This PES project has been encouraging forest restoration and conservation, as well as soil conservation, in rural private properties since 2009. As of mid-2015, 320 ha of forests was conserved, 68 ha of protected areas was restored and 100 ha of soils was conserved through more than 40 contracts signed in the Cancan and Moinho watersheds, representing 5% of the total basin areas. The resources for the PES are provided by charges for the use of water resources (Taffarello, Calijuri, Viani, Marengo, & Mendiondo, 2015), instead of fees (since the charge for water use in Brazil is set as a public price). This procedure reflects the direct application of the ‘user-pays principle’ and the ‘provider-recipient concept’ and its negative and positive externalities, respectively.

The Water Producer/PCJ project began hydrological monitoring in 2013 through a partnership with nongovernmental organizations (NGOs), governmental secretaries and universities. This monitoring will potentially attract new investments on account of greater confidence in the project (Naeem et al., 2015). But some water security questions related to the Water Producer PCJ project still remain, such as: (1) are the actions of PES programmes enough to improve and maintain water quality in critical headwaters?; and (2) how could discharge measurements in the field help optimize novel monitoring & early-warning hydrologic cycle strategies?

4.1.3 The 2013-14 drought in South-East Brazil

Water security is intrinsically related to the adaptive capacity of a society with respect to water extremes, especially in anticipating periods of water scarcity and droughts. However, drought prediction models are still highly conditioned to the inherent uncertainty of observed variables and methods of estimation (Underwood, 2015). In addition, non-stationary conditions of existing temperature and rainfall records incorporate new challenges to water systems under risks (Borgomeo et al., 2014).

Trends in South American total rainfall and rainfall extremes and links with sea surface temperature were assessed for the period 1960-2000 by Haylock et al. (2006). Likewise, the IPCC AR5 WG2 (Magrin et al., 2014) showed that South America is vulnerable to climate change. Phillips et al. (2009) reported the loss of above-ground biomass carbon as a relevant impact of the severe 2005 drought that occurred in the Amazon forest. Changes in the frequency, intensity, spatial extent or duration of weather and climate extremes can result in extremes of river regimes (De Araújo et al., 2004). Thus, new drought index or methods were proposed by some authors (De Araújo & Bronstert, 2016; Cook et al., 2015; González & Valdés, 2006) for assessing hydrological droughts.

In 2013-14, South-East Brazil faced the most intense drought recorded (Escobar, 2015; Porto & Porto, 2014). Moreover, this effect remains to date (The Economist, 2015). Compared to historical records in South-East Brazil, the Brazilian Meteorology Institute showed that the precipitation in January-March 2014 was approximately 54% (300 mm) lower than the mean values of the 1961-1990 reference period (National Centre of Monitoring & Early Warning of Natural Disasters [CEMADEN], 2015). Satellite images from the Center for Weather Forecasts and Climate Research of Brazil’s National Space Research Institute

(CPTEC/INPE) show that during January and February of 2014 continental vapour clouds from the Amazon failed to carry rain conditions to South-East Brazil.

On the one hand, this 2013-14 drought jeopardized the 2015 public supply water allocations (Escobar, 2015). Besides the impact on 80 million people in Minas Gerais, Sao Paulo and Rio de Janeiro, the Tiete waterway was disabled during the Brazilian rainy season in 2014, resulting in the loss of 5,000 jobs and millions of tonnes of un-transported products (Tundisi & Tundisi, 2015), which shows that the multiple uses of water were affected by this severe drought. On the other hand, water withdrawals from reservoirs with very low levels (Coutinho et al., 2015) also pose problems related to water quality, with the settled sediments, metals, microorganisms and macronutrient over-enrichment, mainly phosphorous (Carpenter, 2005), which increase the water treatment costs. Some of the hydro-socio-economic impacts[5] of this drought were a 25% electricity price increase for 62% of Brazilians (Richards et al., 2015), and an expansion of 150% in fire-prone areas, reducing the amount of vegetation cover in Sao Paulo state. Furthermore, many tourism establishments near reservoirs closed, and food prices increased significantly. In short, at least US$ 5 billion was lost in this 2013-14 drought in South-East Brazil, which was the fifth most expensive natural disaster worldwide in 2014 (Munich RE, personal communication, February 02, 2016).

To reduce the impacts of extreme events, such as severe droughts, hydrologic monitoring is needed, integrating meteorological and quali-quantitative variables of freshwater, especially in critical areas. Gordon et al. (2008) reported that small areas with high soil phosphorous concentrations and high runoff potential were responsible for most of the phosphorus runoff into freshwater. Thus, better water quality could be achieved by managing these critical areas rather than the entire catchment. Moreover, integrating water quality and water quantity can substantially improve our comprehension of how headwaters contribute with nutrient loads to downstream areas, which were responsible for the water supply to 15 million people. Nutrient transportation across scales can increase the trophic state of the reservoirs and also compromises the multiple uses (as a result of algal blooms and anoxic events). Especially under extreme events, the empirical relationships between the LULC and quali-quantity freshwater fluxes at headwater scales allow foreseeing water

[5]'Hydro-socio-economic impacts' expresses the negative effects on socio-environment and economy brought by the 2013-14 drought which persisted in South-East Brazil. It was the worst water supply crisis in the Cantareira Water Supply System compared to the historical data (Marengo et al., 2015). This term was adapted from the 'hydrosocial territories' concept proposed by Boelens, Hoogesteger, Swyngedouw, Vos & Wester (2016).

scarcity at downstream scales. Evident correlations between LULC and water yield, as well as the respective effects on water quality at headwaters, allow preventing water shortages in downstream areas. The main objective of this study is to evaluate freshwater quali-quantitative monitoring during the Sao Paulo 2013-14 drought at defined spatiotemporal scales. Thus, the characterization of nutrient loads related to drainage areas was investigated, as well as water yields in relation to forest cover in nested catchments. The goal is to integrate short-term evidences, as the on-field baseline, to boost long-term monitoring at strategic headwaters for water supply and environmental conservation.

4.2 Material and Methods

4.2.1 Study area

Located in South-East Brazil, the Cantareira System, a 2300-km^2 catchment drainage area connected to the 1,000 hm^{3}of reservoirs and with total water demand of 36 m^3/s (Water National Agency and Sao Paulo State Water and Energy Resource Management Agency [ANA/DAEE], 2013), was affected by the 2013-2014 drought. Because the Cantareira System has a mean residence time of approximately 1 year (CEMADEN, 2015), it failed to fully meet not only 45% of water demand of the Sao Paulo Metropolitan Region (SPMR) of 9 million inhabitants (responsible for 20% of Brazilian economy), but also downstream demands of the Campinas Metropolitan Region, of approximately 5 million inhabitants. Therefore, strategies for reducing water consumption are crucial. The headwaters of the Cantareira System drain into the Piracicaba River, a tributary of the Tietê River, in the left portion of the Parana Basin. **Figure 4.1** shows the sampling points selected for water quality campaigns in 2013-14 among other catchment outlets, automatically generated from digital elevation modelling (DEM-ASTER), with upstream drainage area above the thresholds of 0.60 km , for the Cachoeira and Atibainha subbasins, and above 0.75 km^2 for the Jaguari and Jacarei subbasins. The Cantareira System is considered a strategic transboundary water system (Ditt et al., 2010). Considering the economic and demographic pressures on a megacity, to prevent water scarcity as a result of the unplanned growth of Sao Paulo Metropolitan Region, the government began constructing the system in the 1960s (Braga, 2001). As a great example of grey infrastructure, the connection of freshwater reservoirs was built in two steps. The first ended in 1975, and the second in 1981 (ANA, 2006). Its headwaters form three main river basins, the Jaguari-Jacareí, Cachoeira and Atibainha, with drainage areas within Cantareira System of 1230, 392, and 315 km^2, respectively (Whately & Cunha, 2007).

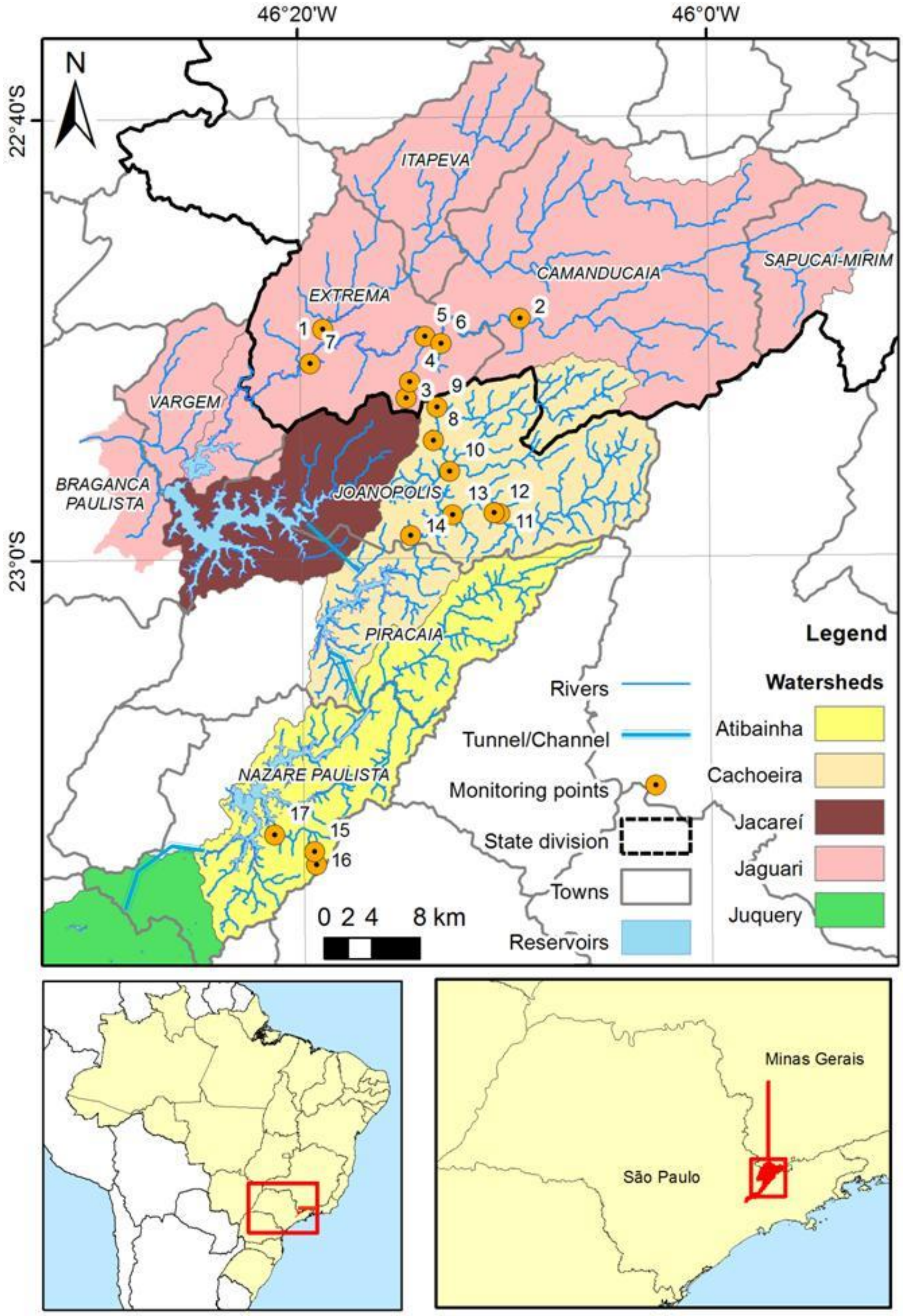

Figure 4.1. Monitoring points (open circles) during the 2013-14 period plotted with outlets of headwaters of the Cantareira Water Supply System.

According to Köppen's climate classification, the local climate is the Cwb-type, high-altitude subtropical climate, with dry winters and regular summers. The region of the PCJ has four major geological domains: the crystalline foundation, sedimentary rocks, the effusive rocks and the sedimentary covers. Geological fractures encompass mainly NE-SW directions. But the Jaguari River is constrained by an average geologic fracture in the E-W direction. These features contribute to the erosion process by increasing the gap between the drains and the top of the slopes, facilitating the occurrence of landslides by sheet erosion (Piracicaba, Capivari and Jundiaí River Basin Committes [PCJ], 2011).

The topography of the region is dominated by the moderate-to-high slopes from the Mantiqueira Mountains, with elevated valleys at altitudes between 800 and 2054 m.a.s.l. The headwaters of the Cantareira System (**Figure 4.1**) are located between coordinates 46°30'W, 22°35'S and 45°50'W, 23°05'S, in the states of Minas Gerais and Sao Paulo. The vegetation is composed of remnants of the Atlantic Rainforest Biome, mentioned earlier, with mean annual precipitation of 1620-1737 mm (adapted from ANA/DAEE, 2013). Between October 2013 and May 2014 this region was characterized by wet summers, and the average precipitation was 870 mm (CEMADEN, 2015) in the city of Extrema (MG), the geographic center of Jaguari-Jacareí, which is the largest basin of the Cantareira System, where the PES has been established for a decade. Comparing the three river basins, more gauge stations were found in the Jaguari-Jacareí sub-basin, which could be a consequence of the favourable institutional context of Extrema (Richards et al., 2015).

In terms of pedology, there are associations of soils with humic-alic and dystrophic red-yellow oxisols (red yellow latosol) with A-horizons, with a high percentage of clay at moderate-to-higher slopes. The soil classes identified by Oliveira et al. (2012) in the Salto catchment (Extrema municipality, MG) are orthents, fluvents, inceptisols and red-yellow oxisols (Brazilian Corporation of Agricultural Research [EMBRAPA], 2006). The compactness coefficient of the soil of the region indicates, under normal rain conditions, the tendency for large floods.

Past LULC changes are reported based on the Instituto Socioambiental [ISA] surveys conducted in 1989, 1999, 2003 and 2010. The LULC conversion from 1989 to 2010 can be summarized as follows. Dispersed urban settlements remained with the same land-use cover, early/middle stages of secondary vegetation increased from 4.6% to 7.4%, and livestock areas dropped from 58.8% to 46.2%; otherwise, reforestation increased from 19.6% to approximately 30%, and advanced secondary succession or primary vegetation remained the same, which was of approximately 15.4% (ISA, 2011).

Resolution Nº. 357/2005 of the Brazilian National Environmental Council – CONAMA (Brazil, 2005) classifies as freshwater "Class 1" the protection of aquatic communities, according to the water quality necessary for the main uses, and which after simplified treatment, can be directed to the public supply and other uses. Also, the Sao Paulo decree Nº 8486/1976 (Sao Paulo, 1976) considers as "Class 1" the water for domestic supply without previous treatment or with only with simple disinfection. The Sao Paulo State Decree Nº 10755/1977 classified as "Class 1": (1) the Atibainha and Cachoeira rivers and all their tributaries upstream of the respective Cantareira System reservoirs; and (2) the Jaguari river and all its tributaries upstream of the confluence with the Jacareí river at the municipality of Bragança Paulista (SP).

4.2.2 Nested Catchment Experiment

Exploratory nested catchment experiment (NCE) field campaigns identified river cross-sections of the highest interest for future installation of gauging stations. Based on LULC, hydrologic monitoring points were chosen at the main tributaries of Jaguari-Jacarei, Cachoeira and Atibainha using a Nested Catchment Experiment (NCE) methodology (**Figure 4.1, Table 4.1**). NCE helps to understand the hydrologic process (McDonnell et al., 2007) and to define the hydrologic controls on non-point pollution transport (Scanlon et al., 2004). Exploratory NCE field campaigns to identify river cross-sections for future installation of gauging stations and systematic NCE field campaigns addressed both qualitative and quantitative river measurements. We performed two exploratory field campaigns to identify and select sampling sites, considering: (1) the scales in which changes in land use had a sufficient footprint to yield impacts within a short time frame; (2) the comparison between paired watersheds, i.e., reference versus intervention ones; and (3) safety and accessibility conditions. Accordingly, we planned four systematic campaigns (**Table 4.1**) following seasonal patterns and according to WMO (2010) guidelines to verify whether there are discrepancies between different seasons and to show the seasonal behaviour of quali-quantitative river flow variables.

Despite the distance between the sampling sites, they are in the same river basin (Piracicaba River). Moreover, they are at the same latitude (between -23.2º and -22.8º), and thus subjected to the same climatic conditions.

Table 4.1.Nested Catchment Experiment (NCE) of quali-quantitative river flow variables.

NCE	N	Period	P (mm)	API (mm)	T_{air} (^{o}C)	T_{water} (^{o}C)
1	17	23-25 Oct. 2013	0.0	117.9	20.4 (17.1, 26.5)	19.8 (18.8, 20.6)
2	17	3-5Dec. 2013	35.3	123.7	20.9 (14.6, 27.8)	21.0 (19.8, 23.3)
3	17	14-15 March 2014	0.0	114.6	21.8 (17.4, 26.4)	20.8 (20.2, 21.3)
4	17	23-25 May 2014	1.3	32.5	15.5 (13.4, 19.4)	16.7 (16.0, 17.3)

Note. N = Number of samples of river cross-sections. P = total rainfall during NCE. API = antecedent precipitation index of 15 days before NCE. T_{air} = mean and range of air temperature during field NCE. T_{water}: mean and range of water temperature during field NCE.

In all campaigns, the antecedent precipitation index of 15 days (API-15d) was calculated using data from the Sao Paulo State Water and Energy Resource Management Agency (DAEE, 2014). The 17 NCE sites indirectly receive non-point pollution from urban areas of Itapeva-MG, Camanducaia-MG, Extrema-MG, Joanópolis-SP and Nazaré Paulista-SP cities, with a total population of 76,251 inhabitants (Brazilian Institute for Geography and Statistics [IBGE], 2014), and an average population growth of +2.2 %/y.

Of these six field campaigns, the highest API-15d (123.7 mm) was in December 2013. Considering only systematic NCE campaigns, the minimum API (32.5mm) was in May 2014. Mean air daily temperature during field campaigns varied from 15.5 to 21.8 ºC, but with temperature intervals between daily minima and daily maxima ranging from 13.4 to 27.8 ºC (**Figure 4.2**).

Because these campaigns were carried out in October/2013, December/2013, January/2014 and May/2014, water and air temperatures are expected to change. When rainfall was lower, air and water temperatures were different due to lower evaporation. Instead, due to higher evaporation the air and water temperature values are closer because of precipitation. The API-15d showed the behaviour expected for each campaign month, despite its absolute magnitude within a drought year.

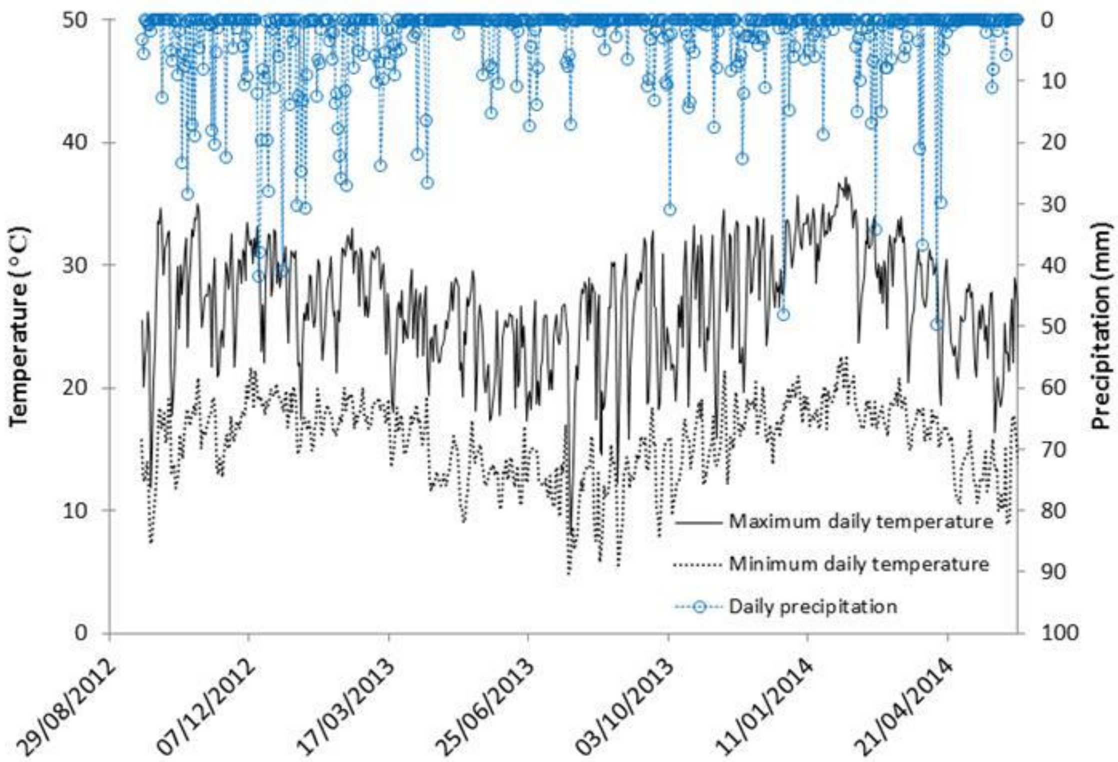

Figure 4.2. Daily precipitation (inverted vertical axis), with daily minimum and daily maximum temperatures, during the nested catchments experiments.

4.2.3 Water quantity monitoring

A calibrated current meter and rotation counter were used for the discharge measurements. A metal wading rod was used to measure shallow-depth waters; for deeper cross-sections, a propeller current meter with rotation counter installed on an aluminium boat fixed to a meter-graduated steel wire was used (WMO, 2010). For all measurements, instantaneous velocities were sampled to assess the mean cross-sectional velocity and flow discharge. On average, all river cross-sections were sampled with observed velocity profiles separated by a distance of approximately 25 cm from each other; this strategy assured assessing the representative mean velocity at the cross-sections. Sampled observations were double-checked, either in the field or in the lab. Flow-discharge observations followed the WMO (2010). In addition, graduated river stages were installed with topographic references related to mean sea level.

4.2.4 Water quality monitoring

For an overview of the contributing watersheds and to help understand runoff processes, a general water quality characterization was performed to demonstrate the situation of the river during the experiments. This procedure is meant to improve the development of water resources management policies and to calibrate a predictive model through the measurement of some parameters co-located with discharge gauging, since the loadings estimates are a requirement for the study objectives.

Thus, at all 17 river cross-sections we analysed instantaneous water quality variables of hydrogenionic potential (pH), water temperature, electrical conductivity, turbidity, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), total solids (TS), NO_3, NO_2, PO_4, thermotolerant coliforms and *Escherichia coli*. The observed variables were analyzed following the American Public Health Association [APHA] (Rice, Baird, Eaton, & Clesceri, 2012). The pH was estimated in the lab through APHA 40500 H^+-B Electrometric method, electrical conductivity (EC, in µmho/cmunits) was performed with APHA 2510 B, and turbidity (in NTU units) using the APHA 2130 B method. In turn, the COD (in mgO_2/L) and the BOD (inmgO_2/L) were estimated through, respectively, APHA 5220 D–colorimetric and 5210 B – 5-day BOD Test methods. TS (in mg/L) were assessed by APHA 2540B method.

Regarding Nitrogen and Phosphorus loads, Total Nitrogen was evaluated through APHA 4500 NB (Macro Kjeldahl), N-NO_3 (nitrate,in mg/L) by APHA 4500 NO_3—B (Spectrophotometric Method), N-NO_2 (nitrite, in mg/L) through APHA 4500 NO_2-B (colorimetric method), N-NH_3 (ammonia,in mg/L) through 4500 NH_3-C, and P-PO_4 (phosphate, in mg/L) through APHA-4500 P-E (ascorbic acid). Finally, thermotolerant coliforms (colony-forming units, CFU/100 mL) and *E. coli* (CFU/100 mL) were evaluated using APHA 9223B (substrate enzyme test). In the depuration process of water bodies, freshwater monitoring is fundamental to understand pollutant concentration changes throughout the year in line with the seasons (Bottino et al., 2010).

4.3 Results

4.3.1 Land-use and land-cover change at experimental catchments

Table 4.2 shows four systematic field campaigns at river cross-sections using NCE. It also shows the respective recorded land-use and land-cover (LULC) data for the areas, upslope of NCE river cross-section, at Cantareira System headwaters. **Table 4.2** shows the features of sampled NCE sites. All 17 experimental sites have average river bed slopes ranging from 0.24% to 1.18%, with sinuosity >1.2, entrenchment ratios of cross-sections >

1.4, with transitional sandy-gravel bedslopes, and width-to-depth ratios from 1.5 to over 4.8 (Rosgen & Silvey, 1998).

The main LULC in the river basins was classified in three main mixing uses and cover: sparse human settlement and/or urban areas (Settl.), open mixed areas for cattle and range (Range), and mixed natural forests, and/or riparian forests and/or reforestation (Forest). Riparian vegetation is densely occupied by a mixture of endemic hydromorphic species, co-existing with many exotic species, such as *Eucalyptus* sp. and *Bambusoideae* sp. The monitoring points (**Table 4.2**) were located at the headwaters of the main tributaries of Cantareira System reservoirs - three at Atibainha Basin (ATI), seven at Cachoeira Basin (CAC) and seven at Jaguari Basin (JAG).

Table 2 also shows two columns to the right: the forest LULC growth between 1989 and 2010 and the rate class called LULC. In summary, the table shows an average LULC forest growth in spatial extent of 42.7% between 1989 and 2010. The last column is composed of five fields. The first three fields show the categorical growth of the three main LULC, in the period 1989-2010, for settlement, range and forest, respectively. The fourth field of this code represents the Horton's geomorphological order at the NCE; "†"means that the experimental NCE drains directly into the reservoir, and is not connected to the main stem of the river tributary. The fifth (last) field represents whether Horton's order at the NCE point is equal to ("=") or higher than (">") Horton's order of the upstream NCE, when there is an upstream NCE. In that fifth field, symbol "‡"means that incremental area, upstream of the NCE point, equals the total drainage area (there is no upstream NCE).

For example, for site Nº 16 (Reference Moinho in **Table 4.2**), the code '0/±/1/‡' means a field evidence collected at a NCE river cross-section with an adjacent draining area with no-change (0%) in LULC human settlement, with positive ("+") growth of LULC range areas and, likewise, with negative ("-") growth of LULC forest areas. Furthermore, the last column of **Table 4.2** is underlined when the catchment has positive LULC forest.

Nine (9) river cross-sections were characterized with LULC of the adjacent area equalled to the total drainage area (depicted with symbol "‡", **Table 4.2**). The other eight (8) river cross sections have LULC related to the upslope incremental catchment, between two sampling points. According to digital elevation modelling, six river cross sections were surveyed as Horton's 1st-order basins, three as 2nd-order, one as 3rd-order, five as 4th-order and two as 5th-order. Horton's 1st-order drainage areas ranged from 0.66 to 11.9 km^2, and also Horton's 5th-order which ranged from 289 to 925 km^2.

Table 4.2. Summary of systematic field campaigns at river cross-sections across Nested Catchment Experiment (NCE) systems, with respective municipalities, drainage areas and historic land-use and land-cover change (LULC) of adjacent incremental areas, upslope of NCE river cross-section, at headwaters of the Cantareira Water Supply System, Brazil, between October 2013 and May 2014.

Site	Name of sampled NCE (type of cross section)	Horton's order at NCE and at tributary	Coordinates of river cross section (West, South)	Drainage Area (ha)	LULC-1989 (%)			LULC-2010 (%)			Forest rate (%)	LULC rate code*
					Settl.	Pasture	Forest	Settl.	Pasture	Forest		
1	F23 Camanducaia (natural)	4 → 5 (JAG)	46°18'51" , 22°49'36"	51122	2	81	17	2	79	19	11,9	0/-/+/4/‡
2	Upper Jaguari (natural)	3 → 5 (JAG)	46°09'18" , 22°49'09"	28100	1	29	70	1	31	67	-3,8	0/+/-/3/‡
3	Upper Posses (natural)	1 → 5 (JAG)	46°14'47" , 22°52'45"	400	0	93	6	0	90	10	57,9	0/-/+/1/‡
4	Middle Posses (natural)	1 → 5 (JAG)	46°14'44" , 22°51'57"	700	1	94	5	1	94	5	7,5	0/0/0/1/=
5	Posses' Outlet (natural)	1 → 5 (JAG)	46°13'53" , 22°49'59"	1190	3	91	6	3	91	6	-3,8	0/0/0/1/=
6	Salto Outlet (natural)	2 → 5 (JAG)	46°13'07" , 22°50'18"	4800	1	86	13	1	82	17	33,1	0/-/+/2/‡
7	ParqueEventos (natural)	5 → 5 (JAG)	46°19'31" , 22°51'12"	92532	3	79	18	4	73	23	27,6	+/-/+/5/>
8	Intervention Cancan (V-weir)	1 → 5 (CAC)	46°13'26" , 22°54'41"	201	2	89	9	2	85	13	44,4	0/-/+/1/‡
9	Reference Cancan (V-weir)	1 → 5 (CAC)	46°13'17" , 22°53'13"	126	2	65	33	2	40	58	76,1	0/-/+/1/‡
10	PCD Cancan - F30 (natural)	4 → 5 (CAC)	46°12'43" , 22°56'06"	9700	2	78	21	2	68	30	44,2	0/-/+/4/>
11	Cachoeira dos Pretos (natural)	4 → 5 (CAC)	46°10'18" , 22°58'00"	10141	0	47	52	0	29	70	34,8	0/-/+/4/‡
12	Chalé Ponto Verde (natural)	4 → 5 (CAC)	46°10'32" , 22°57'41"	15000	1	81	18	1	56	43	143,1	0/-/+/4/=
13	Cachoeira Bridge (natural)	4 → 5 (CAC)	46°12'34" , 22°58'05"	20963	2	92	6	2	78	20	218,2	0/-/+/4/=
14	F24 - Cachoeira (natural)	5 → 5 (CAC)	46º14'24", 22º59'39"	28922	0	61	38	1	51	48	25,6	+/-/+/5/>
15	Intervention Moinho (V-weir)	2 → 4 (ATI) †	46º19'29" , 23º13'19"	310	9	43	48	7	40	53	11,9	-/-/+/2/‡
16	Reference Moinho (V-weir)	1 → 4 (ATI) †	46º19'24" , 23º13'55"	66	0	4	96	0	17	83	-13,9	0/+/-/1/‡
17	PCD Moinho Outlet (natural)	2 → 4 (ATI)†	46º21'19" , 23º12'36"	1692	3	57	40	4	52	44	11,6	+/-/+/2/>

Notes:
Settl. = sparse human settlement and/or urban areas. Pasture = open mixed areas for cattle and range. Forest = mixed natural forests, and/or riparian forests, and/or reforestation. Forest rate (%) = fraction of forested LULC growth between 1989 and 2010. LULC rate code = categorical growth of different LULC, in the period 1989-2010.ATI = Atibainha Basin. CAC = Cachoeira Basin. JAG = Jaguari Basin.

* See main text for explanation.

†: NCE draining directly to reservoir not connected to main stem of river tributary.

‡: Adjacent incremental area upslope equals total drainage area.

Regionalized similarities among nested catchment experiments were the result of inter-related factors. Observed seasonal water yield of catchments ranged between 5% and 18% of accumulated precipitation for the period of October 2013 to May 2014, thereby differentiating two catchment groups (**Figure 4.3** and **Figure 4.4**). On the one hand, some catchments had higher water yields: the Cancan-Intervention catchment (A=2.01km^2, with water yield of 146 mm), the three main sub-basins together draining into the reservoirs (A=1940 km^2, water yield of 151mm) and the JAG System (A=1234km^2, with water yield of 141mm), with authorized water withdrawal of 13mm/year (ANA/DAEE, 2014).

On the other hand, three other catchments had lower water yields: the Cancan-Reference catchment (A=1.26km^2, with water yield of 74mm), CAC system (A=393km^2, with forest land use cover of 60%, water yield of 59 mm) and ATI system (A=313km^2, with forest land use cover of 71% (Pereira &Teixeira Filho, 2009), water yield of 41mm). In general, **Figure 4.4** shows that the experimental results had an inverse relationship between water yield and forestry cover in the catchment areas.

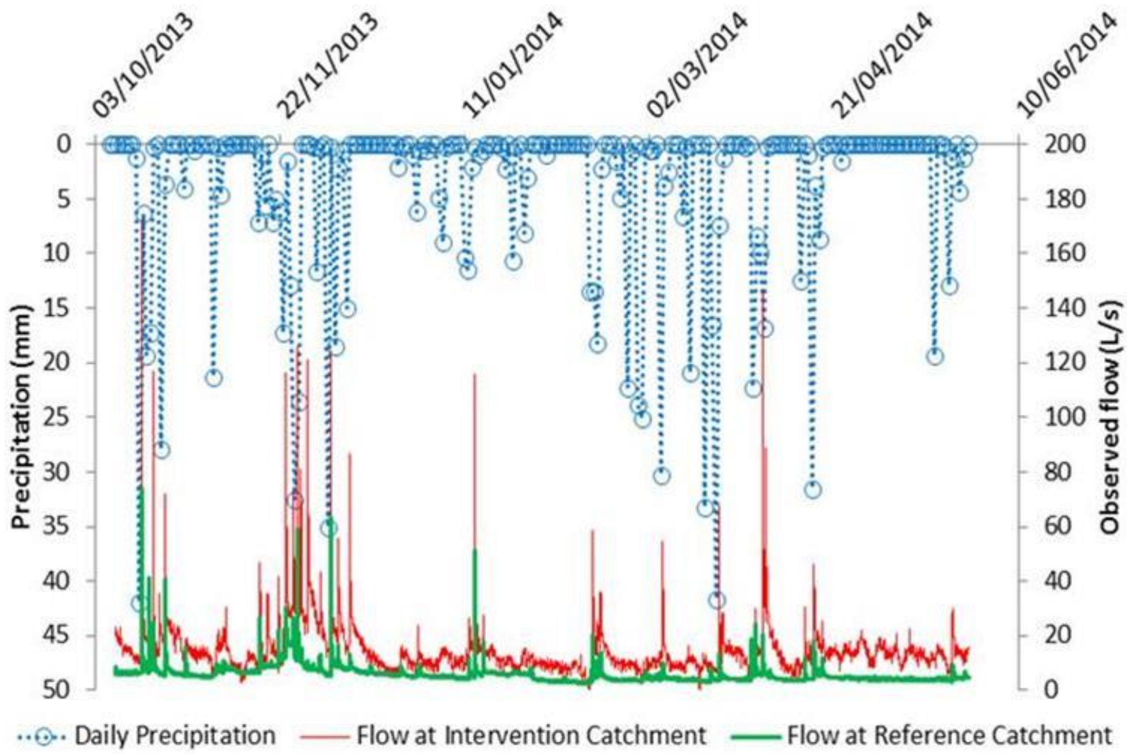

Figure 4.3. Daily precipitation and observed flow at two experimental sites (reference and intervention areas in Cancã catchment, Joanópolis, SP) in the headwaters of the Cantareira Water Supply System.

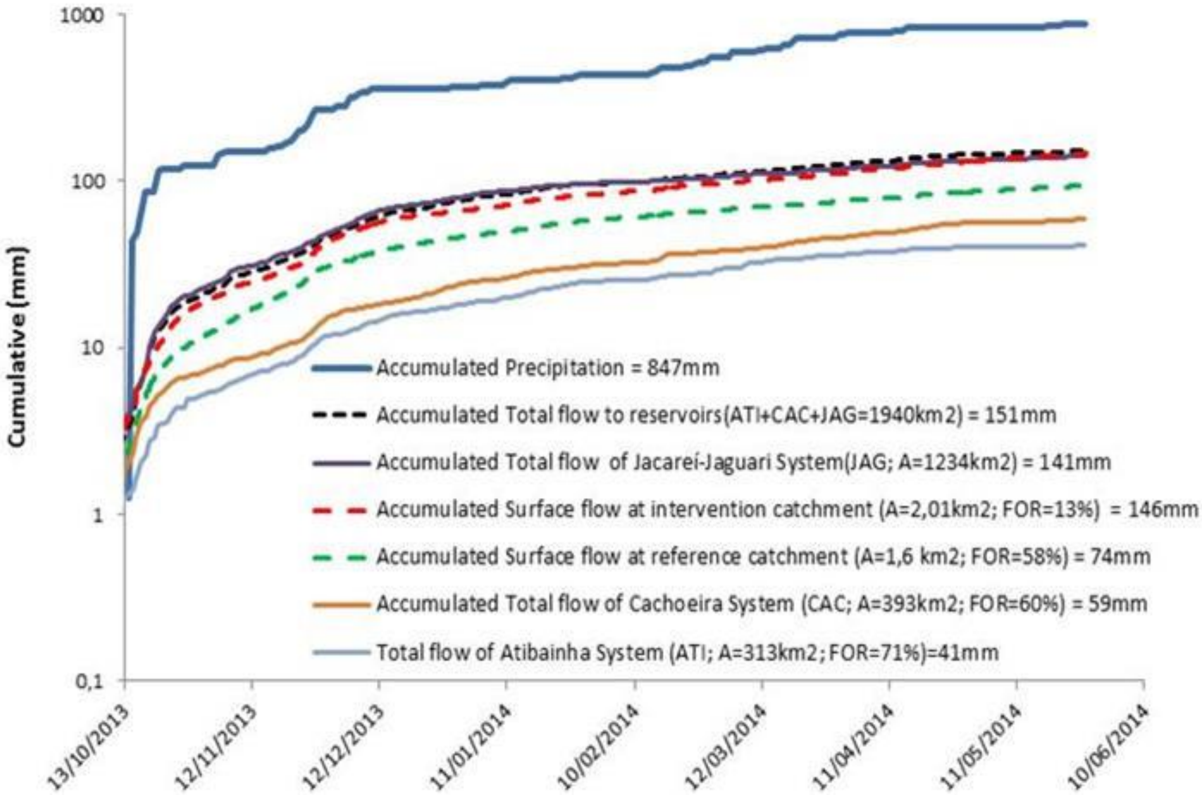

Figure 4.4. Seasonal water yield for nested catchments of Cantareira Water Supply System for the period of October 2013 to June 2014. "A": drainage area of the catchment, "FOR": % of soil covered by forests in the catchment.

4.3.2 Water quantity and quality monitoring

Appendix-B summarizes all quali-quantitative results from our episodic freshwater monitoring in the headwaters of Cantareira System. Part of these data was used as input and for calibration of the ecohydrologic model performed in scenarios simulations (see Chapter 5 of this thesis).

The median sampled pH was 6.9, with a sample mean of 6.9±0.2. Median electrical conductivity (EC) for all sampled data was 41.0 µmho/cm (42.0 ± 21.6 µS/cm), ranging between a minimum of 13.0 µS/cm and a maximum of 133.9 µS/cm. The former minimum value was related to highly-oxygenated headwaters, i.e., *Cachoeira dos Pretos*, with a drainage area of 101.4 km^2, during the rainy periods in December 2013. Conversely, the lowest electrical conductivity was seen at *Posses Outlet*, with drainage area of 11.9 km^2, with significant interference of farm-to-urban conversion, which influenced the river water quality.

The median BOD was 2.0 mgO_2/L, with means of 2.4 ±1.8 mgO_2/L, and a narrow range between 1.0 to 6.0 mgO_2/L. Factors such as turbulence, metal toxicity, organic compounds and nitrogen can influence BOD results.

Figure 4.5 summarizes the observed water quality variables for the period October 2013 to May 2014 at tributaries of the Jaguari, Cachoeira and Atibainha sub-basins. For example, median COD was 16.0 mgO_2/L, with a mean of 19.0 mg O_2/L, and a maximum of 98.0 mg O_2/L for the Atibainha sub-basin (drainage area of 1,642 km^2).

For all experiment surveys, the median TS was 45 mg/L, with a maximum of 305 mg/L at *Parque de Eventos*, with drainage area of 925 km^2, and an estimated TS load of 215 t/km^2 per year.

In terms of total coliforms, the median value was of 65,000 colony-forming units (CFU/100 mL), with high variability. For example, the total range of thermotolerant coliforms ranged between 14.0 (*Cachoeira Outlet*, 289 km^2) and 9.6×10^5 CFU/100mL (*Parque de Eventos*, drainage area of 925 km^2). The sampled water data show that no cluster from flow discharges versus water quality concentration can be inferred. For example, in **Figure 4.5**, only two intervals of observed flow discharges were surveyed during the field campaigns, i.e., $0.06 \leq Q \leq 0.14$ and $0.8 \leq Q \leq 20.1$ m^3/s.

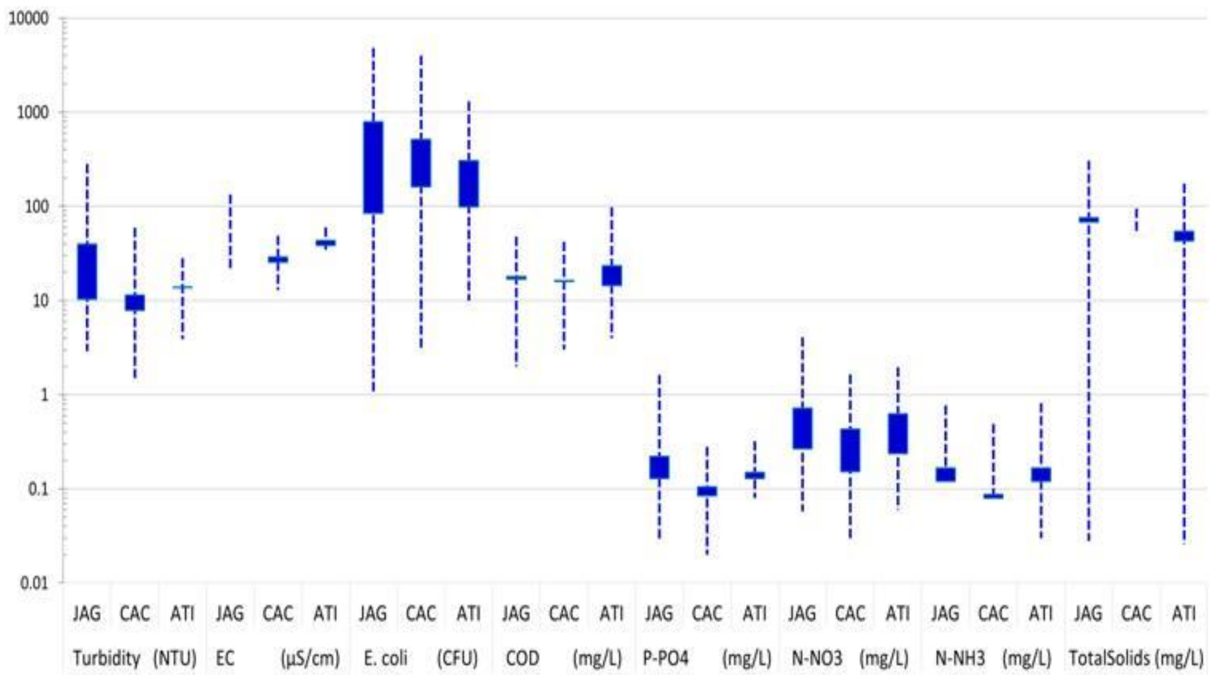

Figure 4.5. Some observed water quality variables, with dimensional units, for 2013–14 at main river tributaries of the Jaguari (JAG), Cachoeira (CAC) and Atibainha (ATI) sub-basins of the Cantareira System, Brazil.

4.3.3 Variability of P-PO_4 loads

P-PO_4 concentrations have a median value of 0.12 mg/L, with high variability (0.16 ± 0.20 mg/L), with total range between a minimum of 0.02 mg/L (*Cachoeira dos Pretos*, drainage area of 101.4 km^2) and a maximum of 1.62 mg/L (*Parque de Eventos* – Extrema, drainage area of 925 km^2).

An empirical relationship (**Table 4.3**) of PO_4^{-3} load (kg/day) was obtained for all field campaigns, with R^2=83%. The lower specific phosphate load, the pollutant load per drainage area, was found for site 9 (*Domithildes*, Reference Cancan area), in **Figure 4.1**, with 0.027 kg P-PO_4^{-3}/ha per year, and the highest load was for site 7 (*Jaguari*, *Parque de Eventos*), in **Figure 4.1**, with 2.397 P-PO_4^{-3} /ha per year.

Figure 4.6 shows that there is not enough evidence to regionalize empirical P-PO_4^{-3} concentration and flow discharges. Otherwise, when PO_4^{-3} load was related to the drainage area (**Figure 4.7**), seasonal NCE observations were better grouped.

Table 4.3. Empirical PO_4^{-3} and NO_3^{-2} relations with drainage area (in ha) at nested catchment experiments performed between Oct., 2013 and May, 2014.

Period (sample)	PO_4 load (kg P-PO_4/day)		NO_3 load (kg N-NO_3/day)	
	Equation	R^2	Equation	R^2
Oct./2013 (N=17)	$1.10^{-5}.A^{1.5389}$	87%	$1.10^{-5}.A^{1.5416}$	94%
Dec./2013 (N=17)	$4.10^{-4}.A^{1.1861}$	95%	$3.10^{-4}.A^{1.1906}$	95%
Mar./2014 (N=17)	$2.10^{-5}.A^{1.2962}$	90%	$9.10^{-5}. A^{1.2557}$	94%
May/2014 (N=17)	$7.10^{-5}.A^{1.2210}$	82%	$6.10^{-4}.A^{1.2886}$	82%
All data (N=68)	$6.10^{-5}.A^{1.2879}$	83%	$9.10^{-5}.A^{1.3433}$	87%

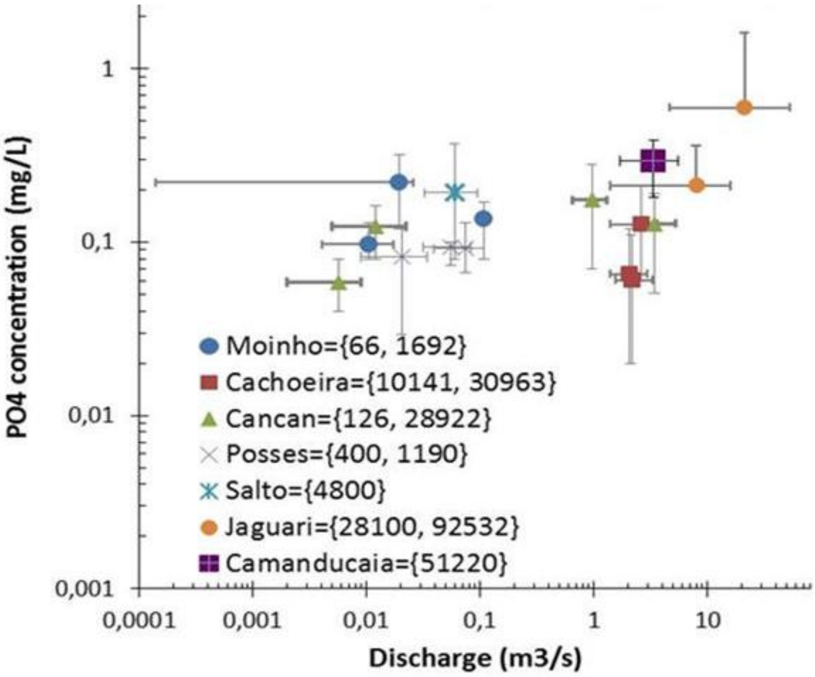

Figure 4.6. Experimental evidences of phosphate concentrations versus observed flow discharges at 17 experimental nested catchment experimentsites in the Cantareira System.

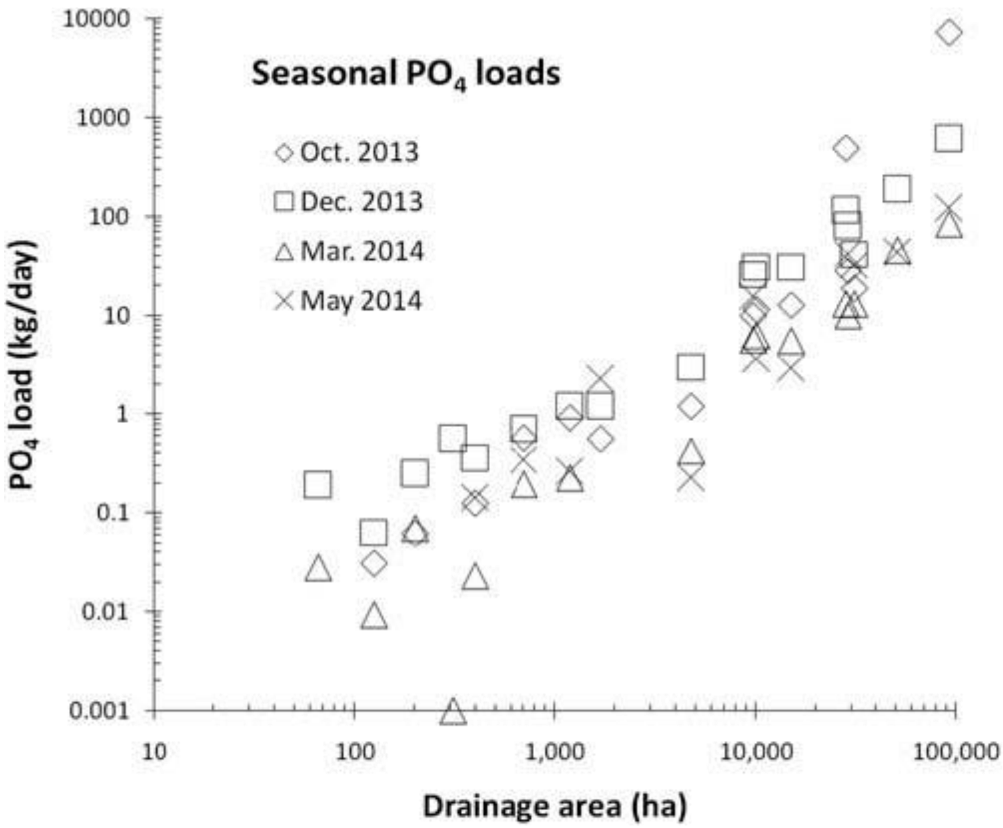

Figure 4.7. Experimental evidence of seasonal phosphate load variability related to drainage area at 17 nested catchment experiments in the Cantareira System.

4.3.4 Variability of N-NO_3 loads

Figure 4.5 shows that the loads found for nitrate were higher than for phosphate at the three sub-basins (JAG, CAC and ATI) in all field investigations. **Figure 4.8** shows there is not enough evidence to regionalize empirical N-NO_3^{-2} concentration and flow discharges. However, for nitrate, the highest load was found in May/2014 (**Figure 4.9**). The median concentration of nitrate in May/2014 was 1.68mg/L. This result was 14 times as high as the N-NO_3 concentration in October 2013, 10 times that found in December 2013 and 6 times than that found in March 2014.

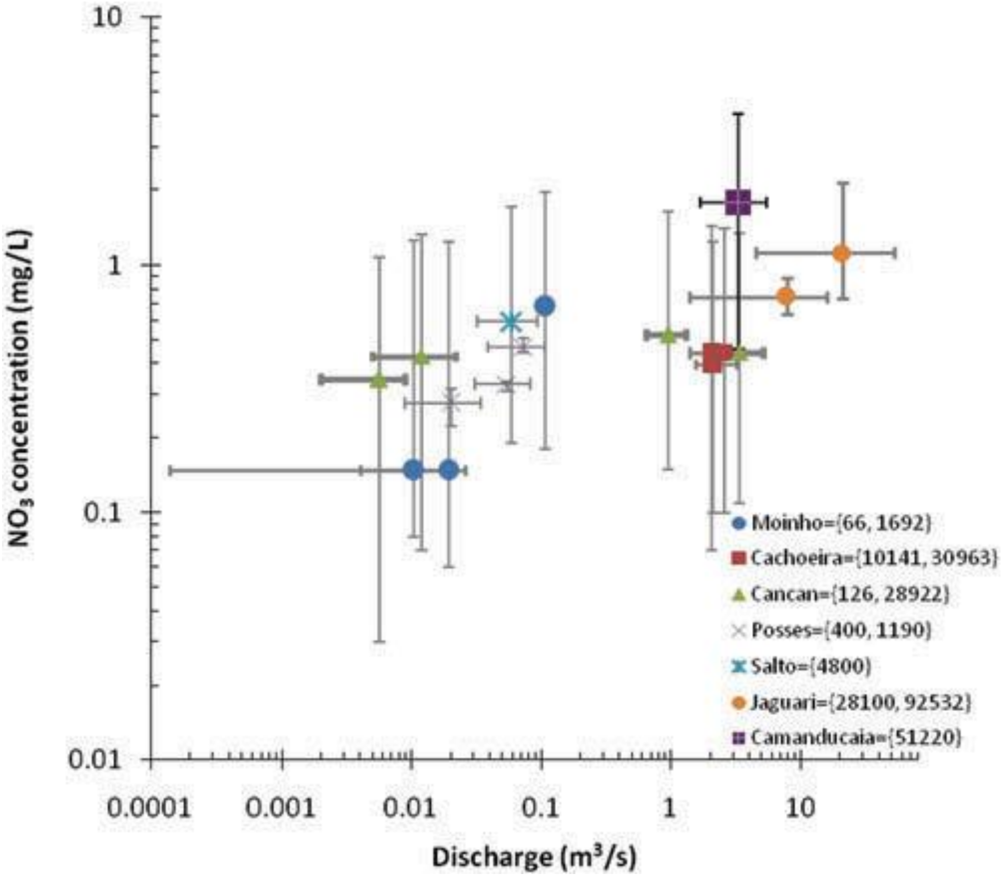

Figure 4.8. Experimental evidence of nitrate concentrations versus observed flow at 17 nested catchment experiments in the Cantareira System.

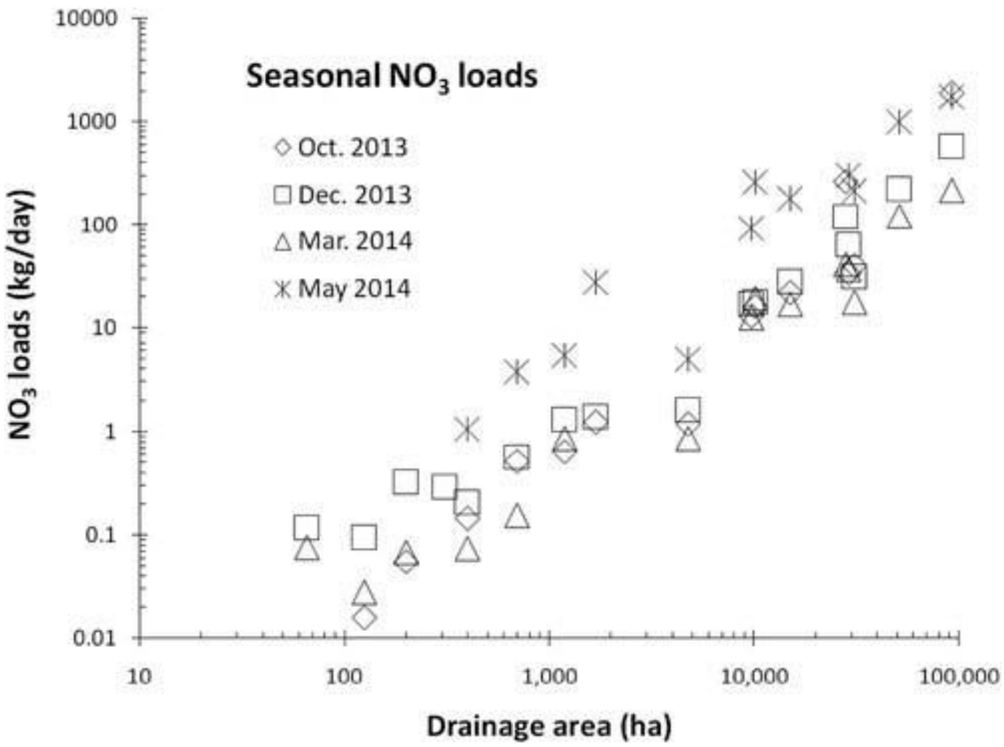

Figure 4.9. Experimental evidence of discharge seasonal nitrate load variability related to drainage area at 17 nested catchment experiments in the Cantareira System.

Considering both phosphate and nitrate loads, based on **Figures 4.7** and **4.9**, equations were developed to find the expected load for phosphate and nitrate corresponding to each drainage area from the 17 experimental sites (**Table 4.3**). Among them, the findings for nitrate are highlighted, where R^2 between 94% and 95% was achieved in most of the seasonal assessments.

4.4. Discussion

Discussion of the results from the field campaigns is presented in the following paragraphs. Also discussed are the effects of some water pollutants, the water quantity and quality impacts, and water challenges.

4.4.1. Water quantity & quality monitoring

In each of the campaigns described in **Table 4.1**, quality and quantity evaluations were performed at 17 sites. The main differences in the results were related to uncontrolled patterns, such as precipitation occurrence among field campaigns. The greatest difference is related to the fourth field campaign, showing lower API (32.5 mm, which represents 33.4% of the mean API) resulting from the more intense drought conditions. The findings are comparable because (1) the sample sites were at the same river basin and at the same latitude, and thus subjected to the same climatic conditions; (2) they resulted from rainfall-runoff transformation effects; and (3) the state of the land-use cover within the experimental catchments.

LULC changes are relevant factors that impact quality, quantity and seasonal aspects of water resources. Concerning water quantity, the results showed an inverse relationship between water yield and forest cover in the catchments (**Figure 4.4**), which confirms previous studies (Germer et al., 2009; Pereira & Teixeira Filho, 2009). However, Ellison, Futter & Bishop (2012) highlighted that more forested catchment reducing water availability and precipitation can be easily notable at local scales. Small catchments can receive precipitation from other areas. Thus, the consequence of deforestation, less evapotranspiration and less precipitation can be clearly seen at larger spatial scales. At regional scales, forest–water relationships play a key role in providing the atmospheric vapour that becomes precipitation. In short, forest cover and its impact on water yield depend on the catchment scale; thus, this issue should be placed under scrutiny. Thus, we recommend caution with regard to generalizing our results because they were sampled during a rainfall anomaly season (see Marengo et al., 2015).

The presented procedure, which integrates water quality, quantity and meteorological variables, provides some contributions for preventing repetition of the 2013-14 drought. First, we developed an integrated monitoring network at different spatial scales, and, using meteorological, qualitative and quantitative freshwater variables, an additional early-warning system was addressed. Previous to this drought, the integration of qualitative and quantitative aspects of water resources seldom occurred in Cantareira headwaters. Second, this integrated monitoring helped the management capacity regarding the drought conditions. For example, the reaction of Brazilian water managers regarding drought evidences was water demand and availability control. On 5 March 2014, the Brazilian National Water Agency [ANA] and the Sao Paulo Department of Water and Electricity [DAEE] released the Resolution Nº 335 to regulate new patterns of water withdrawals from the Cantareira reservoirs of Jaguari-Jacareí, Cachoeira and Atibainha (ANA, 2016). Third, our field work in 2013-14 motivated a strategy change concerning the official monitoring system at the headwaters of Cantareira System. Before 2013 there were only seven online rain-gauge stations; after 2014 this number increased by a factor of six (see CEMADEN, Cantareira System Report, 2015). Furthermore, a significant increase in the number of online water-level stations, local water levels, experimental V-notch weirs, and *in situ* quali-quantitative flow observations were installed after 2014. This shows a resilient strategy in-progress to cope with future risks in these strategic river basins to ecosystems and water supply.

With regard to water quality, pollutant loads include a combination of natural and anthropogenic factors due to land use and land cover. Progressive changes in LULC can alter pollutant concentrations and behaviour, reducing biodiversity and increasing uncertainties. For example, Magurran (2016) and Newbold et al. (2015) reported that land use caused species richness loss (alpha-diversity loss) and its possible impacts on ecosystem functioning.

Although we expected high field observations uncertainties in terms of water quantity and quality, we found evidence of regional behaviours of loads *versus* drainage areas (**Figure 4.7** for PO_4^{-3} loads and **Figure 4.9** for NO_3 loads). Nevertheless, specific loads in kg per day per km^2, for both PO_4^{-3} and NO_3, show low empirical correlations. Thus, specific-load curves per drainage area do not seem appropriate for these sampled data.

The threat posed by sediments in the freshwater ecosystems has increased due to anthropogenic factors. TS deposition contributes towards turbidity, stress behaviour during the early stages of natural consolidation of soils deposited under water, and potential impacts from the synergisms between nutrients. We found maximum TS of 305 mg/L at *Parque de Eventos - Extrema*, with an estimated TS load of 215 t/km^2 per year. In terms of TS, our most polluted site (among the 17 NCEs) appears to be 2.5 times less polluted than a basin in Australia. Bainbridge et al. (2014) reported 530 t/km^2 per year in the Burdekin River catchment, a dry tropical catchment, in a five-year study period. Although it is a medium-sized river catchment, the adjacent urban areas of Extrema have affected the river water quality. In 2014 Extrema had approximately 32,402 inhabitants (IBGE, 2014), with a population growth rate of 3.3 % per year. Other water quality variables also presented extreme values at the same field site.

Thermotolerant coliforms ranged between 14.0 (*Cachoeira Outlet*, 289 km^2) and 9.6 X 10^5 CFU/100mL (*Parque de Eventos*, 925 km^2). These results in medium-size drainage areas are related to impacts of two different conditions, one from urban loads and the other from auto-depuration processes in rural areas. Some authors (Lyon et al., 2012; Ouyang, Nkedi-Kizza, Wu, Shinde & Huang, 2006) recommend special actions related to the inherent variations of real catchments in terms of their characterization. For example, Ouyang et al. (2006) reported that except for electrical conductivity, the most important parameter to provide water quality variation for one season was not important for another season.

4.4.2 Variability of P-PO_4 loads

The precipitation in December/2013 (**Figure 4.3**) may be responsible for the increase in the pollutant loads carried into the rivers, as was the case for phosphate. Considering the seasonal variability, the phosphate concentration was the highest in December 2013 (mean 0.18 mg PO_4^{-3}/L) in most of the monitoring sites. However, PO_4^{-3} concentration appears to have increased in the drainage area of the catchments under study (**Figure 4.7**). This behaviour is addressed by other authors (e.g. Scanlon et al., 2004), who point to the fact that PO_4^{-3} load transfers increased from headwaters to downstream areas. However, PO_4^{-3} specific loads in the drainage area increased in a similar way.

In experimental catchments with drainage areas between 66 and 310 ha, specific loads ranged from $8\times10^{-4}$to 2.8×10^{-1} kg P-PO_4^{-3} per km^2 per day. These specific loads showed wide variability, and apparently related to a combination of factors like LULC, size of drainage area, antecedent moisture conditions and farm best management practices. On the one hand, lower specific P-PO_4^{-3} loads at micro-catchments of Cancan and Moinho can be associated with the progressive decline of land use cover of native Atlantic rainforest. Additional small pools associated with medium forest cover of 53% (Intervention Moinho) also decreased specific P-PO_4^{-3} loads. But when this forest cover dropped to 13%, specific P-PO_4^{-3} loads increased (Intervention Cancan). These results may be associated with greater land use cover of native Atlantic rainforest, forming containment barriers and preventing the direct entry of surface runoff into streams. On the other hand, Site 7 (*Jaguari-ParqueEventos*, 925 km^2), receiving urban loads from Extrema city, as well as agriculture and industrial wastewater, had the highest specific loads, of 7.9 kg P-PO_4^{-3}per km^2 per day. Scanlon et al. (2004) found that neither topographic descriptor was found to satisfactorily conform to the concentration-versus-discharge observations, thereby indicating that local catchment sediment delivery factors or in-stream channel processes are likely to be responsible for the observed differences. Although our observed discharge intervals had a gap of mean discharge measurement of 0.1 - 0.8 m^3/s, there is still not enough evidence to accomplish a regionalized curve or behaviour in terms of P-PO_4^{-3} concentration and discharges, as shown in **Figure 4.6**.

4.4.3 Variability of N-NO_3 loads

Considering the increasingly dry conditions observed during the months of this study - which persisted and intensified until early 2015 (The Economist, 2015) -, the lower flows led to higher concentrations of pollutants and affected the aquatic ecosystem overall. As a result, there was a death of 20 tonnes of different fish species in the Piracicaba River in February, 2014 (Marengo et al., 2015). The higher nutrient load level is one of the most threatening factors for the biodiversity of native fish. This can be explained by the proliferation of microorganisms in dry conditions, which consume the remaining oxygen in the water.

This study found that pollutant loads and drainage areas (0.66-925 km) have different correlations. Nitrate is more closely related to drainage area than phosphate. Nitrate loads are higher than phosphate loads in all field/lab experiments and in all sub-basins. The equations related to the expected phosphate and nitrate loads corresponding to each drainage area (**Table 4.3**) led us to highlight our findings for nitrate, where R^2 between 94% and 95% was achieved in most of the seasonal assessments.

Around 95% of nitrate load variability can be explained by the size of the contribution or drainage area and vice-versa. The remaining 5% can be explained by other factors that were not measured, such as synergism between nitrate and other nutrients, deeper water layers, eutrophication, etc. Similar results were found for phosphate in December 2013. This very high correlation (95%) can help companies and the government to predict water pollution based on experimental data and improve the goals of the River Basin Plan, in a key research-for-action initiative. For the observations in **Table 4.3**, the empirical ratio of $N\text{-}NO_3$ to $P\text{-}PO_4$ was very low, ranging from 1.5 (for A=1 km^2) to 2.2 (for A= 1000km^2).

It is known that nitrogen is an essential macronutrient which regulates primary production in terrestrial and aquatic ecosystems. Excess nitrogen has been linked to many environmental concerns, including the disruption of forest ecosystem functions, acidification of streams, eutrophication, hypoxia and algal blooms. These processes may be some of the impacts of recent climate change.

Since nitrogen is highly reactive and mobile in terrestrial and aquatic ecosystems, it also serves as a surrogate for many contaminants in the water, which is important in understanding the linkages between headwaters and downstream receiving waters.

4.5 Conclusions

The objective of this chapter was to integrate short-term evidence, as the on-field baseline, to stimulate long-term monitoring at strategic headwaters constrained by hydrological extremes. Using evidence from 17 sites through nested catchment experiments during field surveys in the 2013-14 period, characterized by a low-precipitation anomaly in South-East Brazil, the importance is highlighted of an integrated quali-quantitative freshwater monitoring in the Cantareira System, one of the main water supply systems in South-East Brazil. The study findings indicate that: (1) for water quantity, catchments with less forest cover present higher water yields, suggesting a possible inverse correlation between forest cover and water yield; (2) for water quality, empirical evidence of loads (phosphate and nitrate) *versus* drainage area, as regionalization procedures for rating curves, presented better relationships than water quality concentration *versus* flow discharges; (3) from this regionalization, 95% of total variance of phosphate and nitrate loads was explained using drainage areas as independent variables; and (4) this nutrient migration from headwaters to downstream areas could have impacts of load accumulation and eutrophication in water supply reservoirs.

Based on these experimental data, the results could assist decision-making, regarding actual and new water rights permits for industrial, domestic, farming, energy supply users and the environmental needs. A good example of how this procedure can contribute to avoid the aggravation of the water crisis is the Joint Resolution ANA/DAEE Nº 335 of 5 March 2014, which reviewed the operation standards of the three reservoirs, which are downstream of the 17 campaign sites, where the discharge was measured. This reinforces data quality and density, making decision-making more robust.

The 2013-14 drought in South-East Brazil is a recent example of the urgent need for enhanced integrated monitoring of water quality and quantity as part of a robust strategy for achieving water security. Given the impacts of the Sao Paulo water crisis, there is an increasing concern over vulnerabilities and impacts on quality, quantity and seasonal aspects of water resources. Thus, environmental conservation programmes are a possible adaptation strategy, by converting land use to environmentally-friendly land cover. This research has the potential to be applied to other relevant regions in South America which are also facing recent extreme events, since freshwater monitoring brings an interesting set of primary data. Through new and reliable knowledge this study has the potential to improve the River Basin Plan goals, in a key research-for-action initiative. Moreover, the partnership between universities, NGOs, and federal, regional and local governmental agencies was (and is) fundamental to stimulate freshwater monitoring, in not only qualitative, but also quantitative terms, and assess the protection of watersheds.

Further research is needed for continuing and expanding long-term monitoring and early-warning strategies in critical watersheds, dependent upon the role played by long-term climate change and its influence on ecosystem services. Finally, we suggest updating the Brazilian water quality standards according to more restrictive frameworks for actual water security.

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CHAPTER 5

MODELING FRESHWATER QUALITY SCENARIOS WITH ECOSYSTEM-BASED ADAPTATION IN THE HEADWATERS OF CANTAREIRA SYSTEM, BRAZIL*

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Abstract

Freshwater fluxes are influenced by the volume and quality of water at the headwaters of strategic river basins under change. Although hydrological models provide hypothesis testing of complex dynamics occurring at river basin scales, freshwater quality modeling is still incipient at many river catchments. In Brazil, approximately only one in twenty modeling studies assesses freshwater nutrients, which limit the policies regarding hydrological ecosystem services. This paper aims to compare freshwater quality scenarios under different land-use/land-cover (LULC) change, one of them related to Ecosystem-based Adaptation (EbA) approach in subtropical headwaters. Using the spatially semi-distributed SWAT (Soil and Water Assessment Tool) model, nitrate and total phosphorous loads were modeled in Brazilian subtropical catchments ranging from 7.2 to 1037 km^2. Part of these catchments are eligible areas of the Brazilian PES-programmes *Water Producer* and *Water Conservator* in the Cantareira Water Supply System, which until the drought in 2013-15 supplied water to 9 million people in the Sao Paulo Metropolitan Region. We considered freshwater quality modeling of three LULC scenarios, with no climate change, as: (i) *recent past scenario* (S1), with the historic LULC records in 1990, (ii) *current land use scenario* (S2), considered the LULC for the period 2010-2015 as the baseline, and (iii) *future land use scenario* (S2+EbA). The latter scenario proposed forest cover conversion with restoration through EbA in protected areas according to the Basin Plan of the Piracicaba-Capivari-Jundiaí watersheds by 2035. The three LULC scenarios were tested with the same records of rainfall and evapotranspiration observations in 2006-2014, which comprised the occurrence of extreme drought events. We propose a new indicator for hydrologic services assessment related to the grey water footprint (greyWF) and water yield estimated. The Hydrologic Services Indicator (HSI), as a non-dimensional factor of comparing water pollution loads (WPL) for referenced and non-referenced catchment, composing water pollution levels from nitrate, total phosphorus and sediments. On the one hand, leaching simulations of nitrate and total phosphorous allowed the regionalization of greyWF at different spatial scales under LULC changes. According to critical threshold of reference catchments, HSI identified basins into less sustainable and more sustainable areas. On the other hand, conservation practices simulated through S2+EbA scenario envisaged not only additional, viable best management practices, but also preventive decision making at the headwaters of water supply systems.

Key words: water quality modeling; Ecosystem-based Adaptation; SWAT; grey water footprint; land-use/land-cover change; Brazil.

5.1. Introduction

The Basin Plan comprises the main management tool, the planning for sustainable use of water resources in both spatial and temporal scales. For sustainable water allocation, river plans are based on accurate data on actual water availability per basin, taking into account water needs for humans; environmental water requirements and the basin's ability to assimilate pollution (Mekonnen et al., 2015). However, adaptive management options such as Ecosystem-based Adaptation (EbA; see CBD, 2010; BFN/GIZ, 2013) and water footprint (WF, Hoekstra & Chapagain, 2008) have rarely been incorporated in the Brazilian Basin Plans. Moreover, integrated quali-quantitative simulations and indicators of human appropriation of freshwater resources are seldom used in river plans. The WF as an environmental indicator in watershed plans was used in some countries like Spain (Velázquez et al., 2011; Aldaya et al., 2010). In Brazil, recent glossary of terms released by Brazilian National Water Agency (ANA, 2015) incorporates the WF concept to support water resources management.

The WF (Mekonnen & Hoekstra, 2015; Hoekstra et al., 2011) measures both the direct and indirect water use within a river basin. The term water use refers to *water withdrawal*, as the consumptive use of rainwater (the green water footprint) and of surface/groundwater (the blue water footprint), and *water pollution*, i.e., the volume of water used to assimilate the pollutant loads (the grey water footprint, GWF, see Chapagain et al. 2006; Hoekstra & Chapagain, 2008; Hoekstra et al., 2011). In addition, the water footprint assessment, proposed by Hoekstra et al. (2011), encompasses four phases: (1) Setting goals, (2) Accounting, (3) Sustainability assessment, and (4) Response formulation. It is worth noting that WF studies can be restricted to one specific activity of these phases or be related to more than one phase. At the water footprint response formulation phase, the EbA options, represented by best management practices (BMP) at the catchment scale, could represent a trade-off on greyWF (Zaffani et al., 2011; see Chapter 2 of this thesis). The advantage of quantifying the effects of pollution by volume, instead by concentration, is that water pollution can be considered as a demand from non-consumptive water uses (Mekonnen & Hoekstra, 2015; Hoekstra & Mekonnen, 2012), in the same measure units, becoming water demand and availability comparable.

In the context of integrated water resources management associated with land-use/land-cover (LULC) change, many existing conflicts over water use could be prevented (Winemiller et al., 2016; Aldaya et al., 2010; Oki & Kanae, 2006). For example, LULC influences water quality, which affects the supporting[6] and regulating[7] ecosystem services (Mulder et al., 2015; MEA, 2005) and needs to be monitored for adaptive and equitable management in the river basin scale (Taffarello et al., 2016; Chapter 4 of this thesis).

In spite of discussions regard the lack of representativeness of data used in early studies with greyWF (Wichelns, 2015; Zhang et al., 2010; Aldaya et al., 2010; Aldaya & Llamas, 2008), we argue that the greyWF method may account hydrologic services and provide a multidisciplinary, qualitative-quantitative integrated and transparent framework for better water policy decisions. Understanding these catchment-scale ecohydrologic processes requires not only low-frequency sampling and automated, *in situ*, high-frequency monitoring (Viswanathan et al., 2015; Bieroza et al., 2014; Halliday et al., 2012), but also the use of ecohydrologic models to protect water quality and quantity. However, freshwater quality modeling, associated with EbA, greyWF and LULC is still incipient in many river catchments. In Brazil, approximately only 5% of modeling studies evaluate nutrients into freshwater (Bressiani et al., 2015), which limit the policies on regulating ecosystem services.

In this research, we propose the regulating ecosystem services be addressed by the greyWF because it considers the water volume for self-purification of receiving water bodies affected by pollutants (Zhang et al., 2010). Thus, the hypothesis of this research is: conservation practices, addressed by BMP or EbA, and other types of land use conversion which impact hydrology and the ecosystem services (Winemiller et al., 2016) in the catchment and sub-basin scales. In these scales, the greyWF can evaluate the changes in the regulating hydrologic services. Among the three water footprint components, in this study we assessed greyWF for nitrate, total phosphorous and sediments in 20 sub-basins in the headwaters of Cantareira Water Supply System. The goal of this study is to compare freshwater quality scenarios, one of them related to EbA options through BMP, and to assess GWF under different LULC changes. This method is addressed through Nested Catchment Experiments (NCE, see Taffarello et al., 2016a and 2016b, Chapter 3 and Chapter 4 of this thesis) at a range of scales, from small catchments of 7.7 km^2 to medium-size basins of 1200 km^2 at subtropical headwaters responsible for the water supply of Sao Paulo Metropolitan Region (SPMR). This chapter consists of four sections. The first section provides a brief description of the context, gap, hypothesis and our research goals. The second section

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[6]Examples of supporting services: nutrient cycling, primary production, and soil formation.

[7] Examples of regulating services: self-depuration of pollutants, climate regulation, erosion control, flood atenuations and water borne diseases.

describes the simulation methods used in the watershed scale and development of three LULC scenarios. We then propose some ecosystem-based adaptation (EbA) approaches related to water pollution. Finally, we discuss *how* the grey water footprint for nitrate or total phosphorous could be an EbA option for improving decision-making and water security in subtropical catchments under change.

5.2. Material and Methods

5.2.1. The case-study area

Two of the most vulnerable areas in the Brazilian South-East are the Tietê and Piracicaba-Capivari-Jundiaí (PCJ) watersheds, particularly due to its high population (14 million inhabitants), In an attempt to ensure public water supply, the government built the Cantareira System, an inter-basin transfer, in two stages: **a)** between 1968 and 1974, at the end of a 35 year period that underwent a severe drought in the Piracicaba watershed, and **b)** in 1982, with the inclusion of two additional reservoirs that regularized the increasing rainfall from mid-1970s until 2005 (Zuffo, 2015).

The study area comprises the part of the Cantareira System that drains into the Piracicaba river and which is the headwater of the Piracicaba basin (**Figure 5.1**). This basin is located in the borderline of the state of Minas Gerais and Sao Paulo. The water supply system in the Piracicaba watershed consists of three main reservoirs which are provided with water from the Jaguari-Jacarei, Atibainha and Cachoeira watersheds. Their water is directed to three main reservoirs named after their water suppliers: the Jaguari-Jacarei, Cachoeira and Atibainha basins (drainage areas are, respectively, 1230 km , 392 km and 312 km). The Jaguari, Cachoeira and Atibainha rivers are the main tributaries of the Piracicaba River Basin, which are tributaries of the Tiete River system, left affluent of the Parana Basin. The Cantareira System consists of two more reservoirs, located closer to the Metropolitan Region of São Paulo: Paiva Castro and Águas Claras. These two reservoirs are not part of our study area. To simplify our simulations, we did not model the flow to the dams (we did not include the dams and the complex water transfers). The water from these five reservoirs is crucial for the water supply to South America's biggest city, Sao Paulo, as well as the Metropolitan Region of Campinas.

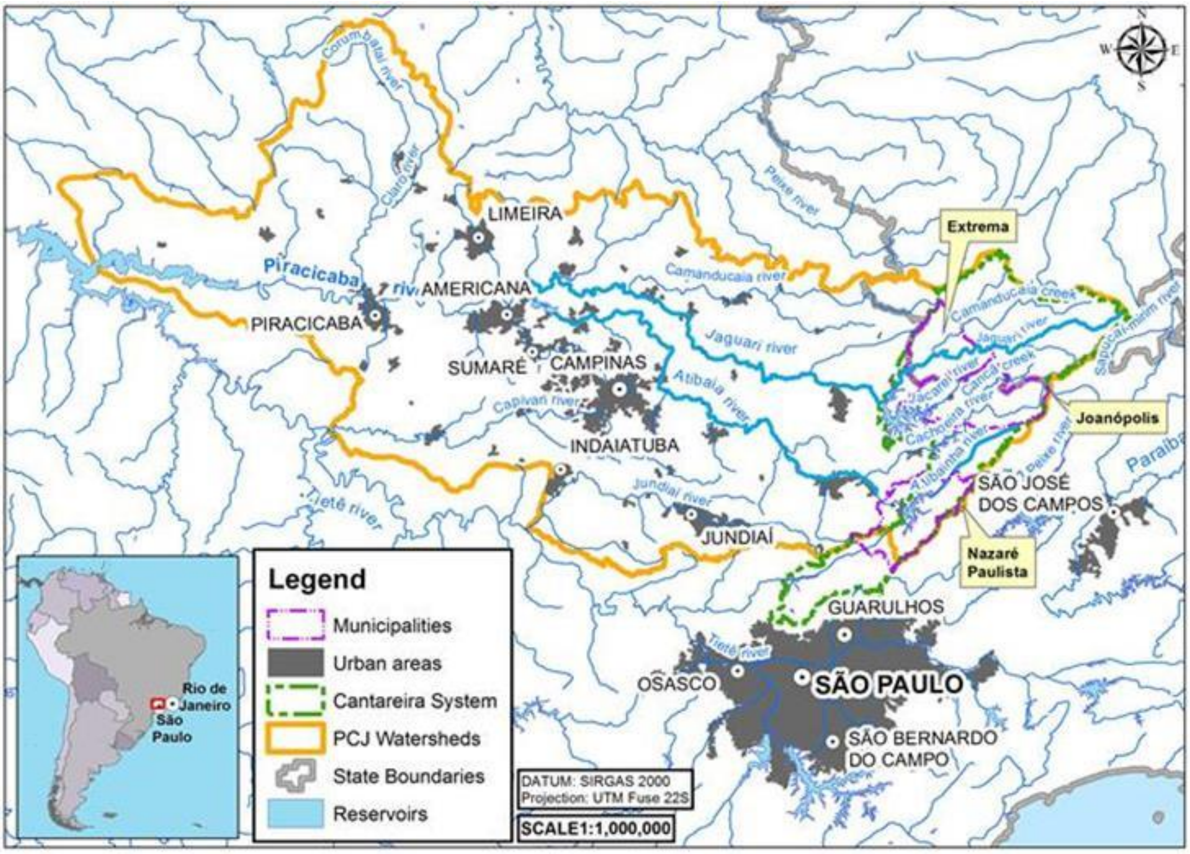

Figure 5.1. Location of Cantareira Water Supply System in the Piracicaba and Upper Tietê watersheds.

With respect to the water quality, the headwaters of the Cantareira System are classified as “class 1” for Jacareí, Cachoeira and Atibainha watersheds, and “class 2” for the Jaguari watershed, according to CONAMA Resolution Nº 357/2005 (Brazil, 2005) and Sao Paulo Decree Nº 8468/1976 (Sao Paulo, 1976), which means that, with the exception of the Jaguari watershed, the others can be used without previous treatment. And regarding the water volume, this region has been intensely impacted by a severe and recent drought (Taffarello et al., 2016; Escobar, 2015; Whately & Lerer, 2015; ANA, 2015; Porto & Porto, 2014). As a result of this serious water crisis, the new ruling on the average flow of the transfer limits of the Piracicaba watershed to the Upper Tiete watershed was postponed from 2014 to May 2017 (ANA, 2015). The Cantareira System is located in the Atlantic Forest biome, considered a conservation hotspot because of its rich biodiversity. In spite of that, 78% of the original forest cover of the Cantareira watershed has been deforested over the past 30 years (Zuffo, 2015). In 2014, the native forest cover was 10% in Extrema, 12% in Joanópolis and 21% in Nazaré Paulista (SOS Mata Atlântica/INPE, 2015). To counteract deforestation, some environmental/financial trade-offs have been developed in the Cantareira headwaters for the protection of downstream water quality and the regulation of water flows. These are

Ecosystem-based Adaptation (EbA) initiatives, in which rural landowners receive economic incentives to conserve and/or restore riparian forests and implement soil conservation practices (see Chapter 3 of this thesis). The first Brazilian EbA approach was the *Water Conservator Project*, created in 2005, implemented in Extrema, Minas Gerais (Richards et al., 2015; Pereira, 2013). The Cantareira System also has, since 2009, the *Water Producer/PCJ* (Guimarães, 2013), a pioneer project in the state of Sao Paulo, which promotes: (i) forest restoration in permanent preservation areas (PPA); (ii) conservation of remaining forest fragments; and (iii) soil conservation. As a pilot project, it focuses on providing subsidies to larger scale projects (Padovezi et al., 2013). Both projects were established through public-private partnerships, strengthening EbA in Brazil.

5.2.2. Databases and model

Figure 5.2 shows the spatial data used in this study, which schematizes a greyWF method which was developed and applied to assess the regulating hydrologic services. The simulations were enhanced by model parameterization with qualitative and quantitative primary data (Mohor et al., 2015a; Mohor et al., 2015b; Taffarello et al. 2016b). This can reduce uncertainties of the model, facilitate data interpretation and provide consistent information. We conducted six field campaigns between 2012 and 2014, in partnership with ANA, CPRM, TNC-Brazil, WWF, USP/EESC, and municipalities. We have installed three data collection platforms (DCP) in catchments of Posses, Cancã and Moinho, and level and pressure sensors in paired sub-basins *(i)* with high original vegetation cover, and *(ii)* in basins that receive payment for ecosystem services due to participating in the *Water Producer/PCJ* project.

Worldwide uses of environmental service models are increasing (Posner et al., 2016). Some examples of ecohydrologic models with progressive applications in Brazilian basins are SWAT (Bremer et al., 2016; Francesconi et al., 2016; Bressiani et al., 2015), the models reviewed by de Mello et al. (2016), Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Sharp, 2016; Tallis et al., 2011), and Resource Investment Optimization System (RIOS) (Vogl et al., 2016). In the hydrological models like Qual 2K, Qual 2E, SWMM, and SWAT, input data are converted into system's outputs, with both quantity and quality variables, which represent the water balance and water quality conditions. Depending on the input data availability, the user determines whether the simulations will be carried out over annual, monthly, daily, sub-daily time (Boithias et al., 2015), and scheduled time. Since in

Brazil daily water quality data are limited, and considering the study's objectives, especially related to the dry season (extreme event that persisted for three hydrologic years in the Cantareira), we chose to run in a monthly resolution. Then, the precipitation of 2010 was applied in the three scenarios.

The Soil and Water Assessment Tool - SWAT-TAMU (Arnold et al., 1998; Arnold and Fohrer, 2005) is a public domain conceptual spatially semi-distributed model, widely used in ecohydrological and/or agricultural studies at river basin scale (Krysanova & Whyte, 2015; Krysanova & Arnold, 2008). It divides the basin into sub-basins based on an elevation map and the sub-basins are further subdivided into Hydrological Response Unit (HRU). Each HRU represents a specific combination of land use, soil type and slope class within the sub-basin. The model includes climatic, hydrological, soil, sediments and vegetation components, transport of nutrients, pesticides, bacteria, pathogens, BMP, and climate change in a river basin scale (Srinivasan et al., 2014; GASSMAN et al., 2014; Arnold et al., 2012).

The international applications of the ecohydrologic SWAT model have expanded. There have been at least 2600 published SWAT studies (SWAT Literature Database, mid-2016), with at least 400 global peer reviewed studies published/year in the last 3 years. Approximately 100 studies were presented in *2016 SWAT Beijing Conference* (SWAT, 2016). Over 160 studies were presented in the *2015 SWAT Sardinia Conference* (SWAT, 2015) and in the *SWAT Purdue Conference*, also held in 2015, 118 studies were presented. Of these studies, 8% assessed the transport of nutrients in watersheds (SWAT Purdue, Book of Abstracts, 2015). Researches using SWAT, not only for quantity, but also for water quality and ecosystem services assessments (Francesconi et al., 2016; Abbaspour et al., 2015; Duku et al., 2015; Dagupatti & Srinivasan, 2015; Gassman et al., 2014) and also as an educational tool for

comparing hydrologic processes (Rajib et al., 2016) have increased in recent years.

Next, we obtained and organized secondary data from the region upstream of the Jaguari-Jacareí, Cachoeira and Atibainha reservoirs. We then set up a database originating from several sources: Hidroweb (ANA, 2014); Basic Sanitation Company of the State of Sao Paulo (SABESP); Integrated Center for Agrometeorology Information (CIIAGRO, 2014); Department of Water and Power (DAEE); National Institute of Meteorology (INMET) from the Center for Weather Forecasts and Climate Studies (CPTEC/INPE).

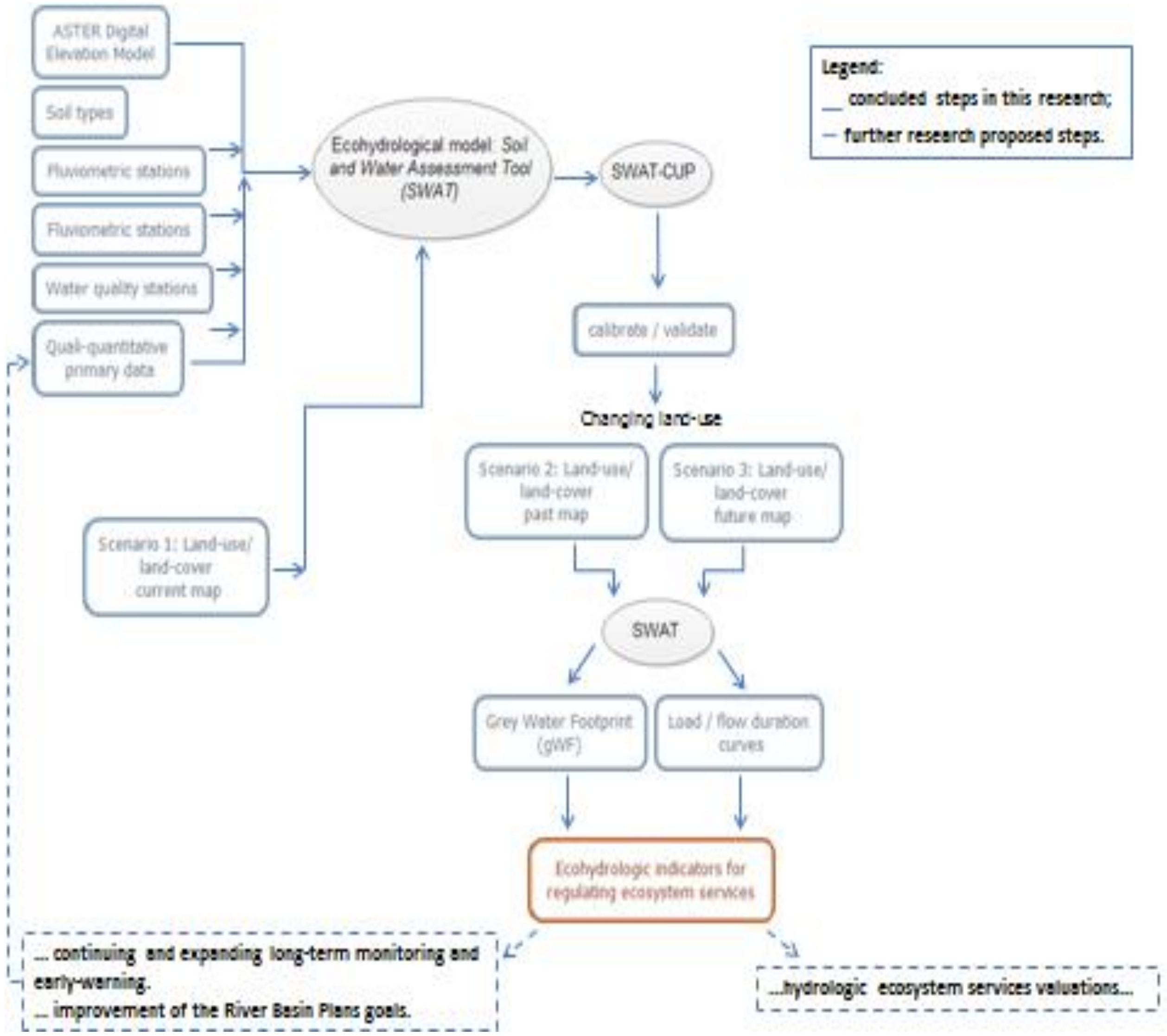

Figure 5.2. Methodological scheme for assessing hydrologic services based on GWF.

Annex-A summarizes all hydrological, pedological, meteorological and land-use data used as input for the delineation and characterization of the watersheds. The topographical data used was the Digital Elevation Model "ASTER Global DEM", 2ª version, 30-m (Tachikawa, et al., 2011), available free of charge at: http://gdex.cr.usgs.gov/gdex/. We selected the area as defined by UTM coordinates: -22.5833 (north latitude) and -23.333 (south latitude); -45.8333 (east longitude) and -46.6667 (west longitude). The depressions of this DEM were fixed before making it available to users.

5.2.3. Model Set up

The initial model set-up used the ArcSWAT interface, integrated to ArcGIS 10.0 (Environmental Systems Research Institute - ESRI, 2010), (ArcSWAT 2012.10.15 in ArcGIS

10). Simulations of the HRU-based SWAT model were conducted for the 2004–2014 period. The first 2 years served as a warm-up period for the model to assume realistic initial conditions. The delimitation of the basin using ArcSWAT requires a drainage area threshold, and this value is used to outline the sub-basins. We determined the threshold of 710 ha, dividing the geographical space to represent the 17 sampling sites in the research field as sub-basins, adding the three reservoirs, which resulted in 20 sub-basins (**Table 5.1**). We highlight that the basin was designed up to the confluence of the Jaguari and Atibaia Rivers, forming the Piracicaba river, to integrate all areas of interest in the same SWAT project.

The definition of similar HRU was accomplished using the soil maps of Sao Paulo (Oliveira, 1999), and land use maps developed by Molin (2014; et al. 2015) from LANDSAT 5 TM imagery for 2010, processed for a 1:60,000 scale. Although 5 years have elapsed, as it is one of the best available land use maps of this region, we used this map to represent the current scenario. Next, we adapted the land use map developed by Guimarães (2013), which represents a 2010 land use scenario for the Cantareira System with the restoration of the most fragile degraded parcels (greatest potential for sediment production).

Table 5.1. Sub-basins delimited in SWAT with drainage areas and geographic locations.

SWAT sub-basin	Gauge station	Drainage area (km^2)	Coordinates	
			Lat.	Long.
1	AltoJaguari	302.2	-22.820	-46.154
2	F23	508.1	-22.827	-46.314
3	F28	276.8	-22.806	-45.989
4	Salto	15.0	-22.838	-46.218
5	Pq Eventos	926.5	-22.853	-46.325
6	Posses Exut	11.9	-22.833	-46.231
7	Portal das Estrelas	7.1	-22.820	-46.244
8	F25B	971.9	-22.850	-46.346
9	Domithildes	9.9	-22.886	-46.222
10	B. Jaguari	1037.0	-22.896	-46.385
11	F30	15.1	-22.935	-46.212
12	Ponte Cach.	121.0	-22.967	-46.171
13	Chale Pt Verde	107.9	-22.964	-46.181
14	Cach Pretos	101.2	-22.968	-46.171
15	B. Jacarei	200.5	-22.959	-46.341
16	F24	293.5	-22.983	-46.244
17	B. Cachoeira	391.7	-46.209	-46.276
18	F34	129.2	-23.073	-46.209
19	B. Atibainha	313.8	-23.182	-46.342
20	Moinho	16.9	-23.209	-46.357

We adapted the land use classes of Guimarães (2013) to agree with the land use classes of Molin (2014). Additionally, we assumed that the Second Scenario of Guimarães (2013), who used the INVEST model to provide the ecological restoration benefits in the Cantareira System, could be achieved in 2035, considering the investments provided under the PCJ River Plan (Cobrape, 2011) for the recovery of riparian forests in the Cantareira System (in the PCJ Basin Plan this is called Tendency Scenario). As in the region the restoration of riparian forests is mostly due to Water-PES projects, which was recognized as an Ecosystem-based Adaptation (EbA) alternative (CBD, 2010; BFN/GIZ, 2013; Taffarello et al., submitted, Chapter 2), we identify the third scenario as S2+EbA. Thus, **Figure 5.3** shows the land-use changes over time.

In the "Trend Scenario"(PCJ-COBRAPE, 2011), the municipalities covered by the Cantareira System could reach a 98% collection rate, collected sewage treatment rate of 100% and $BOD_{5,20}$ removal efficiency of 95% (Cobrape, 2011). We emphasize that in Brazil the current allowed discharge is only based of the $BOD_{5,20}$ parameter. Some studies have suggested the inclusion of other parameters such as dissolved oxygen, nitrate and phosphate polluting loads, and sediments to assess the water quality (Cruz, 2015; Cunha et al., 2014). Regarding the treatment costs for drinking supply, ecosystem-based adaptation options, such as watershed restoration, seems to be more cost-effective than several technologies for water treatment (Cunha; Sabogal-Paz & Dodds, 2016)..

5.2.4. Defining contributing areas of sub-basins

The discretization sub-basins were taken up to fit, if feasible, the same NCE sites of available field observations (see Chapter 4 of this thesis). In-site samples were feed into SWAT distributed model, also with points of qualitative and quantitative monitoring of 17 control points. This procedure, combined with the addition of three reservoirs and river mouth around the Cantareira System, resulted in the automatic design of 20 sub-basins, with a threshold of 7.1 km^2 to define sub-basins (**Figure 5.8**). This threshold is close to the minimum drainage area sampled (Taffarello et al, 2016; see Chapter 4 of this thesis). Drainage areas ranged approximately 10 to 1000 km^2. For optimized calibration, we defined 49 HRU inside the 20 sub-basins. In other words, SWAT model defined 49 different combinations of soil type, soil cover and slope classes in our study area.

We highlight some SWAT model limitations when we compare the simulated to observed water flows, especially in the dry season. For example, when the model was discretized on a daily resolution, the adherence level between observed and simulated flows was considered good. However, the model has not fitted well to observed values during the drought period (Fev./2014-May/2014). These differences were more significant for water quality parameters, such as nitrate and total phosphorous. We point that the macronutrient loads found in May 2014 were clearly higher than the loads we have found in previous sampling, which occurred in wetter period (Taffarello et al. 2016). For the sample collected in May, the model significantly underestimated the pollutant loads of nitrate. This behavior, arising from the recent and most severe drought faced by the Cantareira System (Nobre et al., 2016; Escobar, 2015; The Economist, 2015; Porto & Porto, 2014, Palmer *et al.*, 2014), shows the urgent need for the improvement of the SWAT model performance during extreme events, especially to capture non-linearities with impacts in regulating ecosystem services.

5.2.5. Calibration & validation

We used the SWAT CUP 5.1.6.2 interfaces and Sequential Uncertainty Fitting (SUFI-2 algorithm) for calibrating the quantity and quality parameters and also for validating the simulations in the sub-basins. Quantitative calibration was performed in stations that had more than two full years of observed data, i.e., 8 stations, namely: Posses outlet, F23, F24, F25B, F28, Atibainha reservoir, Cachoeira reservoir, Jaguari and Jacarei reservoir (**Table 5.2**). The calibration period was from October 2007 to September 2009, the period with observed data in all of the above 8 stations. Validation took place from January 2006 to September 2007 and from October 2009 to June 2014. Calibration and validation of SWAT at the stations with over 2 years of data were rated as “good”, according to the classification by Moriasi et al. (2007), since the Nash-Sutcliffe Efficiency (NSE) criterion (Nash & Sutcliffe, 1970) was greater than 0.65, except for the Posses outlet, which presented the logarithmic Nash-Sutcliffe of flows (a criterion that gives greater weight to smaller flow rates) of less than 0.5 which was rated as “unsatisfactory”.

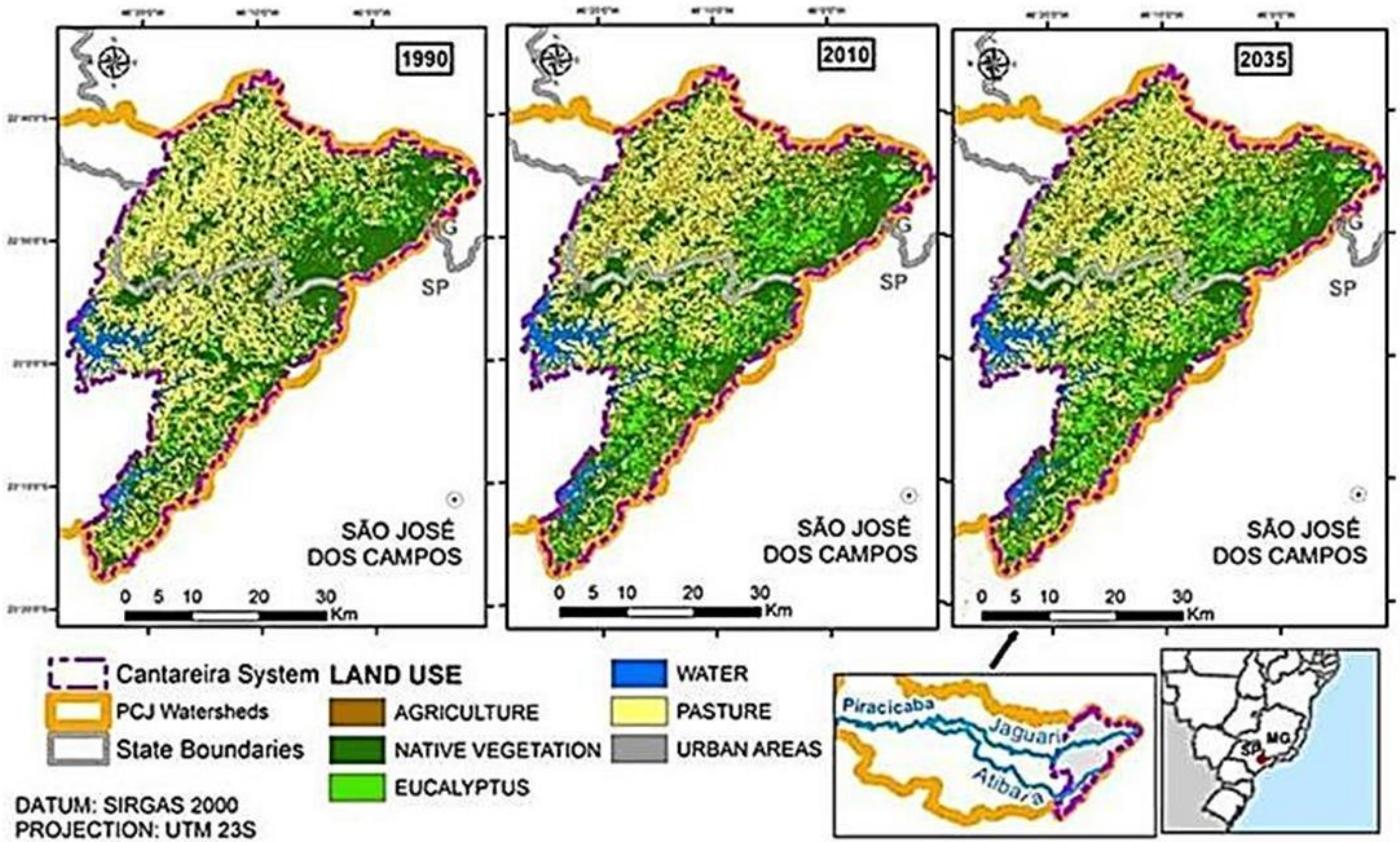

Figure 5.3. Land use change during 1990 (Scenario S1), 2010 (Scenario S2) and 2035 (Scenario S2+EbA) in the headwaters of the Cantareira Water Supply System.

The Percent Bias (PBIAS) statistics indicates the bias percentage of simulated flows relative to the observed flows (Gupta et al., 1999). Thus, when the PBIAS value is closer to zero, it results in a better representation of the basin, and in lower estimate tendencies (Moriasi et al., 2007). As a general rule, if |PBIAS| < 10%, it means a very good fit; 10% < | PBIAS |< 15%, good; 15% < | PBIAS | < 25%, satisfactory and | PBIAS | > 25%, the model is inappropriate. On the other hand, the NASH coefficient translates the application efficiency of the model into more accurate predictions of flood flows, and using the classification: NASH> 0.65 the model is rated as very good; 0.54 < NASH < 0.65 the model is rated as good and between 0.5 and 0.54, it is rated as satisfactory.

Table 5.2. Characteristics of quantitative calibration and validation of SWAT in studied catchments (Moriasi et al., 2007).

Gauge station	Area (km)	Pbias (%)	NSE (-)	NSE Log (-)	Pbias (%)	NSE (-)	NSE Log(-)	Performance level of calibration and validation (Moriasi et al., 2007)
		Calibration			Validation			
Posses	13.3	-22.0	0.68	0.52	15.4	0.78	0.38	Unsatisfactory/very good
F28	281.5	5.3	0.80	0.68	14.2	0.72	0.31	Very good/good
F24	294.5	-13.3	0.69	0.71	-1.7	0.65	0.34	Satisfactory/satisfactory
Atibainha	331.7	-14.5	0.60	0.55	1.7	0.71	0.54	Satisfactory/good
Cachoeira	397.3	-26.6	0.49	0.31	-46.7	0.27	0.05	Unsatisfactory/unsatisfactory
F23	511.2	-1.8	0.88	0.90	12.0	0.84	0.77	Very good/ very good
F25B	981.4	3.6	0.91	0.89	11.4	0.77	0.72	Very good/ very good
Jag+Jac	1276.9	-12.0	0.83	0.87	-8.4	0.82	0.73	Very good/ very good

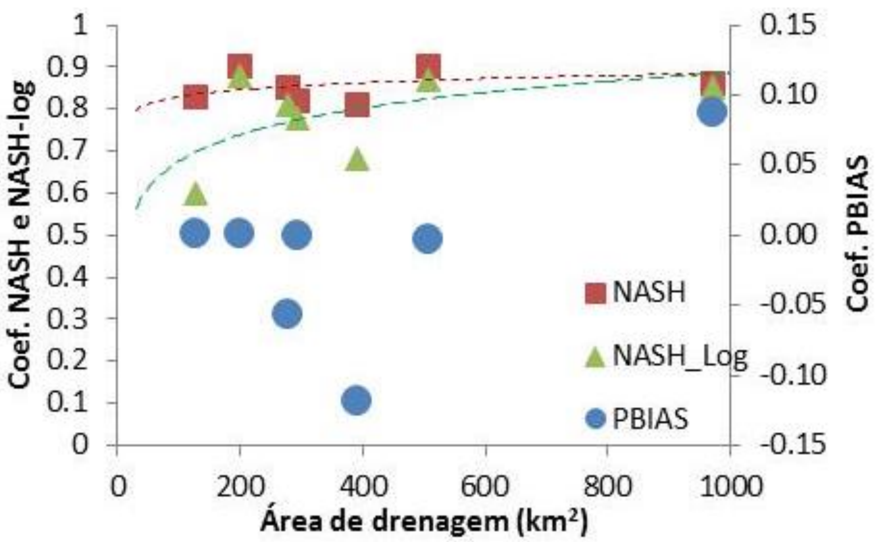

Figure 5.4. Model calibration related to drainage areas of catchments in the Cantareira System.

In the results obtained for different basin scales (**Figure 5.4**), the PBIAS and NASH coefficients (including NASH for logarithms) indicate adequate quantitative adjustments. As the SWAT simulations include more than 200 parameters, based on literature surveys (Duku et al., 2015; Bressiani et al., 2015; Arnold et al., 2012; Garbossa et al., 2011), we selected approximately 10 parameters (see **Table 5.3**) to complete the calibration to simulate streamflow processes and nutrients dynamics. These parameters refer to key processes which represent soil water storage, infiltration, evapotranspiration, flow channel, boundary conditions (see Mohor et al., 2015b) and main water quality processes at hillslopes. Although our calibration is mainly focused on water yield as total runoff, freshwater quality features through pollutant loads were performed in the scenarios.

Moreover, to reduce the uncertainty of our predictions, we used approximately 2500 primary data derived from the experimental stage of this research to measure the parameters, reducing the uncertainties in the estimates of variables in the ecohydrological modeling stage of our research. Our decision to complement field and laboratory methods with computational tools in order to understand the behavior of basins is justified by Tucci (1998), who explains the need for flow and other hydrological variables measurements, in addition to using the models, because *"none methodology can increase the existing information in the data, but can better extract the existing information."* As a parametrization result of field investigations and ecohydrological modeling, **Figure 5.5** shows parts of calibrated model performance (lines) against field observations (dots with experimental uncertainty) for flow discharges, nitrate and total phosphorus loads for catchment areas ranging from 7.1 to 508 km^2. Finally, other water quality variables were studied from data from field sampling.

Differences in flow rates and water quality (for the variables nitrate, phosphate, $BOD_{5,20}$, turbidity and fecal coliforms) for the 20 sub-basins were evaluated using flow and load duration curves for the three scenarios proposed in this study: (i) *recently past scenario* (S1), including the recorded past events for land use in 1990, (ii) *current land use scenario* (S2), which considered land uses for the 2010-2015 period as the baseline, and (iii) *future land use scenario* (S2+EbA), supposing a forest cover conversion in the protected areas, through EbA options, according to the PCJ River Basin Plan by 2035. Using these curves, from the methodology exposed by Hoekstra et al. (2011), and based on Duku et al. (2015) and Cunha et al. (2012), we estimated the grey water footprint (GWF). Next, we developed an ecohydrological index to assess the regulating hydrologic services.

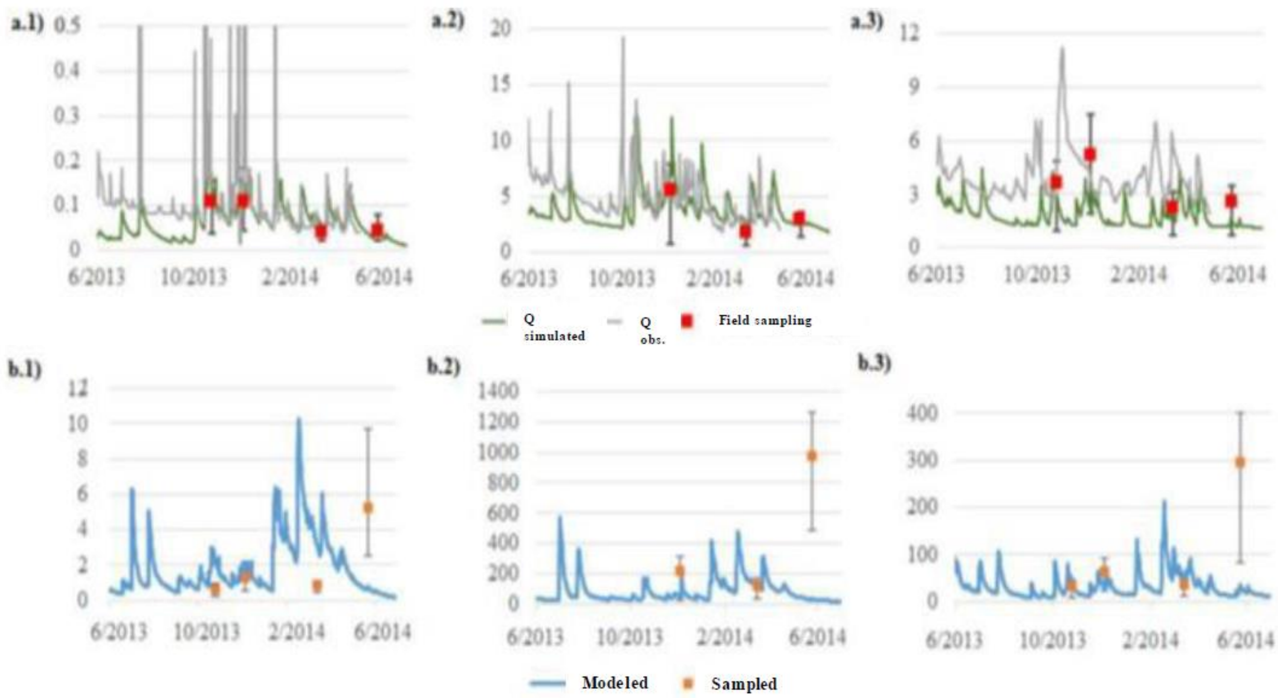

Figure 5.5. Comparison between (a) flows discharge (m^3/s) and (b) nitrate loads (kg/d) measured at field and simulated by SWAT, at monitored stations of (1) *Posses Outlet* (A=12 km^2), (2) *F23* (*Camanducai*a, A = 508 km^2), and (3) *F24* (*Cachoeira*, A= 293.5 km^2). The uncertainty bars were determined using the instantaneous velocities measured in the river cross-sections in the 2013-14 field campaigns.

5.2.6. A new index for hydrologic services assessment

Also, we propose a new index for hydrologic services assessment related to the grey water footprint. On the one hand, this new indicator encompasses the former theory related to environmental sustainability of the greyWF, according to Hoekstra et al. (2011). In this work, as a relevant local impact indicator, Hoekstra et al. (2011) propose calculating the 'water pollution level' (WPL) within the catchment, which measures the degree of pollution. WPL is defined as a fraction of the waste assimilation capacity consumed and calculated by taking the ratio of the total of greyWF in a catchment (ΣWF_{grey}) to the actual runoff from that catchment (R_{act}), or, in a proxy manner, the water yield or mean water yield or long-term period (Q_{lp}). This assumption is that a water pollution level of 100 per cent means that the waste assimilation capacity has been fully consumed. Also, this assumption approaches that when WPL exceeds 100 per cent, ambient water quality standards are violated, as:

$$WPL[x,t] = \frac{\sum WF_{grey}[x,t]}{R_{act}[x,t]}$$

It is worth mentioning that, for some experts, the forementioned equation can overestimate the flow necessary to dilute pollutants. For that reason, it is recommended new insights of composite indicators or thresholds, as follows.

On the other hand, the above assumption could overestimate WPL because it would fail considering the combined capacity of water to assimilate multiple pollutants (Hoekstra et al., 2012; Smakhtin et al., 2005). Conversely, in this work, we define an alternative indicator related to the three following fundamentals. First, the WPL should be extended to a composite index, thereby representing weights of each pollutant related to the actual runoff, here as a proxy of long-term runoff, i.e.:

$$WPL_{composite}[x,t] = \frac{\sum\{w[x,t]\cdot WF_{grey}[x,t]\}}{R_{act}[x,t] \cong Q_{lp}[x,t]}$$

$$\sum w[x,t] = 1$$

$$0 \leq w[x,t] \leq 1$$

For this new equation, weights should be assessed, either from field experiments or even from simulation outputs. Second, I define a threshold value of WPLcomposite regarding the reference catchments with non-developed conditions which suggest more conservation conditions among other catchments of the same region, as $WPL_{reference}$. For this work, we selected *Domithildes* catchment, as the reference catchment with conservancy measures. From this reference catchment we define the referenced, composite water pollution level, as $WPL_{composite,ref}$ and with a derived the Hydrologic Service Index, as a non dimensional factor of comparing WPL for referenced and non-referenced catchment, as follows:

$$HSI[x,t]_{greyWF} = \frac{[WPL[x,t] - WPL_{composite,ref}]}{WPL_{composite,ref}}$$

5.3. Results and Discussion

In the following section we present results from field observations, useful not only for ecohydrologic parameterization, but also to elucidate features regarding GWF and hydrologic services. Next, we compare GWF outputs from simulations of LULC scenarios, including EbA options, to finally propose a new hydrological services indicator.

Table 5.3. Calibrated SWAT parameters in the headwaters of Cantareira Water Supply System.

	Description	Parameter	Fitted values
Water Quantity	Initial SCS curve number (moisture condition II) for runoff potential.	CN2	<0.25
	Soil evaporation compensation factor.	ESCO	<0.2
	Plant uptake compensation factor.	EPCO	<1.0
	Maximum canopy storage (mm).	CANMX	Varies by vegetal cover
	Manning's coefficient "n" value for the main channel.	CH_N2	0.025
Water Quality	Nitrate percolation coefficient	NPERCO	0.2
	Minimum value of the USLE C coefficient for water erosion related to the land cover	USLE_C	Varies by land use (< 0.4)

5.3.1. Data from field sampling

The variations in LULC affect freshwater quality which, in turn, affect the dynamics of aquatic ecosystems (Zaffani et al., 2015; Botelho et al., 2013; Hamel et al., 2013; Bach & Ostrowski, 2013; Kaiser et al., 2013). These changes impact the hydrological services, especially the regulating and supporting ecosystem services (Mulder et al., 2015; Molin, 2014). Some of the water quality and quantity variables from our freshwater monitoring are relevant in the hydrological services assessment, thus they are presented in **Table 5.4**. These variables were selected due to its relation to the anthropic impacts into the water bodies and as a function of its sanitary relevance.

Table 5.4. Maximum and minimum values of quali-quantitatives variables observed during field campaigns of Oct. 2013-May 2014 in the headwaters of Cantareira System, South-East, Brazil.

Sub-basin	Flow discharge MIN. (m^3/s)	Flow discharge MAX. (m^3/s)	Electrical conductivity MIN (µS/cm)	Electrical conductivity MAX (µS/cm)	pH MIN.	pH MAX.	BOD MIN (mg./L)	BOD MAX (mg/.L)	COD MIN (mg/.L)	COD MAX (mg./L)	E. Coli MIN (ufc)	E. Coli MAX (ufc)
Upper Posses	0,009	0,034	54	63	6,6	7,0	<1	<1	6	19	10	870
Middle Posses	0,031	0,082	53	63	6,8	7,0	<1	<1	8	26	14	260
Outlet Posses	0,039	0,107	65	133	6,7	7,1	2	2	5	24	1	2000
Outlet Salto	0,032	0,093	22	62	6,6	7,2	4	4	4	22	4	4800
F23	1,706	5,500	44	60	6,7	6,9	6	6	18	48	17	3600
Upper Jaguari	1,387	6,283	23	59	6,9	7,0	2	2	2	28	2	100
Parque de Eventos	4,568	20,689	38	50	6,6	6,9	2	6	11	36	31	4100
Cachoeira dos Pretos	1,460	3,060	13	17	6,7	7,0	<1	<1	6	20	33	37
Chalé Ponto Verde	1,540	3,223	14	16	6,8	7,1	<1	2	6	21	3	290
Ponte Cachoeira	1,400	3,618	15	20	6,3	7,0	2	3	6	26	340	4000
F24	2,250	5,174	22	28	6,7	6,9	2	4	10	34	5	690
Intervention Cancã	0,005	0,022	39	48	6,7	7,0	3	3	3	22	40	730
Reference Cancã	0,002	0,009	42	48	6,6	7,1	2	2	5	27	5	650
F30	0,641	1,297	36	40	6,8	7,1	3	4	9	42	140	3400
Intervention Moinho	0,003	0,055	34	41	6,1	7,1	5	8	6	22	17	160
Reference Moinho	0,004	0,017	34	35	6,7	6,9	<1	<1	4	16	690	2400
Outlet Moinho	0,081	0,162	51	60	6,8	7,0	<1	<1	6	23	99	1300

Among the water quality variables sampled in field step, we highlight turbidity because it indicates a proxy estimation about the total suspended solids in lotic environments (UNEP, 2008), related to the LULC conversion and reflect the changes in the hydrological services. The **Figure 5.6** shows the direct correlation between turbidity and size of the sub-basins. Turbidity can indirectly indicate anthropic impacts in streams and rivers (Martinelli et al., 1999). The lower turbidity mean values were observed in two more conserved sub-basins (which presented higher amounts of forest remnants): 2,7 NTU in the *reference Cancã* farm and 4,7 NTU in *Upper Posses*. Other conserved subbasins also presented low mean values of turbidity (< 6,5 NTU): *intervention Cancã* farm (6,2 NTU), and *Cachoeira dos Pretos* (6,4 NTU). We found the highest turbidity, above 40 NTU considered the maximum established water quality conditions for Class 1 according to environmental standards (BRASIL, 2005), in the *Parque de Eventos* (76,8 NTU), *F23* (69,5 NTU) and *Salto outlet* (50,8 NTU). However, these three sampling sites are located at water bodies of Class 2, which the maximum turbidity allowed is up to 100 NTU (BRAZIL, 2005). Thus, it shows that, although these areas have the highest urbanization among sampled sites, they are in accordance to Brazilian environmental resolutions. Arroio Júnior (2013) found a decreasing relation between turbidity and drainage area in another catchment located in Sao Paulo state.

Temporal patterns of turbidity point that in 11 from 17 monitored sites, on the one hand, the higher values of turbidity occurred in December 2013, the unique field campaign with significant precipitation (35,3 mm) and with higher antecedent precipitation index (API = 123,7mm). This can be due to the carrying of allochthone particles which are drained into rivers by precipitation. Similarly, Arroio Júnior (2013), also observing higher turbidity in rainy month (December 2012) which can lead to erosive processes. On the other hand, Zaffani et al. (2015) show that turbidity did not varied over the hydrological year in medium-size, rural and peri-urban watersheds ranging from 1 to 242 km^2. In this case, other factors can have influenced, such as deforestation, seasonal variability, soil use type, sewage and mining (CETESB, 2015; Tundisi, 2014). Our study shows two catchments with maximum turbidity higher than Brazilian environmental standards (Brazil, 2005): 67 NTU for *Upper Jaguari* and 59 NTU for *Cancan outlet*, one site under this limit (Cancan outlet) and three sites with maximum turbidity above 100 NTU: *Parque de Eventos*, in Jaguari river, with 283 NTU; *F23 gauge* in Camanducaia river, with 180 NTU, and *Salto outlet*, with 160 NTU. These sites do not obey the Class II Standards. On the other hand, the **Figure 5.7** presents a multidimensional chart which integrates hydraulic and water quality variables.

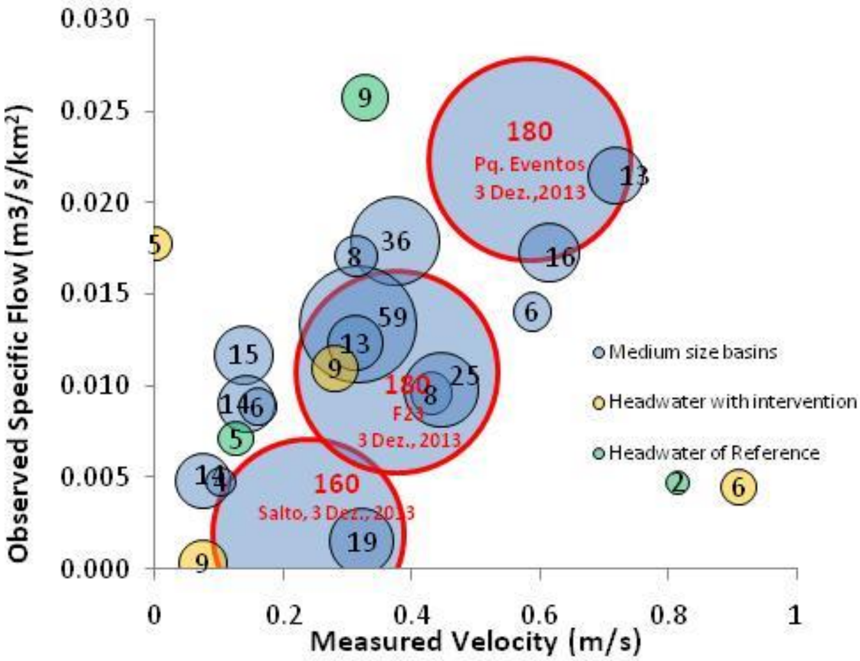

Figure 5.6. Experimental sampling of turbidity, observed flowsand mean velocities in river cross sections of 17 catchments in Cantareira System headwater (Oct. 2013 - May2014)

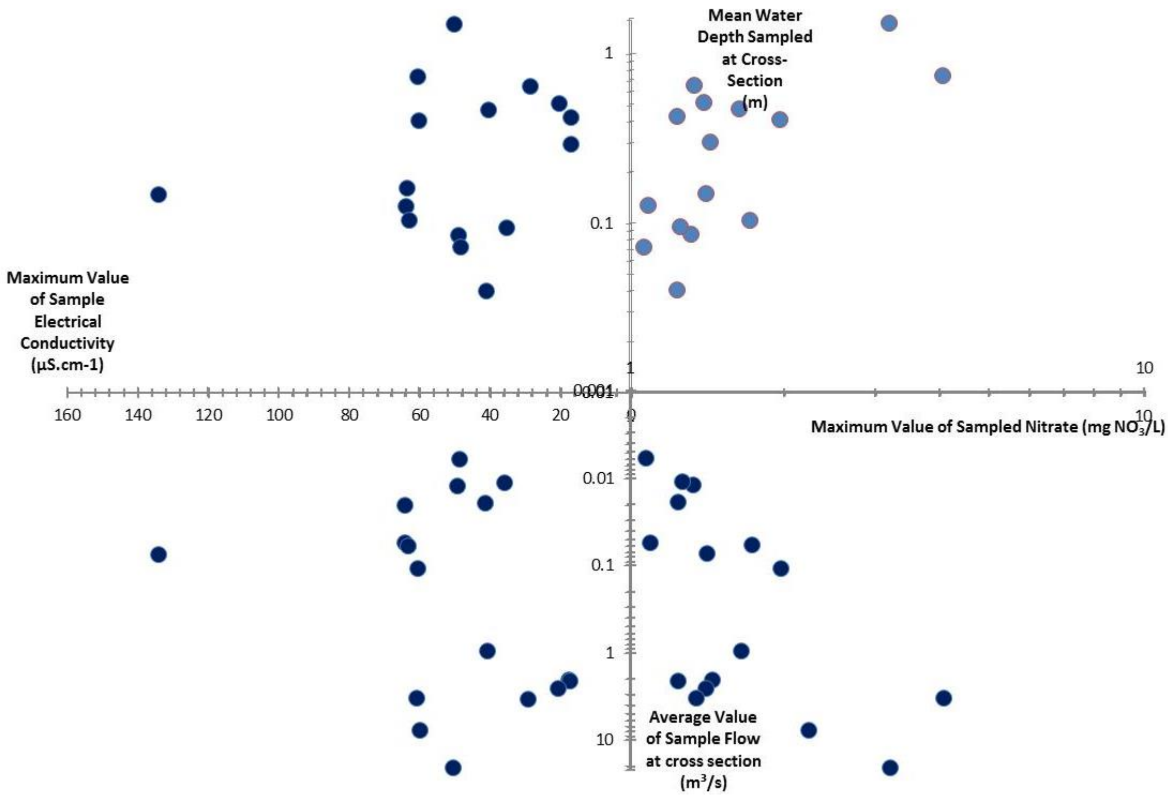

Figure 5.7. Multidimensional chart of hydraulic and water quality variables sampled in field campaigns in the headwaters of Cantareira Water Supply System between Oct. 2013 - May 2014.

Figure 5.7 illustrates empirical relations from field sampling throughout experimental surveys in Oct.2013-May2014, thereby enhancing non-linear relations and complexity of not-sampled factors. The choice of maximum values for electrical conductivity and nitrate concentrations is because it can represent the limit conditions for the rivers autodepuration and aquatic ecosystems health. The right quadrants of **Figure 5.7** show a positive relationship between nitrate concentrations and flow both discharges and mean water level. It is possible to infer that higher concentrations of macronutrients would be found in downstream areas. This trend can be associated to the nutrients migration (Cunha et al., 2013), land-use change (Zaffani et al., 2015), besides punctual pollution. In addition, the absent of riparian forest in 70% of protected area (36.844 ha) of the Cantareira System (Guimarães, 2013) can increase the sedimentation and make the pollutants filtration more difficult, leading to higher nitrate concentrations downstream. Furthermore, we could not evidence clear relationships between electrical conductivity and measurements of water level and flow discharges (**Figure 5.7**, left side). Besides, the untypical values of 135 μS/cm and 0.074 m^3/s show higher sensitivity of physico-chemical and hydraulics variables to the external factors, hydrodynamics or seasonal local influences. Santos (2014), in a water quality evaluation in watersheds with implemented conservation practices (*Posses* and *Salto*), found electrical conductivity lower than 50 $\mu S.cm^{-1}$ in forest remnants areas, and more than 100 $\mu S.cm^{-1}$ in the stretch of Jaguari river between our SWAT subbasin 1 (*Upper Jaguari*) and subbasin 5 (*Parque de Eventos*), where anthropization covers 3 % of area. In general, areas with higher anthropization rates present higher ionic concentrations (Martinelli et al., 1999; Piccirelli Santos, 2014), which can be shown by the electrical conductivity. However, outliers values difficult a better comprehension of geomorfological health of rivers and of the functioning of complex riverine ecosystems with very high biodiversity, as occurs in this subtropical region.

5.3.2. Setting time-steps of hydrologic modeling under scenarios

The changes in hydrologic services can be evaluated by a wide number of models (Carvalho-Santos et al, 2016; Duku et al, 2015; Quilbé & Rousseau, 2007), especially those more user-friendly for stakeholders and policy makers. Simulations in this watershed-scale ecohydrological model (Williams et al, 2008; and Borah & Bera, 2003) allow the quantification of important variables for ecosystem services analysis and decision-making. The evaluation of the results from simulations approaches the balance of the components of the hydrological cycle at defined geographic and temporal scales. Hydrological models with freshwater quality routines (eg., QUAL-2K, QUAL-2E, SWMM, SWAT) represent the water balance and the coupling processes of water quality. Considering the integrated ecohydrological processes of an entire river basin, thereby linking LULC changes, greyWF outputs and EbA tradeoffs, we here propose a spatially-distributed model which incorporates the regional variabilities of field observations in 17 NCE sites (see Chapter 4), with time steps in accordance with expected intra-annual river regimes, pointing high flows and low flows. In our case, using SWAT for assessing the regulating ecosystem services permit a versatility with ecohydrological aspects of water yield and intra-annual regime, integrating water quantity and quality to assess expected greyWF under semi-distributed modeling with some computational constraints (Tucci, 2015; Santos, 2009). Depending on the availability of input data, as a user we can determine the simulations carried by the more appropriate time-steps (Boithias et al., 2015). Considering the frequency of qualitative and quantitative data available, and according the field experiments (see Chapter 4), monthly time step was defined appropriate to hypothesis testing of GWF and water yield under different LULC scenarios, including EbA. A common test period for all LULC scenarios was selected with several years. In our case, the test period ranges from 01 Jan., 2006 to 30 June 2014. This period has the rain-anomaly of drought conditions of 2013-14. In summary, different LULC scenarios were tested with the same input data series.

5.3.3. LULC change scenarios

We then evaluated the three land-use scenarios. A past-condition scenario (S1, in 1990), a present-condition (S2, in 2010) and a future (S2+Eba, in 2035) LULC scenario, applying the same weather input datafiles, are shown in **Table 5.5**. This allow us to compare the mainly soil uses in 1990, 2010 e 2035 into 20 sub-basins of Cantareira System.

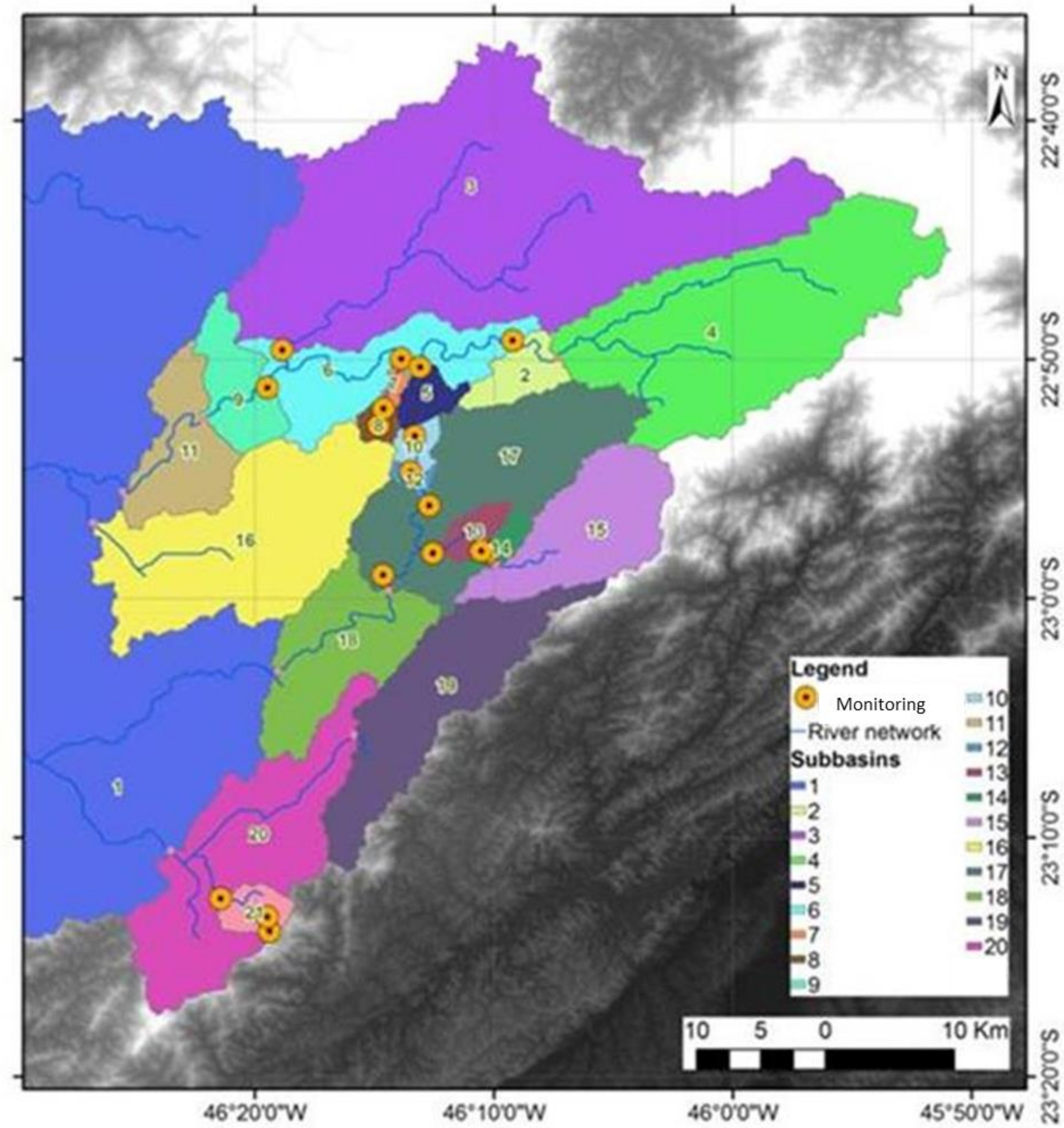

Figure 5.8. Study area divided into sub-basins for hypothesis testing through semi-distributed SWAT model.

Table 5.5.LULC changes in 20 sub-basins, headwaters of Cantareira System, for scenarios of S1 (LULC in 1990), S2 (LULC in 2010) and S2+EbA (LULC in 2035).

Sub-basin	Gauge station	Dranaige area(km^2)	Equivalent scenario timeline	Land-Use/Land-Cover (% of drainage area)				
				Native forest	Euca-lypto	Pasture	Agri-culture	Urban
1	Upper Jaguari	302.20	1990	47	6	35	12	0
			2010	33	13	34	20	0
			2035	66.2	21.1	8.2	4.6	0.3
2	F23	508.10	1990	37	2	52	9	0
			2010	34	2	44	19	0
			2035	36.2	2.3	42.5	18.6	0.5
3	F28	276.80	1990	78	8	11	3	0
			2010	69	22	6	3	0
			2035	69.1	21.3	6	3.3	0.3
4	Salto	15.06	1990	40	1	50	9	0
			2010	29	2	53	16	0
			2035	31.5	2.4	50.5	15.5	0
5	Pq. Eventos	926.50	1990	35	1	50	11	3
			2010	36	2	44	15	3
			2035	45.8	8.2	31.9	13.5	0.6
6	Posses outlet	11.99	1990	22	2	67	9	0
			2010	13	1	70	16	0
			2035	15.6	0.7	70.2	13.5	0
7	Portal Estrelas	7.17	1990	24	0	62	14	0
			2010	15	1	72	12	0
			2035	17.1	0.6	70.5	11.8	0
8	F25B	971.90	1990	33	2	50	10	5
			2010	38	1	43	13	5
			2035	45.5	7.9	32.3	13.5	0.8
9	Domithildes	9.93	1990	51	0	37	12	0
			2010	52	5	30	13	0
			2035	56.4	4.6	27.3	11.7	0
10	B. Jaguari*	1037.00	1990	37	1	52	11	0
			2010	40	2	41	16	0
			2035	45	8	32.6	13.6	0.8
11	F30	15.14	1990	30	1	57	12	0
			2010	28	4	54	14	0
			2035	47.3	4.4	35,8	12.5	0
12	Ponte Cachoeira	121.00	1990	31	0	62	7	0
			2010	31	9	48	11	0
			2035	58.9	20.1	15.3	5.7	0
13	Chale Pt. Verde	107.90	1990	39	8	46	7	0
			2010	29	31	30	10	0
			2035	62,1	21.5	11	5.1	0
14	Cachoeira dos Pretos	101.20	1990	59	8	27	6	0
			2010	66	20	9	5	0
			2035	66.2	20.3	8.7	4.6	0
15	B. Jacareí*	200.50	1990	32	0	52	13	2
			2010	39	5	42	13	2
			2035	32.7	2.7	32.1	10.3	2
16	F24	293.50	1990	56	4	32	8	0
			2010	47	18	25	9	0
			2035	53.2	17.8	21.3	7.7	0
17	B. Cachoeira*	391.70	1990	35	6	47	11	0
			2010	42	21	27	10	0
			2035	50.1	18.1	22	7.9	0
18	F34	129.20	1990	59	9	23	9	0
			2010	61	19	10	10	0
			2035	61.4	19.3	9.9	9.3	0
19	B.Atibainha*	313.80	1990	49	7	30	13	0
			2010	60	18	13	9	0
			2035	56.3	17.5	10.8	8.8	0
20	Moinho	16.90	1990	46	10	27	17	0
			2010	49	22	17	13	0
			2035	49.9	21.4	16.2	12.5	0

In **Table 5.5**, sub-basin B. Jaguari has significant percentage of surface waters, occupying 1% of sub-basin 10 and 20% of sub-basin 15. We evaluated the effects of LULC change scenarios in 20 catchments within Jaguari, Cachoeira and Moinho sub-basins, South-East Brazil. Concerning the land-use change, the main soil uses 25 years ago were: pasture (in 50% of the sub-basins) and native vegetation (in 45% of sub-basins). According to ISA (2012) and Molin (2014), the 5% of remaining area were divided into vegetables, eucalyptus, sparse human settlements, bare soil and mining. The main activity in the past (1990) was the extensive cattle for milk production by small farmers in the region (ANA, 2012; Veiga Neto, 2008).

In the S2 Scenario (2010), the main soil use is pasture in 58% of the sub-basins and forest in 40% of them. Between 1990 and 2010 there was a significant conversion of soil cover, with a slow reduction of pasture areas (-2%) and of native remnants (-5%) and with a progressive increase of eucalypto (*Eucalyptus* sp.), an exotic forest in Brazil. The eucalypto soil use varied from +1%, within *Posses* up to +31% in the *Chalé Ponto Verde* sub-basin in 2010. Eucalyptus cover, however, did not achieve 10% of the soil uses in any of the simulated sub-basins in 1990. In the third scenario (S2 + EbA), we hypothesized incentives to policies for forest conservation and restoration, due to the strengthening of EbA in the Cantareira System, and could lead to native vegetation achieve percentages between 15% in *Posses outlet* and 69% in *F28 sub-basin*. In this scenario the higher percentages of native vegetation will occur in the sub-basins *F28, Upper Jaguari and Cachoeira dos Pretos*.

By assessing the temporal trends of increment or reduction of native remnants, we examined the periods 1990-2010 versus 2010-2035. Between 1990 and 2010, forest increased positively in 50% in sub-basins of *Domithildes*, which a reference headwater catchment of the Water Producer/PCJ project, (see Taffarello et al., 2016, Chapter 4 of this thesis), *Moinho, Cachoeira dos Pretos, F34, B. Jacareí, B. Atibainha, B. Cachoeira, Pq Eventos, F25B* and *B. Jaguari* (**Figure 5.9**). Related to the 2010-2035 period, the model was set up with increasing of native vegetation in all sub-basins, either from native remnant in 2010 and even from new BMP practices of reforestation with native species in 20 sub-basins until year 2035 (**Figure 5.9**). The hidro-services in *Posses* and *Salto* catchments and in the *Cachoeira* sub-basin will be increased in 2035 as a function of the efforts on EbA which currently exist in the region (Richards et al., 2015; Piccirelli Santos, 2014; Gonçalves, 2013).

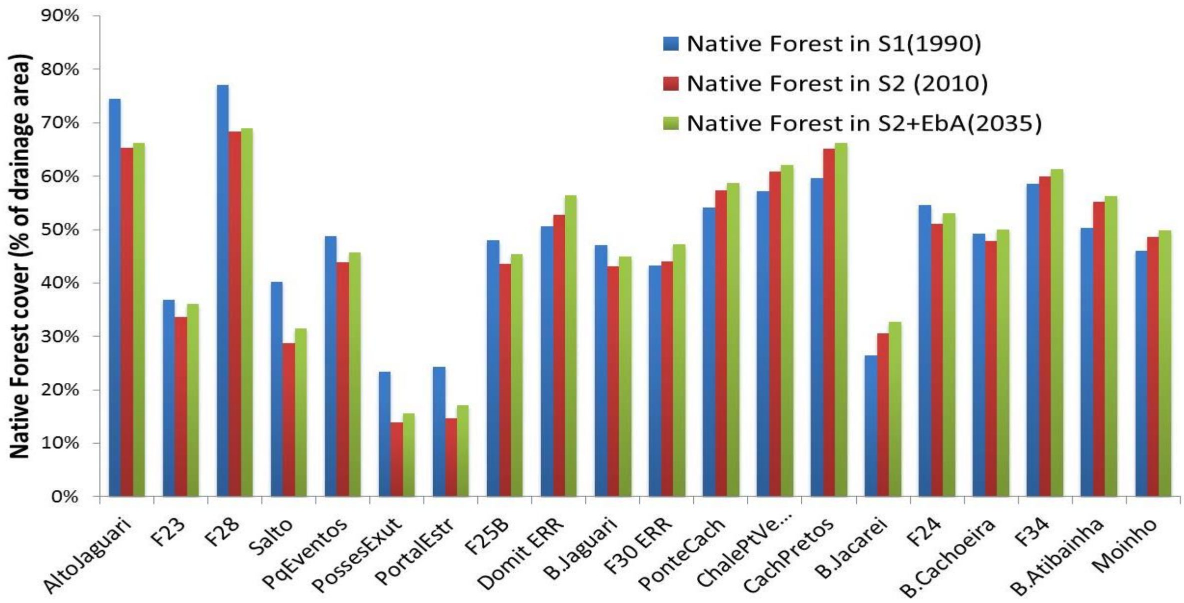

Figure 5.9. Native forests cover in S1 (year 1990), S2 (year 2010) and S2+EbA (year 2035).

Despite this general increasing of native forest cover, we highlight the deforestation occurred in the *F23* sub-basin, Camanducaia river. Currently, although it has 34% of native forest cover, this rate trend to have reducing since 1990. *F23 outlet* (sub-basin 2) presented 37% of native forest cover in 1990, becoming 34 % in 2010 and, the S2+EbA Scenario shows that F23 would achieve 36.2% of native forest in 2035, backing to the 1990's rates. Another critical situation is the *Posses outlet* (SWAT sub-basin 6): despite the conservation efforts which have been performed in the region through *Water Conservator* project (see Richards et al., 2015; Piccirelli Santos, 2014; Pereira, 2013), the current percentage of native remnants is 13%, which can become 16% in 2035, however not achieving the 1990's rate (22%). This can potentially disrupt the regulating and provision hydrologic services provided by Posses sub-basin and needs to be deeply evaluated.

Next, we analyze spatio-temporal patterns of the main soil uses which competing with forest cover: pasture and eucalypto. First, related to pasture, we observe that it was the main use in the past in 60% of the sub-basins (in 1990) and, currently, it became the majority LULC by ca. 40%. Our scenarios indicate that, as a function of the EbA strengthening, encouraging the links between environmental conservation and forest restoration, 20% of the sub-basins can be mainly occupied by pasture (sub-basins 2, 4, 6 and 7). This rate is reasonable, considering rural sub-basins. Moreover, the reducing of pasture in the Cantareira System was more evident in the 1990-2010 period than in the 2010-2035scenario. This can be explained by, at least, three factors: i) rural landowners awareness of the relevance of conversion from pasture to native forest for the generation and maintenance of ecosystem services in the Cantareira System (Saad, 2016; Extrema, 2015; Mota da Silva, 2014; Padovezi et al., 2013; Gonçalvez, 2013; Veiga-Neto, 2008); ii) seasonal changes in the ecosystem structure which can increase the ecosystem resilience (Mulder et al., 2015) and observed significant increasing, mainly in the 1990-2010 period, of non-native species plantation.

Second, related to eucalypto cover, the future scenario shows an increasing threat to the regulating and supporting services as a result of the exotic forest in expansion. In 2035, eucalypto cover can encompass, in average, 12% of the total area of the 20 catchments here studied. This is significant in comparison with 10% in 2010 and only 2% in 1990 for the same catchments. This scenario until 2035 takes attention for the maintenance of hydrologic services, because eucalypto monocrop can potentially impact not only on headwaters but on entire landscapes, threatening ecosystem dynamics. Moreover, these plantations, with an average wood yield of 50 to 60 $m^3$of *Urograndis* per hectare, need for higher amounts of agrochemicals, due to lower population diversity and lower adaptation to climate change (Kageyama & dos Santos, 2015). In short, here we highlight the threat on biodiversity that have been brought by alien species in headwaters and the changes that it can promote on native species (Hulme & Le Roux, 2016) which, in turn, impact the ecosystem services.

Considering the river basin as the management unit, the soil uses impact not only on quantity, but also on quality. Thus, we analyse water and nutrient yields, intra-annual regime and duration curves, both in quantity-quality of pollutants, in the following topics.

5.3.2.3. Water yield as a function of soil cover

Although the water-forest system interaction is a classic issue in Hydrology (Hibbert, 1967; Tucci & Clarke, 1998; Adreássian, 2004; Zhao et al., 2012), the comprehension of the impacts of vegetation on quali-quantitatives aspects of water resources needs refinements.

At hydrological methodologies, the use of expressive variable numbers in describing the hydrological regime for riparian ecosystems conservation is valuable (Collischonn et al., 2005). In this context, the assessment of simulations occurs through analysis of balance of hydrological cycle components at determined spatial and temporal scales. The results analysis was performed, on the one hand, from regional comparison related to the size of drainage areas and, on the other hand, by the hydrological function which features water and nutrients availability.

The selection of hydrologic function which characterizes the water availability can be concerned to representativeness of environmental and physical processes which occur at catchment scale in a dynamic way (Cruz & Tucci, 2008). In this work, we selected using quali-quantitative duration curves for integrated assessment of availability and quality of water. The flow-and-load duration curve is a simple and important analysis (Collischonn & Dornelles, 2013). In quantitative terms, the flow duration curve shows the probabilistic temporal distribution of water availability (Cruz & Silveira, 2007), relating the flow discharge passing at one river cross section related to a percentage of time in which it is overpassed or equaled (Cruz & Tucci, 2008).

The three scenarios S1, S2 and S2+EbA resulted in different flow values for the 20 sub-basins (**Figure 5.10**). Based on arithmetic mean of time series of monthly water yield, related to catchment areas, and assessed to all modelled sub-basins (N=20), results point average values water yield of: 31.4 ± 25.2 $L \cdot s^{-1} \cdot km^{-2}$ for S1 (1990), 14.9 ± 11.5$L \cdot s^{-1} \cdot km^{-2}$ for S2(2010) and 21.4 ± 15.3 $L \cdot s^{-1} \cdot km^{-2}$ for S2+EbA (2035), respectively. This very high variation can be due to the complexity of river basin systems and the several sources of uncertainty in the representation of ecohydrological processes.

The three scenarios analized and the ecohydrologic monitoring (Chapter 4) provide different types of information for the same catchments. But how can we integrate the relative importance of information from each source (Kapustka & Landis, 2010)? A detailed study showing the relationship between sensitivity (and uncertainty) of analysis and the effectiveness of Water-PES should be done.

For a while, the decrease of -52.4% in water yield between S1 (1990) and S2 (2010) scenarios (= (14.9-31.3)/31.3$\cdot$100) could be due to marginal increases of eucalypto cover. In fact, between 1990 and 2010, eucalypto cover increased +6.8 % in total land cover, but +181% in relative terms. Other possible explanation is the decrease of native vegetation between 1990 and 2010, with -1.8 % in total land cover, but -4.3%, in relative terms.

In parallel, we evaluate the water yield. Thus, the flow-and-load duration curves summarize the flow and pollutant load variability, thereby showing potential links and impacts for aquatic ecosystem sustainability (Cunha et al., 2012; Cruz & Tucci, 2008). From these curves, we obtained two different behaviours for the studied sub-basins (**Figure 5.10**):

Behaviour I: the water yield in 2010 reduced in relation to 1990 and the water yield in 2035 might overpass the 1990 levels. The examples are:*Upper Jaguari*, *Cachoeira* sub-basin (including *Cachoeira dos Pretos, Chalé Ponto Verde, Ponte Cachoeira, F24 outlet*) and *Moinho* catchment;

Behaviour II: the water yield after 2010 was reduced until 2035 and this water yield recuperation was not possible for the values in 1990. Examples, in decreasing size of drainage areas, are: *Atibainha, B. Jaguari, F25B, Parque de Eventos, F23, B.Atibainha, F34, F30, Salto, Posses Outlet, Domithildes, Portal das Estrelas* (*Middle Posses*).

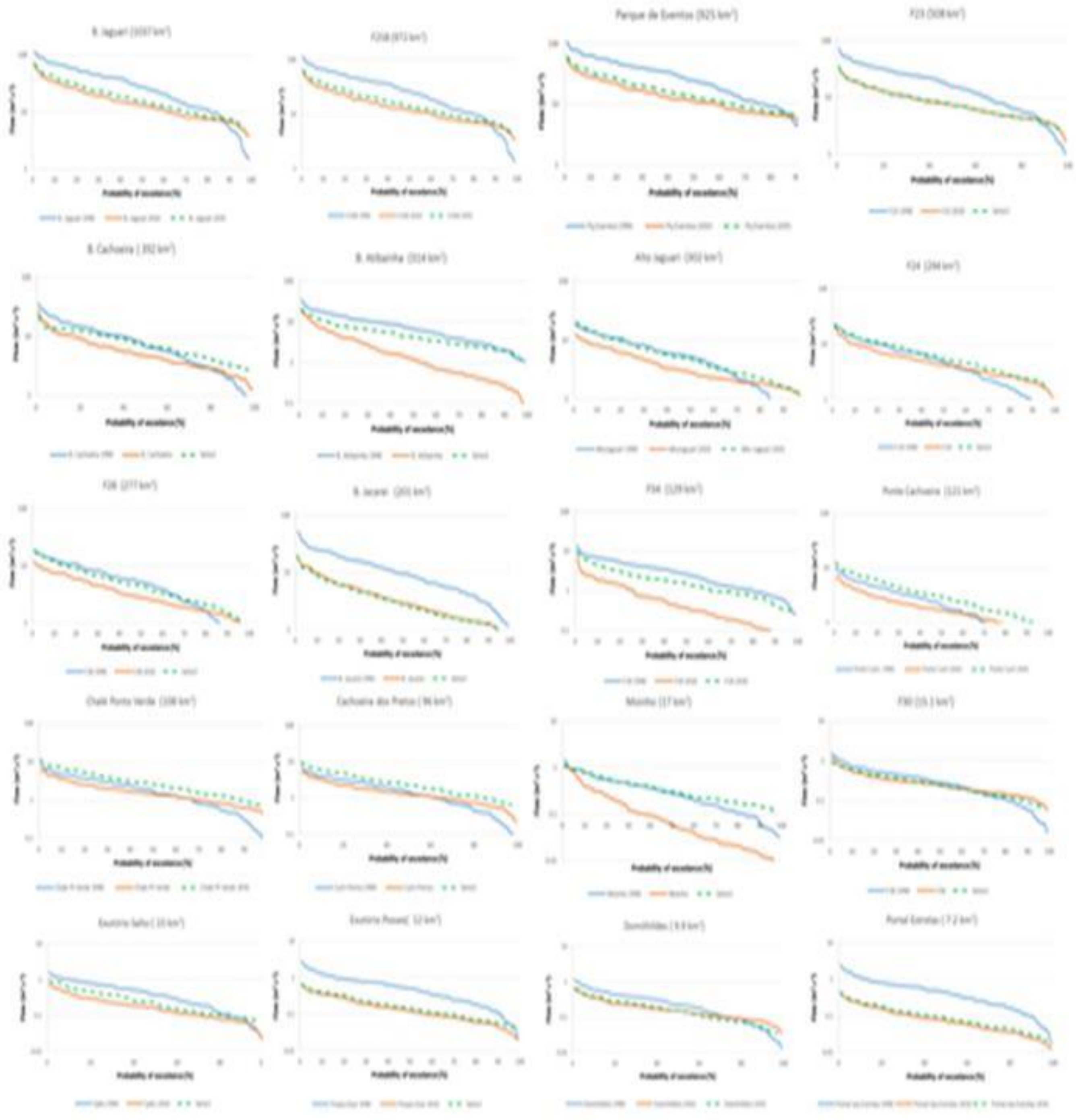

Figure 5.10. Flow duration curves simulated under three LULC scenarios: S1(1990), S2(2010) and S2+EbA (2035) in 20 catchments at headwaters of Cantareira Water Supply System.

On the one hand, according to **Figure 5.11**, the water yield of S1 is inversely proportional to land use of mixed forest cover. The water yield in S2 indicates a constant value of approximately 17 L $s^{-1}km^{-2}$. Also for the S2+EbA scenario, with incorporates the EbA approach through BMP, the water yield is approximately 17 L $s^{-1}km^{-2}$, but with slight increase in the water yield for mixed forest cover higher than 50%. Presumably, this slight increase in the water yield would be related to the type of the best management practices (BMP) of the recovery forests, which still not achieved evapotranspiration rates of the climax stage. In riparian forest under recuperation there are lesser evapotranspiration rates and, thus, more quantity of precipitation reach soil and rivers through canopy. This process could benefit other hydrological components, like runoff, increasing water flows into the rivers. This effect can possibly explain the **behaviour I** catchments (see **Fig. 5.10**).

On the other hand, we observed in *Posses, Salto, Jaguari, Cancã* and *Atibainha* catchments an inverse situation (**behaviour II**). This effect can be related to the hydrologic response produced by: (a) type of catchment; (b) size of catchment; (c) the low soil moisture in the red-yellow latosol (Embrapa, 2016), which did not favor high evapotranspiration rates; (d) the riparian forest, originates from the EbA or Water-PES actions, will be at initial stages, not achieving in 20 years (this explanation thereby assumes the baseline of PES actions held in 2015, spite of existing examples of restored forests in Extrema-MG the higher evapotranspiration rates we usually find in forests at climax); and (e) unpredictability, non-linearity and uncertainty (Ferraz et al., 2013; Lima & Zakia, 2006).

The forest role in the hydrological cycle at river basin scales has been debated for centuries. Riparian native forest, eucalypto and riparian forest in recuperation (orchard) have different hydrological responses. The knowledge about influence of different types and phases of vegetation in the hydrological processes still has gaps to be fulfilled. Bayer (2014) found that the vegetation height and the leaf area index are inversely proportional to the water flows, which corroborate previous studies (Hibbert, 1967). Riparian forest restoration increases the mean evapotranspiration, reducing the water yield (Molin, 2014; Salemi et al., 2012; Lima & Zakia, 2006; Andreassian, 2004). Restoration increases the water storage capability into the catchment throughout the riparian zone, contributing to the higher water flow in the dry season (Lima & Zakia, 2000). This can lead to unexpected results regarding water yield. Furthermore, at small catchments of temperate climate, researchers estimated that deforestation in 40% of the catchment would increase the runoff of 130 ± 89 $mm.year^{-1}$ considering the entire water cycle at catchment scale (Collischonn & Dornelles, 2013). Still there are large dispersion in results from monitoring (usually, in paired catchments or Nested Catchment Experiment - NCE), which makes the forecast of flow discharge as a result of soil use conversion more difficult. Similarly, we found high dispersion in the comparison between water yields *versus* different land cover in 20 sub-basins of subtropical climate (**Figure 5.11**).

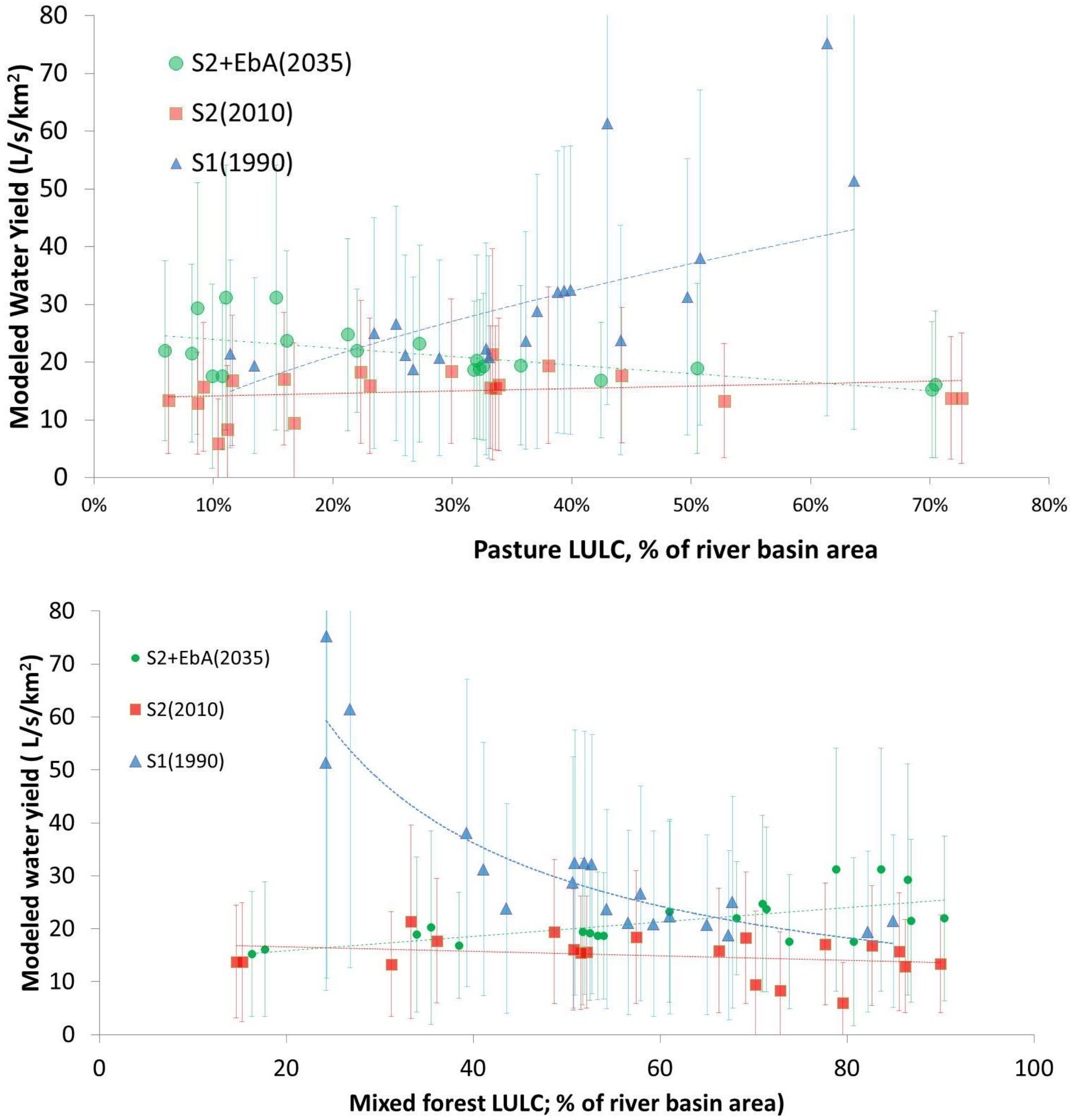

Figure 5.11. LULC scenarios for specific water yield for 20 drainage areas at Jaguari, Cachoeira and Atibainha watersheds, according to S1 (1990), S2 (2010) and S2+EbA (2035) scenarios.

BMP are in progress since 2005 in *Posses Outlet* (sub-basin 6, **Table 5.5**) and *Middle Posses (Portal das Estrelas*, Nº 7), and since 2009 in *Domithildes, F30* and *Moinho* catchments (Subbasins 9, 11 and 20, respectively). These BMP are from *Water Conservator* and Water Producer/PCJ. In these cases, we point to have caution when support PES as the main driver linking reforested cover areas to more water availability (ANA, 2013). Parts of these results and previous investigation, which has been made through NCE (Taffarello et al., 2016, chapter 4 of this thesis), point the opposite, i.e., in the more conserved catchments we found lower water yields. Despite there are many Water-PES programs in Brazil (Pagiola, von Glehn & Taffarello, 2013; Guedes & Seehusen, 2011), measurements of the effect on water yield under forest restoration are still lacking in tropical and subtropical conditions (Taffarello et al., 2016a; Salemi et al., 2012). However, the benefits of riparian forest on water quality, margin stability, reduction of water erosion and silting are also evident in scientific literature (Piccirelli Santos, 2014; dos Santos et al., 2014; Studinski et al., 2012; Udawatta et al., 2010).

5.3.2.4. Relationships between land-use/land-cover change and grey water footprint

For an integrated assessment of hydro-services, we analyze the spatio-temporal conditions of load production at the sub-basin scale. Considering we are studying rural sub-basins, the water pollution is mainly produced by diffuse source regarded to fertilizers and agrochemicals. In this context, we evaluate the GWF evolution to show the behaviours of nitrate (N-NO_3), total phosphorous (TP) and sediments (Sed) yields from simulating scenarios S1, S2 and S2+EbA. First, we calculate the nitrate loads generated from the 20 sub-basins in the three scenarios. Second, we made the same for total phosphorous loads and sediment yields. Third, encompassing the river regime, we calculated the greyWF for nitrate, total phosphorous and sediments in each sub-basin, to develop new sustainable and composite indices.

Concerning nitrate, the sampled concentrations were low (see previous chapter). In addition, SWAT simulations also brought very low outputs, and the greyWF-NO_3 vary from 0.11 L/s per km^2 (in *Atibainha* subbasin, under S2 (2010) scenario) to 2.83 L/s per km^2 (in *Middle Posses* catchment, *Portal das Estrelas*, under S2+EbA (2035) scenario). Considering Brazilian water quality standards for nitrate, the maximum allowed concentration is 10 mg/L (Brasil, 2005). These low amounts of nitrate loads make the greyWF-NO_3 falling to low values in the three scenarios analyzed (**Figure 5.12a**). Complementary, we have also chosen to explore greyWF for total phosphorous and sediments.

In relation to total phosphorous (TP), the load duration curves from S1, S2 and S2+EbA scenarios present disparities. For example, the greyWF for TP decreased in all sub-basins between 1990, 2010 and 2035. In this last period (2010-2035), the model predicts a new behaviour for the greyWF-TP.

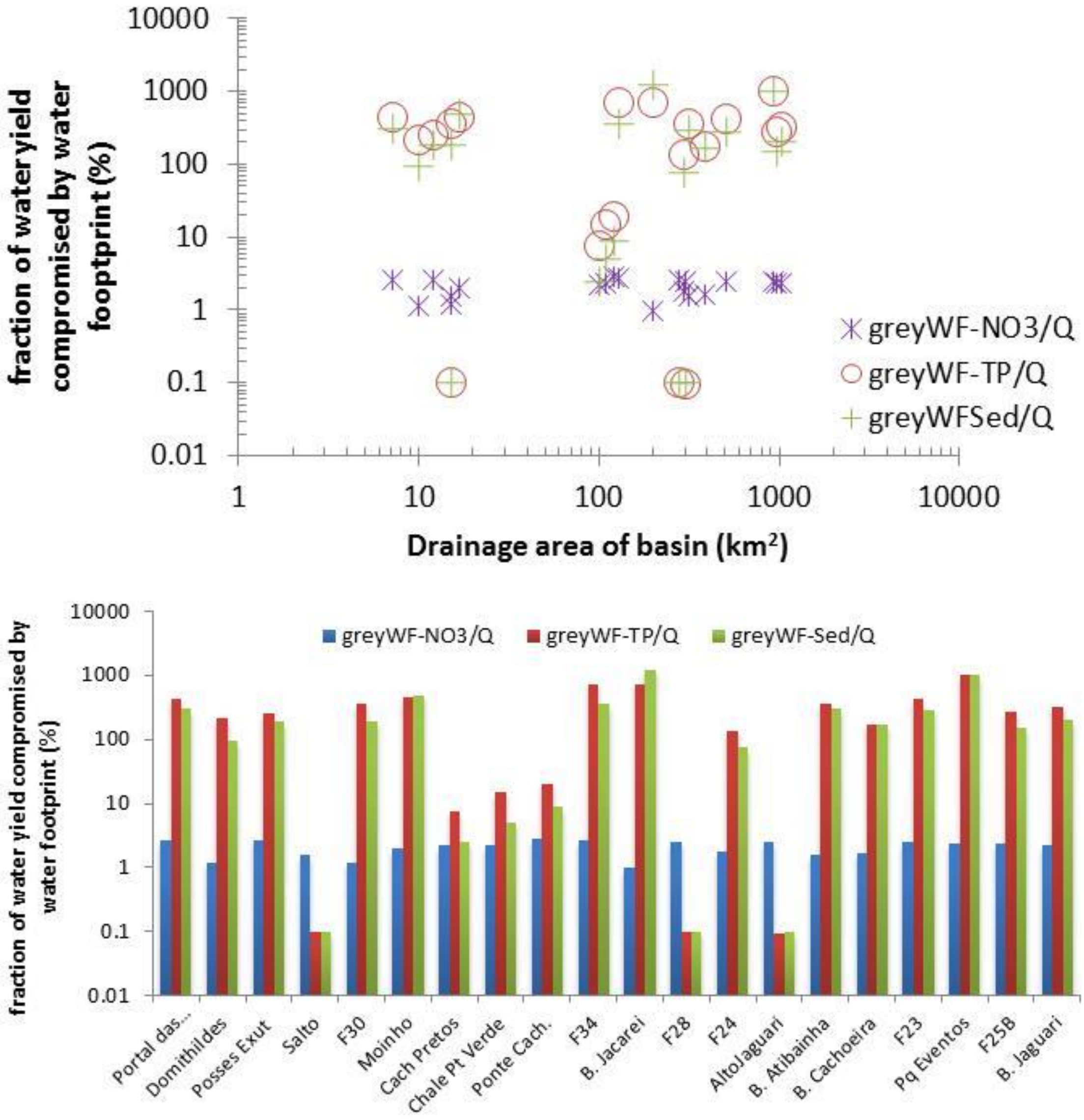

Figure 5.12. Fraction of water yield compromised by the grey water footprint for nitrate, total phosphorous and sediments versus drainage area **(a)**, and showing the studied subbasins **(b)**.

Results of greyWF for TP, NO_3 and sediments allow us to infer some regionalization for nutrient loads. Among the 20 sub-basins studied, we selected 2 sub-basins as study cases to illustrate the links between LULC and greyWF: (1) the *Upper Jaguari* subbasin, and (2) *Domithildes* catchment.

5.3.2.4.1 Case study I: *Upper Jaguari* sub-basin

The Upper Jaguari has 302 km^2 and is the second most upstream sub-basin within the Cantareira System (downstream of only *F28* sub-basin, with 277 km^2). Comparing scenario 1990 (S1) and 2010 (S2), results depicted evidence that native forest decayed aprox. 10 %. Indeed, scenario 2035 (S2+EbA) still assumes a very small decrease of native forest. This fall could be potentially traded off through increasing secondary forests by BMP, that would stabilise the native forest LULC in 70% until 2035.The mean annual simulated water yields, in spite of high variability of simulated scenarios, pointed values of 18 $L.s^{-1}.km^2$ (1990, S1), 13 $L.s^{-1}.km^2$ (2010, S2) and 21 $L.s^{-1}.km^2$ (for 2035, S2+EbA). Variabilities are related to hydrologic conditions simulated in the test period of 2006 until 2014. In turn, this test period was selected due to high availability of rainfall stations under operation, which would potentially better perform distributed modeling at several sub-basis using SWAT. In summary, for the three scenarios simulated, the relationships between the native forest cover and mean water yield are different each other. For scenario S1 (1990), the higher native forest cover, the lower water yield. This scenario behavior is extended at experimental sites, and even extensively documented in the literature (Salemi et al, 2012; Smarthust et al., 2012, Collischon & Dornelles, 2013). In turn, for scenario S2 (2010) the water yield seems not fully related to native forest LULC, oscillating around an average value of 18 $L/s/km^2$. In scenario S2+EbA (2035), however, there is a little increase in water yield when native forest cover is higher than 50%. This proportional relation between water yield and forest cover in the S2+EbA is both controversial and contrary with results published by some authors (e.g. Collischonn & Dornelles, 2013; Salemi et al., 2012). For example, in previous chapter, monitoring data shows reduction in the water yield with higher native forest land cover (Taffarello et al., 2016a). Salemi and coauthors, in a review on the effect of riparian forest on water yield, found that riparian vegetation cover decreases water yield from daily to annual basis.

Furthermore, the greyWF-NO_3 of *Upper Jaguari* basin pointed 0.14 L/s per km^2 for scenario S1 (1990), increased to 0.23 L/s per km^2 for scenario S2(2010) and would grow to ca. 0.54 L/s per km^2 in S2+EbA scenario (in 2035). Lower values of greyWF of nitrates, althouth represent lower water volume needed to dillute nitrates flowing to streams per square kilometer of draining catchment. This results, however, is different of expected in the hypothesis testing through modeling. The null hypothesis says increasing native forest cover is correlated to decreasing nutrient loads flowing to streams. The former results, modelled by SWAT, predicted an increase in greyWF in 2035. Simulated increase of native forest (approx. +5%) would appear to be not enough for buffering nitrogen loads from both pesticides and animals' excrements like mammals or zooplâncton. For deeper analysis, other factors influenced on greyWF should be evaluated at all.

Concerning greyWF in *Upper Jaguari* sub-basin in S2+EbA (2035) scenario, SWAT outputs assessed ca. 0.1L/s per km^2 related to total phosphorous (TP) and 0 L/s per km^2 for sediments. In this subbasin, diffuse pollution from nitrates would be (or lower than) 5 times higher than pollution from TP. Adaptive management are needed to avoid future problems of eutrophication, caused by excessive nitrogen in waters. As nitrogen is highly mobile in freshwater and terrestrial ecosystems, surface water nitrate isotopes could be used to monitor nitrogen variations in catchment-scale attenuation, as proposed by Wells et al. (2016). In this context, the calculus of greyWF for nitrate, using nitrate isotopes ($\delta^{15}N$ and $\delta^{18}O$ of NO_3^{-2}), could be an auxiliary tool in understanding spatial and temporal variations in nitrogen export throughout the catchments.

5.3.2.4.2 Case study II: *Domithildes* headwater

Domithildes catchment (9.9 km^2) is located in Cancã catchment. Similar to Upper Jaguari, Domithildes is one of the most conserved sub-basins, mainly with native forests. By comparing S1 and S2 (see **Figure 5.14**), native forest fraction remained constant (51% in S1(1990) and 52% in S2 (2010). Unlike *Upper Jaguari* sub-basin (see **Figure 5.13**), native vegetation would increase by 56% in S2+EbA (2035). Because Domithildes is adopted as reference basin for Water Producer/PCJ, the augmented fraction of native forest by 2035 would point an increase of secondary forest.

Regarding water yield, *Domithildes* catchment classified as second type of 'subbasins behaviour'. For example, its annual water yield in 2010 (~18 L/s per km^2) was smaller than in 1990 (~ 29 L/s per km^2). Since 2010 onwards, however, water yield would replenish towards S2+EbA conditions in 2035, close to 23L/s per km^2. This positive increment between 2010 and 2035, although, would not achieve values obtained for S1 conditions in 1990.

Other factors, beyond of native vegetation, would influence the hydrologic cycle at *Domithildes* catchment, decreasing water yields in the 2010 scenario (S2). One explanation of this water yield decrease would be the positive LULC of *Eucaliptus sp*. of +5% in 2010 (S2). Salemi et al. (2012) presented a review results as increased annual water use, as evapotranspiration, for each 10% of area covered with eucalypto, pinus, acacia or native subtropical species beside the stream ranged from 11 to 112 mm per year. Smethurst et al. (2015) estimated a water use by native riparian tropical Brazilian forest of 84 mm per year (7% of annual precipitation). Regardless other factors, according to previous statements, +1% of eucalipto land use fraction in *Domithildes* will represent -2 L/s/km^2 of water yield, or -63 mm per year, in the same range of results reported by Salemi (2012) and close to Semthurst et al (2015).

Comparing seasonal water yields, results pointed higher variability around monthly flow averages for S2+EbA (2035) scenario. These deviations in monthly flows of 2035 scenario were higher in wetter months, between November and March. The regulation of water yield, in both rainy and dry conditions, is more effective when quantifyied through variance (Molin, 2014). In spite of these uncertainties, scenarios modeled through SWAT estimated the highest mean monthly water yield in February (38 L/s per km^2) and the lowest mean monthly water yield in September and October (8 L/s per km^2). On the one hand, results pointed that growing rate of native vegetation LULC since 2010 would serve to attenuate both e-flows peaks, especially in the rainy season (see flow duration curves), and pollutants filtration (see duration curves of N-NO3 loads). On the other hand, the more native forest cover, the lower water yield (Bayer, 2014; Molin, 2014; Burt& Swank, 1992). Thus the progressive augmentation of water yield between 2010 and 2035, in companion with higher total forest cover, would indicate other factors, such as forest connectivity, forest climax and secondary factors like BMP, that would produce non-linear conditions for water yield, from the local scale to catchment scale.

Likewise, water yield is related to the absolute value of integrating the flow duration curve. For example, the flow duration curve of S1 (1990) exceeded other scenarios' curves in approximately 75¨% of time, with differentiated behaviour in both peak flows (lower probability) and low flows (higher probability of duration curves).

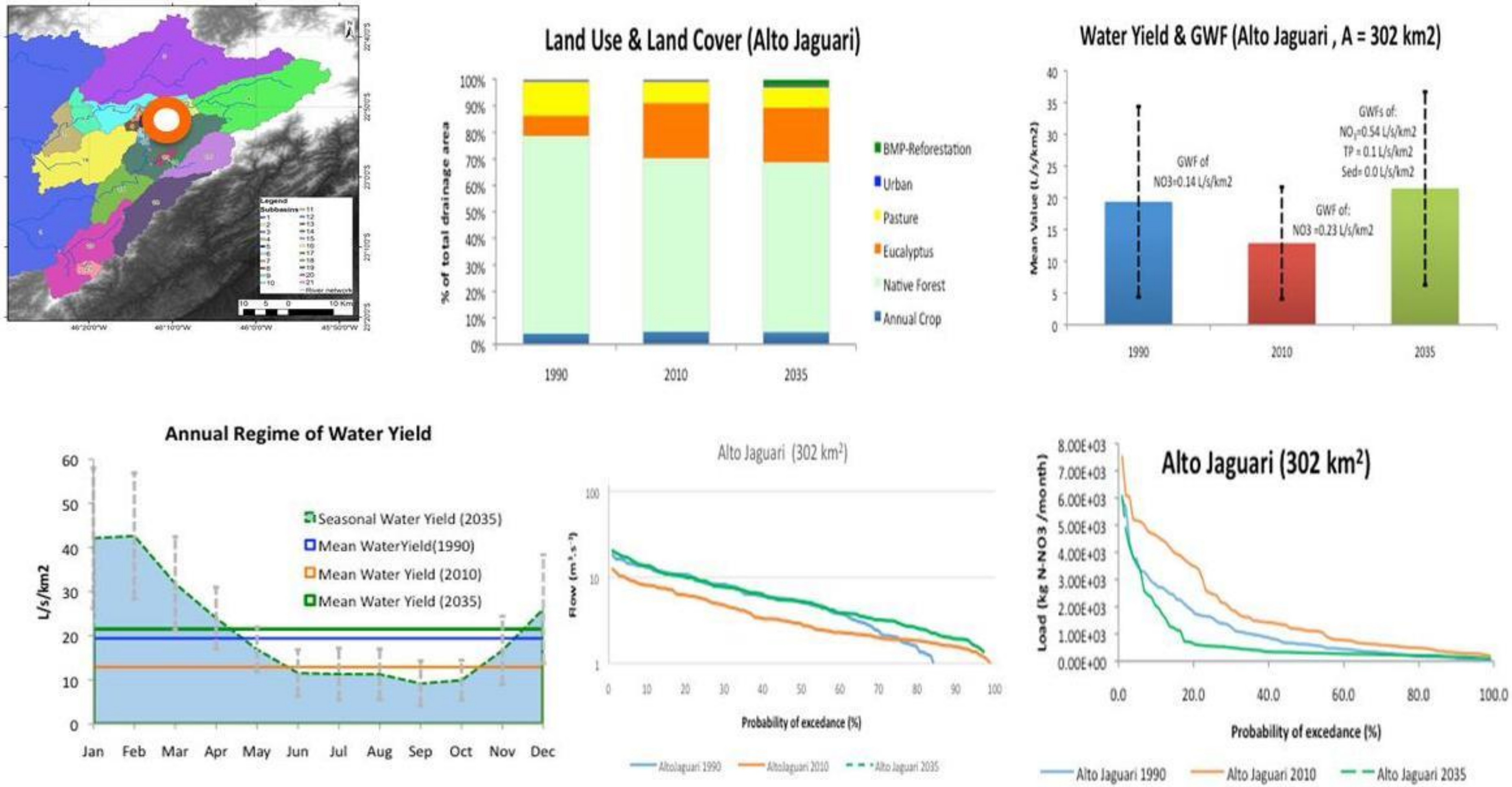

Figure 5.13. Synthesis chart of case study *Upper Jaguari* sub-basin. Left, upper chart: localization at the drainage areas of Cantareira System. Center, upper chart: LULC conditions for scenarios S1 (1990), S2 (2010) and S2+EbA (2035). Right, upper chart: comparison of water yields simulated for conditions of S1, S2 and S2+EbA. Left, lower chart: water yields' scenarios compared with intra-annual regime of S2+EbA scenario. Center, lower chart: comparison of duration curves of flows for S1, S2 and S2+EbA conditions. Right, lower chart: duration curves of N-NO3 loads for S1, S2 and S2+Eb.A

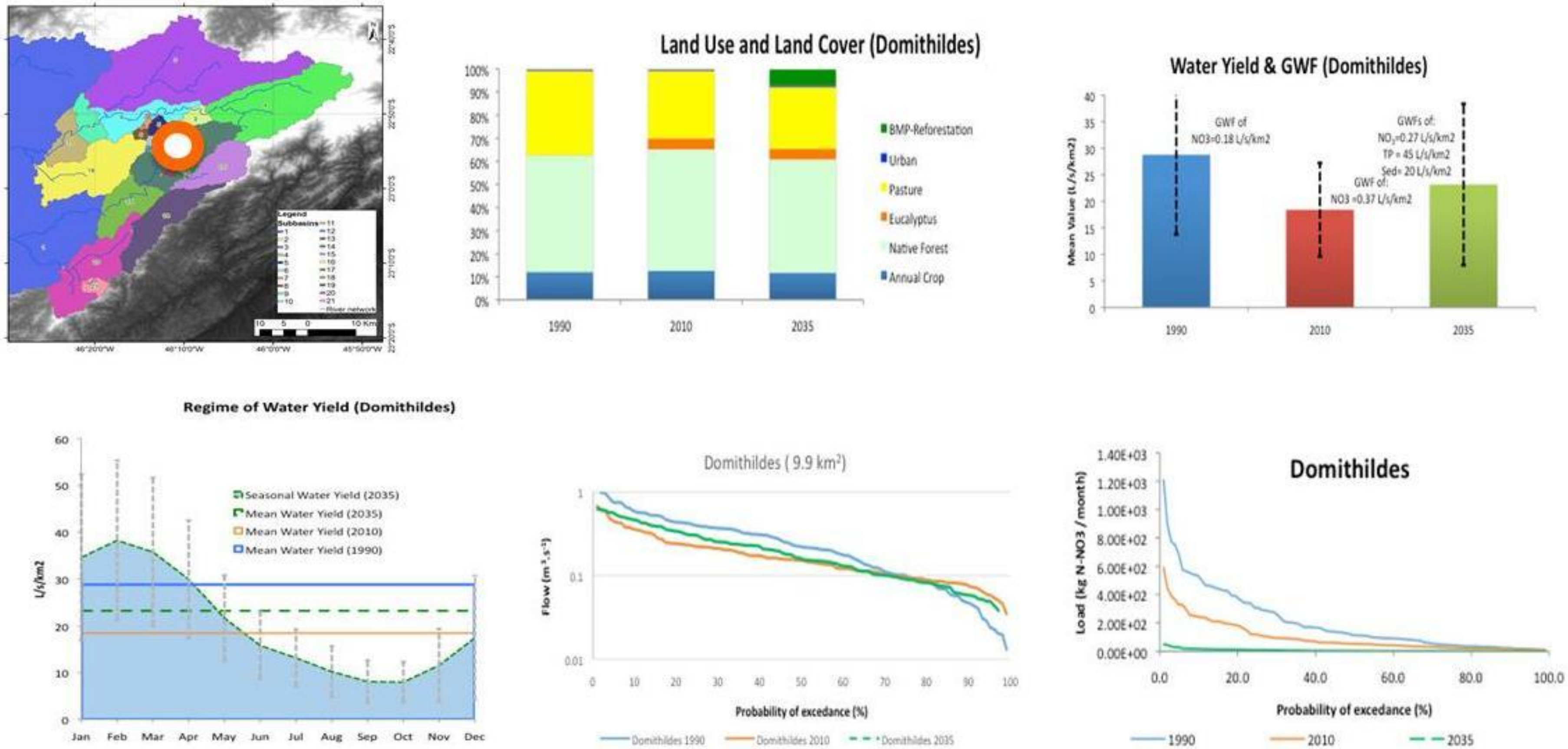

Figure 5.14. Synthesis chart of case study *Domithildes* catchment. Left, upper chart: localization at the drainage areas of Cantareira System. Center, upper chart: LULC conditions for scenarios S1 (1990), S2 (2010) and S2+EbA (2035). Right, upper chart: comparison of water yields simulated for conditions of S1, S2 and S2+EbA. Left, lower chart: water yields' scenarios compared with intra-annual regime of S2+EbA scenario. Center, lower chart: comparison of duration curves of flows for S1, S2 and S2+EbA conditions. Right, lower chart: duration curves of N-NO3 loads for S1, S2 and S2+EbA.

5.3.3. Results of a new index for hydrologic services assessment

A new index for hydrologic service assessment is here developed as a simple relation between greyWF and water yield, using a fraction between water demand (numerator) and availability (denominator). Some authors commonly use this fraction as a direct approach to water scarcity (i.e. Smakhtin, et al., 2005; Hoekstra et al, .2013; McNulty et al., 2010; among others). Therefore, we first assessed greyWF by respective drainage basins (**Figure 5.15**). Then we calculated the water pollution levels.

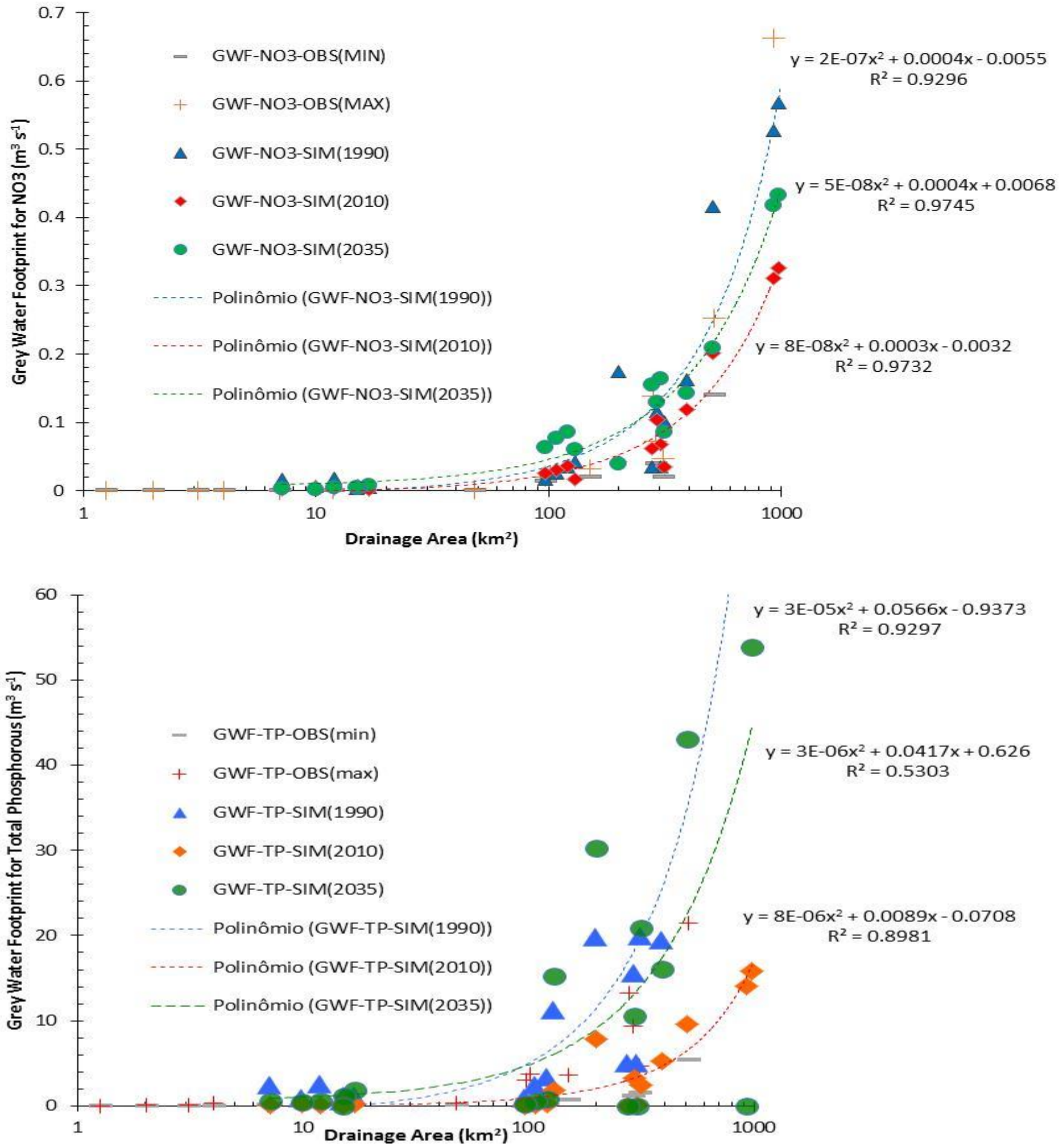

Figure 5.15. Relationships between Grey Water Footprint for Nitrate (upper chart) and Total Phosphorous (lower chart) according to three LULC scenarios (Year 1990, 2010 and 2035) and size of the drainage areas of headwaters in the Cantareira Water Supply System.

Results in **Figure 5.16** show the composite water pollution level (WPLcomposite) *versus* drainage areas and compared with the HSI. The baseline *WPLcomposite,ref* is related to *Domithildes* catchment (horizontal, dotted line in **Figure 5.16**). This line divides the graphic in two regions: less sustainable basins (*HSI*>0) and more sustainable basins (*HIS*<=0). More sustainable basins (*HIS*<0) are *Salto, Cachoeira* nested catchments (*Cachoeira dos Pretos, Chalé Ponto Verde* and *Ponte Cachoe*ira), as well as *F28, F24* and *Upper Jaguari* basin.

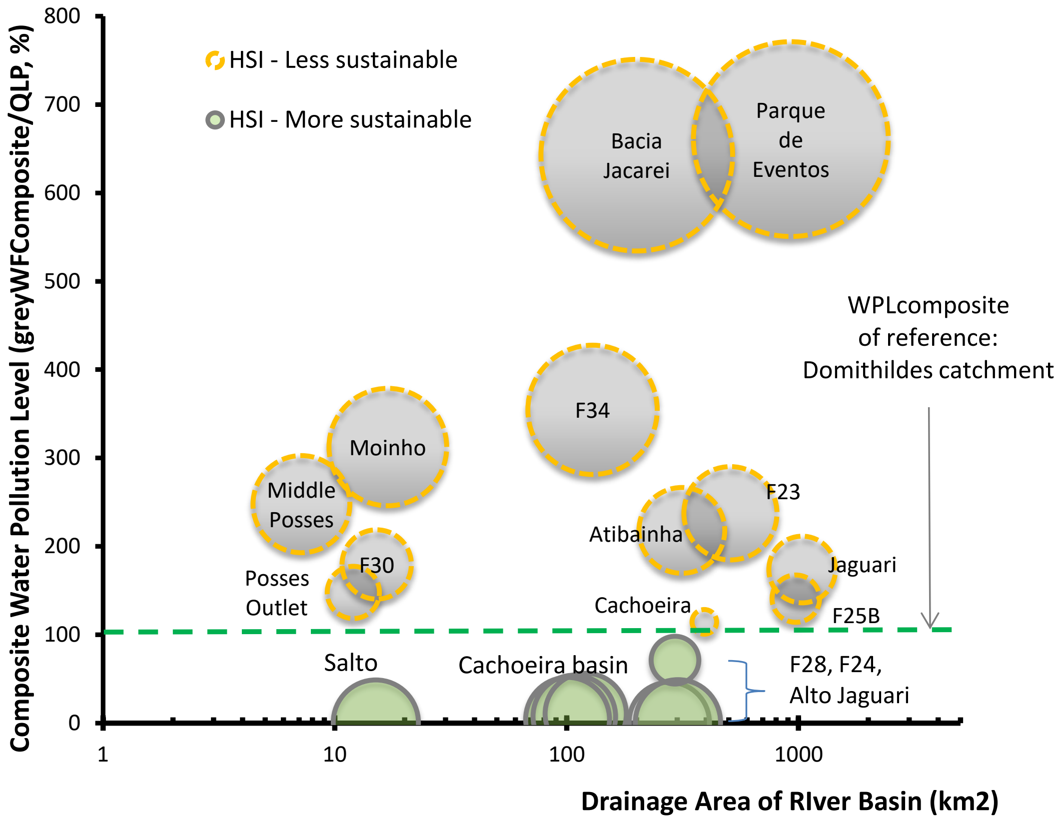

Figure 5.16. Hydrologic Service Indicator (circle ratio) related to drainage area of river basin (horizontal axis) and composite of water pollution index (vertical axis) for S2+EbA scenario. Equal weighs of nitrates, total phosphorus and dissolved sediments are expressed into *WPLcomposite*.

5.3.4. Comparison of field investigation and modeled scenarios

Figure 5.17 compares field, experimental data (see Chapter 4, Taffarello et al., 2016a) with modeled scenarios of land-use and land-cover change, including EbA's hypothesis. The horizontal axis of **Figure 5.17** depicts the water yield of each scenario or water security condition, for disaster risk reduction with EbA (see Chapter 2 and 3). Reference flows were assessed from official policy institutions (see DAEE, 1987).

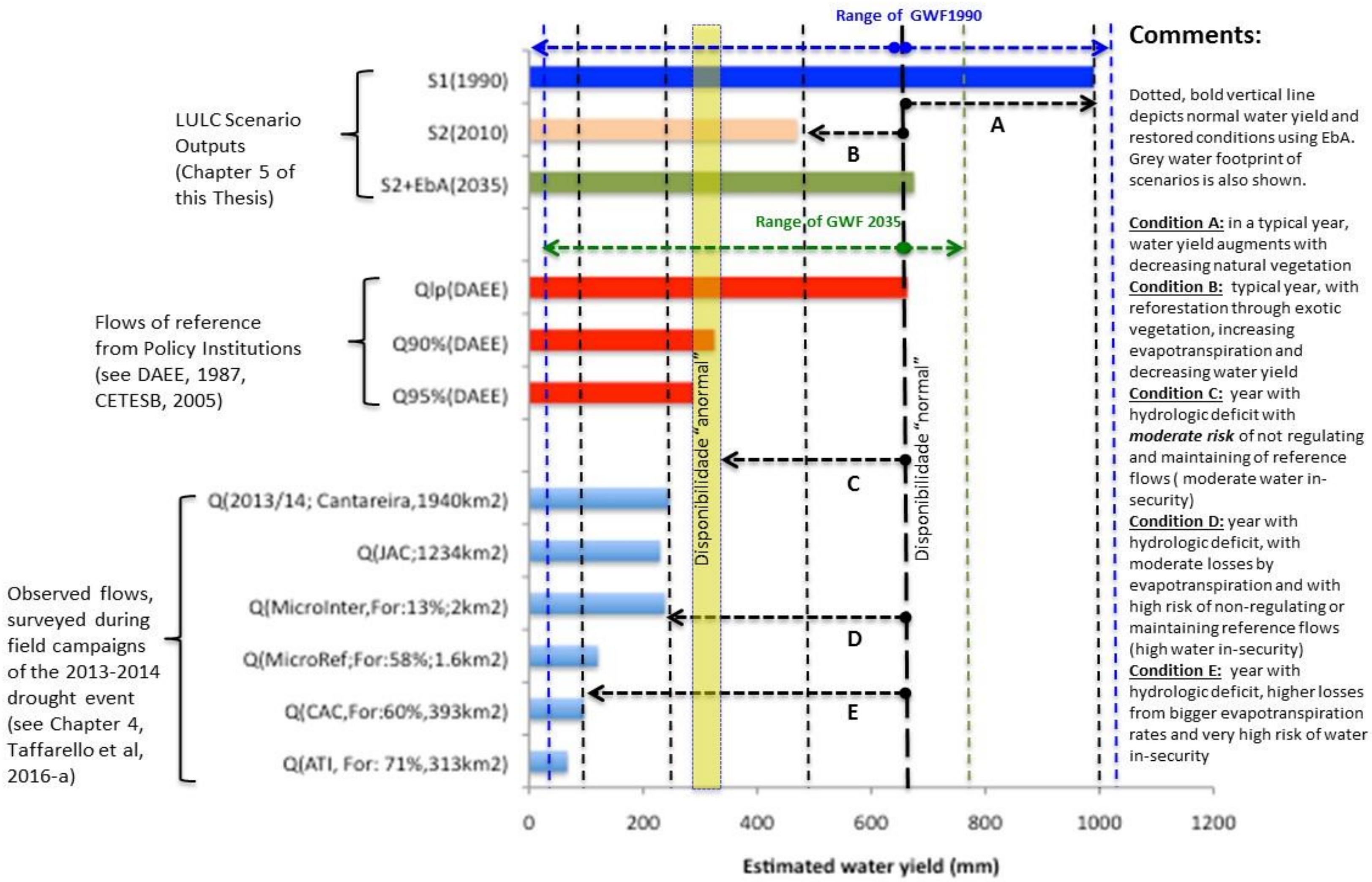

Figure 5.17: Synthetic comparison of water yield related to GWF, EbA, hydrologic services and risks of water insecurity.

5.5 Conclusions and Recommendations

Supported by field experiments and quali-quantitative simulations under different scenarios including EbA options with BMP, our results showed evidence for non-linear relationships among LULC, water yield, greyWF of nitrate, total phosphorus and sediments, which irreversibly affect the composite of water pollution level (WPL), the definition of WPL of reference (here established at Domithildes catchment) and the hydrologic services index (HSI). Despite using semi-distributed model for assessing non-point sources of pollution mainly tested under different LULC scenarios, our results showed that the intrinsic nature of flow-load duration curves, LULC and greyWP are constrained to high uncertainties and to nonlinearities both from *in-situ* sampling and from processes interactions of modelling. Results show the need of considering several uncertainty sources, such as: sensitivity analysis, observed streamflow data, ecohydrologic model performance, residual analysis, etc. To attain goals of EbA, using HSI through GWF assessment and composite of WPL, some conditions are needed, as follows: (i) to avoid the inputs of high-concentrated pollutants, especially growing urban settlements, (ii) to restore riparian vegetation and (iii) trapping and removing inflowing sediments. For rivers ecosystems health, we used HSI, flow regimes and WPLcomposite, as an alternative proposal of defining environmental flows (Tharme, 2003; Olden et al., 2011; Poff & Zimmerman, 2010; Poff & Matthews, 2013). Although the role of vegetation on streamflow has been intensely studied, very few investigations have been reported in Brazil which control nutrient sources, transportation and delivery. Furthermore, from the vision of integrating LULC, EbA and greyWF, further in-field and modeling frameworks are needed, thereby regarding the influence of vegetation on water quality and the role of anthropogenic and natural drivers in catchment-scale ecohydrological processes.

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CHAPTER 6

6. CONCLUDING REMARKS

"The solution of water-related challenges encompasses the environmental literacy, resources management in a transdisciplinary way (Odum & Barrett, 2014) and highlight the water focus on sustainability sciences." (Sivapalan et al., 2014)

This thesis is the first comprehensive, quali-quantitative, and multi-scale assessment on the conversion of land use and its effects on hydrologic services in the overall Cantareira Water Supply System, South-East Brazil. Previous studies on freshwater in the Upper Piracicaba basin (where headwaters of Cantareira System are located) have focused on only one or two catchments and only involve modelling or field works.

Field investigations as well as ecohydrologic simulation models are needed for a complete and reliable accounting to assess hydrological services. The evaluation of hydrological dynamics, which impacts hydrological services, is an interdisciplinary management strategy to optimize the delivery of ecosystem services at catchment scales. This was developed in four steps along this research.

Chapter 2 presents a review of ongoing payment for hydrological ecosystem services in the Brazilian Atlantic Forest and proposes ecohydrological insights which can make PES (Payment for Ecosystem Services) programs a promising tool for the conservation of water resources. First, Chapter 2 presents a concise overall summary of hydrological PES issues at the Latin American and Brazilian national levels. Second, it presents a thorough overview of hydrological/PES in the Brazilian Atlantic Forest biome. I included in this review some projects that, because they are not (yet) aligned with the guidelines of the *Water Producer Program*, are rarely catalogued in publications. The findings presented here demonstrate that, although Brazilian PES projects for watershed protection have increased in the past decade, they lack monitoring and adapting strategies to cope with water challenges in basins under change. The lack of scientific knowledge and monitoring of hydrologic services (methods for testing the delivery of hydro-services) are impediments that prevent strengthening PES for watershed protection in Brazil. Third, I suggest a list of ecohydrological variables which would help to delineate and rank hydrologic-PES projects, possibly helping reduce the vulnerability of land-use or climate change impacts, thereby focusing on the Ecosystem-based Adaption. At last, considering some difficulty to find comparable informations about Water-

PES projects in the Brazil's Atlantic Forest, I recommend publishing Brazilian Water-PES in peer-reviewed journals to provide a broader audience to the initiatives, since new projects can learn from the experiences of previously developed Water-PES projects.

Based on the outcomes of Chapter 2, I then selected one hydrologic-PES issue in the Brazilian Atlantic Forest for an in-depth analysis, asking how anthropogenic disturbances at catchment and watershed scales can influence the hydrologic services using both field investigations (Chapter 4) and ecohydrological watershed-scale models (Chapter 5). To answer this question, I first developed a hydrological monitoring plan, which is the essence of Chapter 3. Therefore, **Chapter 3** introduces the Freshwater Monitoring Plan of the Water Producer/PCJ project. Based on this, it is then possible to evaluate the effects of the conservation project actions under the qualitative and quantitative aspects; and promote incorporating the elements from this plan in water resources planning and management. The proposed freshwater monitoring plan is sufficiently wide-ranging to be adapted and implemented in other catchments which are eligible areas for PES projects. It is observed that the inclusion of a group of interdisciplinary experts in medium and long term monitoring is needed for producing more credible results. This planning is crucial to bring scientifically meaningful, cost-effective baseline data and to implement effective monitoring programs.Only if there are both, baseline and monitoring together, it is possible to verify the additionality of the Water-PES project.

Chapter 4 comprises the results of 17 nested catchment experiments during six field campaigns, December 2012 – May 2014. The sampling sites are located in the drainage area of the Cantareira Water Supply System donor reservoirs, representatives of Jaguari, Cachoeira and Atibainha sub-basins. Comparing reference catchments with intervention catchments (i.e. catchments that have participated in the Water Producer/PCJ project since 2009), it showed an inverse correlation between forest cover and water yield. This implies that water production will possibly be lower with forest increase as a result of the Water Producer/PCJ project and other conservation synergies. However, water quality, ecosystems and humans can benefit from this expected forest increase. In this regard, the regionalization of phosphate and nitrate loads versus drainage area here proposed can indicate the pollutant load for any river stretch in the headwaters of Cantareira System. This nutrient migration from headwaters to downstream areas can cause eutrophication effects in water supply reservoirs. The procedure of regionalized loads for rating curves can be an application guideline for the headwaters of other reservoirs in Brazil or abroad. Considering that these empirical evidences were analyzed during a period characterized as a low-precipitation anomaly in South-East Brazil, the results are even more informative and potentially useful for decision-makers in the future.

Finally, **Chapter 5** concludes that the water needed for regulating ecosystem services can be estimated using the grey water footprint (non-consumptive water use) through a comprehensive, simple and integrated assessment. 20 sub-basins in the Cantareira System were simulated using SWAT (17 from the previous chapter plus the 3 reservoir sub-basins) in three scenarios, past, present and future, where I incorporated EbA assumptions. On the one hand, nitrate leaching simulations, total phosphorous and sediments allowed the regionalization of grey water footprint (greyWF) of each pollutant at different spatial scales under land-use/land-cover changes. On the other hand, the simulated conservation practices not only predict additional, viable and best management practices, but also preventive and robust decision-making for the headwaters of water supply systems. Despite some difficulty to access adequate quality input data for SWAT simulations, the scenarios allowed developing a new ecohydrologic index for assessment of regulating ecosystem services. This index was built from flow/load duration curves and the greyWF, and summarizes the knowledge available in the adaptation measures. It can be the basis for future proper valuation and protection of hydrologic services.

This research has significantly expanded our understanding of subtropical streams facing LULC pressures, by using cutting-edge technological tools (SWAT model and WF indicator) and experimental approach, endorsing ecohydrological monitoring in the headwaters studied. Not only in terms of assessing the model outputs or greyWF estimates, but also in terms of providing appropriate long term monitoring, there are many challenges to overcome as well as opportunities for future research. Despite the need for a more detailed understanding of responses to anthropogenic impacts on water resources, it cannot be used as an excuse to delay conservation strategies and improved management, in light of the rapid loss rates of ecosystem services.

The conceptual model developed in this research is an effective auxiliary method for integrated water resources management, to assure water quality and quantity security for both freshwater ecosystems and humans in strategic catchments under change. Once more, I highlight the cooperation of my co-advisor and advisor, co-authors, international journals reviewers and FAPESP advisor in this knowledge building process. Without them, this work would not be possible.

APPENDIX A - Other Outcomes

1) Zaffani, A.G., Cruz, N.R., **Taffarello, D.** and Mendiondo, E.M. (2015). *Uncertainties in the Generation of Pollutant Loads in the Context of Disaster Risk Management using Brazilian Nested Catchment Experiments under Progressive Change of Land-Use and Land-Cover*. **J. Phys. Chem. Biophys**, 5: 173. doi:10.4173/2161-0398.1000173. (ISSN: 2161-0398, I.F.: 0.96).

ABSTRACT

River pollutant loads encompass a combination of natural and anthropogenic factors related to land use and landcover (LULC). Progressive changes in LULC can significantly alter pollutant behaviors of changing flows and pollutant concentrations, reducing biodiversity, and emerging uncertainties regarded to poor gauged basins. To assess the factors involved in the generation of pollutant loads, this paper examined empirical uncertainties from observed pollutant loads in river basins through nested catchment experiments (NCE). Monitored river flows, concentration and drainage areas of each NCE were associated with LULC in order to determine specific pollution generation coefficients per unit of drainage area (Ys) of BOD, a- chlorophyll, NTK, TSS, and Total Coliforms. Three Brazilian watersheds were tested with drainage areas ranging from 0.93 km to 242 km , and under different conditions of: (1) LULC (urban, forest and agricultural), (2) numbers of NCEs (2 to 11), (3) sampling seasons (1 to 4), (4) antecedent precipitation index (dry or wet conditions) and (5) biomes (Atlantic Forest and Cerrado-savanna). LULC appraisal showed complex upstream-downstream uncertainties of BOD, a-chlorophyll, and TSS from both urban and rural areas. Therefore, limitations of addressing representative values of specific pollution loads were preliminarily regarded due to the lack of continuous spatiotemporal schemes of experimental data at NCEs linked to existing point-sources and progressive LULC. Conclusions of this paper would benefit decision-makers on adapting resilient-driven land use plans to cope with regional pollution disaster risk management in Brazilian river basins.

Keywords: Land-use and land-cover; pollutant load; nested catchment experiments.

2) **Taffarello, D.**, Cunha, D.G.F., Calijuri, M.C. and Mendiondo, E.M. *Land-use/land-cover change evaluation through grey water footprint and load duration curve: watershed management in the Brazilian Jaguari River Basin*. In preparation for **Hydrol. Earth Syst. Sci**. (ISSN 1027-5606, I.F. 3.99).

ABSTRACT

Protecting freshwater resources requires evaluating pollutant loads. This study aims toassess a linking between load duration curves and grey water footprint based on ecohydrological indicators at watersheds under land use/land cover changes. There are some steps to show the applicability of the methodology. First, we considered ecohydrological indicators of flood pulses across river cross-sections, floodplain and regime duration. Second, we applied the methodology to compare total phosphorus-LDCs, TMDL and GWF at Jaguari River to other catchments in the Atlantic Forest biome. Third, we defined new ecohydrological indicators at 5%, 50% and 95% of time, namely, range of ecohydrological load ratio, (rELR), total ecohydrological flow variation (tEFV), and total ecohydrological load variation (tELV). On the one hand, rELR values decreased with catchment size, from 5.63 at Jaguari River to 2.85 and 1.93 at larger scales. On the other hand, tEFV also pointed scale-dependant behavior, ranging from - 157.8 L/s per km^2 at Jaguari River to -32.6 L/s per km^2 and +2.8 L/s per km^2. Results depicted potential hotspots, with surplus of TP ≈ 0.13 mg/L, could co-exist withresilient catchments with surplus of TP ≈ 0.32 mg/L.This integrated method facilitates the visualization of impactson water resources regarding land-use/land-cover change offering a tool for proactive management.

Keywords: ecohydrological indicators; grey water footprint; land-use/land-cover change; water pollution.

APPENDIX B – Primary data from field campaings in Jaguari, Cachoeira and Atibainha subbasins, period Oct.2013-May 2014.

Sub-basin	Drainage area (km^2)	Sampling date	Mean velocity ($m.s^{-1}$)	Flow ($m^3.s^{-1}$)	pH	Turbidity (NTU)	Total solids (mg/L)	Fixed total solids (mg/L)	Total volatile solids (mg/L)	Electric conductivity (µS/cm)	Apparent color	DBO (mg/L)	DQO (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrogen ammonia (mg/L)	Total coliforms (UFC/100 mL)	*E. coli* (CFU/ 100 mL)
Upper Posses	4,00	05/24th/2014	0,127	0,0138	6,72	2,89	70	49	21	60,6	34	<1	16	0,12	0,87	<0,001	0,04	2,8x10	1,3x10
Middle Posses	7,00	05/24th/2014	0,486	0,0390	6,82	3,56	80	22	58	59,47	58	<1	20	0,1	1,09	<0,001	0,07	5,2x10	35
Posses outlet	11,90	05/24th/2014	0,093	0,0430	6,77	5,18	86	31	55	64,96	67	<1	16	0,07	1,41	<0,001	0,07	9,8x10	54
Salto outlet	48,00	05/24th/2014	0,145	0,0325	6,74	6,71	85	25	60	62,81	72	<1	17	0,08	1,72	<0,001	0,07	1,2x10	92
F23 Camanducaia	511,20	05/24th/2014	0,268	2,7866	6,92	11,6	82	42	40	57,84	98	<1	23	0,18	4,07	0,017	0,07	7,7x10	17
Upper Jaguari	281,00	05/24th/2014	ND	Water level 0.65m	6,99	7,8	58	25	33	28,92	70	<1	28	0,17	2,22	<0,001	0,04	2,9x10	2
Pq Eventos Jaguari	925,30	05/24th/2014	0,238	6,3748	6,9	10,4	75	57	18	50,09	92	<1	35	0,22	3,2	0,011	0,06	8,7x10	31
Cachoeira dos Pretos	101,41	05/23th/2014	0,711	2,0637	6,99	7,66	42	39	3	17,03	71	<1	16	0,02	1,44	<0,001	0,05	2,2x10	33
Chalé Ponto Verde	150,00	05/23th/2014	0,577	1,6475	6,96	7,81	43	34	9	16,95	72	<1	16	0,02	1,24	<0,001	0,03	2,2x10	110
Rio Cachoeira bridge	209,63	05/23th/2014	0,53	1,7376	6,95	12,3	42	40	2	20,36	103	<1	26	0,21	1,4	<0,001	0,06	$1,8x10^5$	4000
F24 Cachoeira outlet	289,22	05/23th/2014	0,289	2,5533	6,82	7,98	69	31	38	24,93	77	2	34	0,19	1,34	<0,001	0,06	5,8x10	66
Intervention Cancan	2,01	05/23th/2014	ND	0,0094	6,74	5,73	86	35	51	48,94	61	<1	22	0,12	1,32	<0,001	0,07	8,3x10	40
Reference Cancan	1,26	05/23th/2014	ND	0,0032	6,65	1,63	73	62	11	48,3	24	<1	27	0,04	1,07	<0,001	0,05	2,1x10	250
F30 Cancan outlet	97,00	05/23th/2014	0,227	0,6414	6,83	19,4	94	78	16	38,65	162	<1	25	0,28	1,64	<0,001	0,08	2,6x10	140
Reference Moinho	0,66	05/23th/2014	ND	0,0021	6,94	6,48	108	51	57	35,34	59	<1	16	0,08	1,26	<0,001	0,03	6,1x10	17
Intervention Moinho	3,10	05/23th/2014	ND	0,0001	6,81	22,6	175	47	128	34,15	231	5	98	0,32	1,24	<0,001	0,05	1,3x10	10
Moinho outlet	16,92	05/23th/2014	0,115	0,1623	6,97	14,2	102	63	39	60,26	131	<1	23	0,16	1,96	<0,001	0,09	1,3x10	99

APPENDIX B – Primary data from field campaings in Jaguari, Cachoeira and Atibainha subbasins, period Oct.2013-May 2014 (cont).

Sub-basin	Drainage area (km^2)	Sampling date	Mean velocity ($m.s^{-1}$)	Flow ($m^3.s^{-1}$)	pH	Turbidity (NTU)	Total solids (mg/L)	Fixed total solids (mg/L)	Total volatile solids (mg/L)	Electric conductivity (µS/cm)	Apparent color	DBO (mg/L)	DQO (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrogen ammonia (mg/L)	Total coliforms (UFC/100 mL)	*E. coli* (CFU/ 100 mL)
Upper Posses	4,00	03/14th/2014	0,075	0,009	6,9	3,19	0,034	ND	ND	54,17	28	0	6	0,0292	0,09	<0,001	0	2419,6	ND
Middle Posses	7,00	03/14th/2014	0,418	0,031	6,95	4,63	0,048	ND	ND	53,65	57	4	15	0,0733	0,05	<0,001	0,77	111990	ND
Posses outlet	11,90	03/14th/2014	0,251	0,039	6,86	4,05	0,05	ND	ND	97,96	37	4	5	0,0668	0,25	0,006	0	48840	ND
Salto outlet	48,00	03/14th/2014	0,213	0,038	6,68	17,8	0,028	ND	ND	51,76	116	8	4	0,1292	0,26	<0,001	0	17240	ND
F23 Camanducaia	511,20	03/14th/2014	0,179	1,706	6,76	16,9	0,065	ND	ND	60,5	143	4	18	0,312	0,82	0,019	0,11	61310	ND
Upper Jaguari	281,00	03/14th/2014	ND	1,387	7,06	4,19	0,076	ND	ND	23,64	32	2	2	0,1074	0,34	0,003	0,75	2419,6	ND
Pq Eventos Jaguari	925,30	03/15th/2014	0,181	4,568	6,63	13,8	0,037	ND	ND	43,95	115	3	11	0,2115	0,54	0,01	0,22	173290	ND
Cachoeira dos Pretos	101,41	03/15th/2014	ND	1,385	7,07	10,7	0,032	ND	ND	12,96	27	2	7	0,0522	0,15	<0,001	0	104620	ND
Chalé Ponto Verde	150,00	03/15th/2014	0,48	1,539	6,88	7,96	0,018	ND	ND	14,07	65	2	6	0,0416	0,12	<0,001	0	129970	ND
Rio Cachoeira bridge	209,63	03/15th/2014	0,451	1,403	7,02	8,62	0	ND	ND	16,72	79	3	6	0,1074	0,14	<0,001	0,09	92080	ND
F24 Cachoeira outlet	289,22	03/14th/2014	0,254	2,251	6,79	7,5	0,026	ND	ND	25,95	73	3	10	0,051	0,18	<0,001	0,05	?	ND
Intervention Cancan	2,01	03/15th/2014	0,165	0,005	6,89	4,23	0,03	ND	ND	39,24	39	2	3	0,1633	0,15	<0,001	0,04	1732,9	ND
Reference Cancan	1,26	03/15th/2014	ND	0,002	6,92	1,79	0	ND	ND	46,45	22	0	5	0,0539	0,15	<0,001	0,04	980,4	ND
F30 Cancan outlet	97,00	03/15th/2014	0,210	0,934	6,9	12,5	0,053	ND	ND	40,39	32	2	9	0,0698	0,15	<0,001	0,1	101120	ND
Reference Moinho	0,66	03/16th/2014	ND	0,004	6,96	13,8	0,026	ND	ND	34,13	93	2	4	0,081	0,21	<0,001	0,82	1413,6	ND
Intervention Moinho	3,10	03/16th/2014	ND	0.00014	6,17	19,3	0,057	ND	ND	36,25	179	8	31	0,2221	0,23	0,003	0,15	315	ND

APPENDIX B – Primary data from field campaings in Jaguari, Cachoeira and Atibainha subbasins, period Oct.2013-May 2014 (cont).

Sub-basin	Drainage area (km^2)	Sampling date	Mean velocity ($m.s^{-1}$)	Flow ($m^3.s^{-1}$)	pH	Turbidity (NTU)	Total solids (mg/L)	Fixed total solids (mg/L)	Total volatile solids (mg/L)	Electric conductivity (µS/cm)	Apparent color	DBO (mg/L)	DQO (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrogen ammonia (mg/L)	Total coliforms (UFC/100 mL)	*E. coli* (CFU/ 100 mL)
Moinho outlet	16,92	03/16th/2014	0,144	0,202	6,87	28,27	0,075	?	?	51,14	220	4	12	0,1286	0,37	<0,001	0,19	12445	430
Upper Posses	4,00	12/03rd/2013	0,135	0,034	7,04	6,82	45	7	38	58,62	48	<1	19	0,12	0,07	<0,001	0,29	1,10E+05	8,7E+2
Middle Posses	7,00	12/03rd/2013	0,138	0,082	7,02	14,9	54	41	13	58,93	81	<1	26	0,1	0,08	<0,001	0,11	605	260
Posses outlet	11,90	12/03rd/2013	0,143	0,107	7,1	14,4	56	27	29	70,02	80	<1	24	0,13	0,14	<0,001	0,15	5,30E+05	2,0E+3
Salto outlet	48,00	12/03rd/2013	0,239	0,093	7,24	160	165	137	28	21,98	283	<1	22	0,37	0,20	<0,001	0,15	6,40E+05	4,8E+3
F23 Camanducaia	511,20	12/03rd/2013	0,377	5,5	6,96	180	242	194	48	44,06	323	6	48	0,39	0,46	0,008	0,17	9,80E+04	3,6E+3
Upper Jaguari	281,00	12/03rd/2013	ND	Water level 1,04 m	6,94	12,9	71	45	26	59,6	74	<1	20	0,21	0,22	0,005	0,13	4,70E+03	1,0E+2
Pq Eventos Jaguari	925,30	12/03rd/2013	0,585	20,689	6,72	180	212	173	39	48,71	285	2	36	0,34	0,32	0,004	0,3	7,70E+05	2,1E+3
Cachoeira dos Pretos	101,41	12/04th/2013	ND	3,06	6,79	1,5	63	13	50	13,95	53	1	20	0,12	0,07	<0,001	0,08	4,90E+02	3,7E+1
Chalé Ponto Verde	150,00	12/04th/2013	0,717	3,223	7,1	13,4	82	43	39	14,58	57	1	21	0,11	0,10	<0,001	0,12	9,20E+03	2,9E+2
Rio Cachoeira bridge	209,63	12/04th/2013	0,614	3,618	6,38	15,6	95	51	44	15,26	58	2	25	0,13	0,10	<0,001	0,06	2,40E+03	340
F24 Cachoeira outlet	289,22	12/04th/2013	0,374	5,174	6,88	35,5	49	41	8	22,48	93	2	24	0,18	0,14	<0,001	0,1	1,00E+04	690
Intervention Cancan	2,01	12/04th/2013	0,28	0,022	7,04	9,43	66	13	53	44,9	58	<1	16	0,13	0,17	<0,001	0,09	9,20E+04	7,3E+2
Reference Cancan	1,26	12/04th/2013	0,126	0,009	7,02	5,13	62	45	17	44,88	34	<1	12	0,08	0,12	<0,001	0,06	8,70E+04	6,5E+2
F30 Cancan outlet	97,00	12/04th/2013	0,316	1,297	6,87	59,3	81	72	9	36,03	141	4	42	0,23	0,15	<0,001	0,1	4,30E+02	200

APPENDIX B – Primary data from field campaings in Jaguari, Cachoeira and Atibainha subbasins, period Oct.2013-May 2014 (cont).

Sub-basin	Drainage area (km^2)	Sampling date	Mean velocity ($m.s^{-1}$)	Flow ($m^3.s^{-1}$)	pH	Turbidity (NTU)	Total solids (mg/L)	Total fixed solids (mg/L)	Total suspended solids (mg/L)	Electric conductivity (µS/cm)	Apparent color	DBO (mg/L)	DQO (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrogen ammonia (mg/L)	Total coliforms (UFC/100 mL)	*E. coli* (CFU/ 100 mL)
Reference Moinho	0,66	12/05th/2013	0,327	0,017	6,73	9,46	25	21	4	34,86	41	<1	13	0,13	0,08	<0,001	0,15	7,50E+03	1,6E+2
Intervention Moinho	3,10	12/05th/2013	0,0000 55	0,055	7,15	4,9	65	20	45	41,04	48	<1	11	0,12	0,06	<0,001	0,07	1,70E+03	46
Moinho outlet	16,92	12/05th/2013	0,075	0,081	7,05	13,5	46	33	13	56,25	78	1	19	0,17	0,20	<0,001	0,12	4,10E+05	1,3E+3
Upper Posses	4,00	10/23th/2013	0,123	0,024	6,68	5,71	62	55	7	63,67	42	1	6	0,06	0,07	<0,001	0,09	416	10
Middle Posses	7,00	10/23th/2013	0,431	0,067	6,89	7,88	40	7	33	63,74	63	1	8	0,1	0,09	0,006	0,16	173	14
Posses outlet	11,90	10/23th/2013	0,16	0,106	6,84	6,28	74	13	61	133,94	49	2	12	0,1	0,07	<0,001	0,18	435	1
Salto outlet	48,00	10/23th/2013	0,322	0,073	6,78	18,6	68	58	10	54,71	89	4	14	0,19	0,19	0,005	0,19	8,70E+03	4
Upper Jaguari	281,00	10/23th/2013	ND	ND	7,05	67,4	115	89	26	25,18	130	2	10	0,36	0,19	<0,001	0,12	52	9
Pq Eventos Jaguari	925,30	10/23th/2013	ND	ND	6,8	283	305	166	139	38,87	346	6	24	1,62	0,42	0,01	0,2	9,60E+05	4,1E+3
Cachoeira dos Pretos**	101,41	10/24th/2013	ND	2,00	7,03	5,86	28	12	16	16,31	38	1	6	0,07	0,10	<0,001	0,08	2,80E+04	0
Chalé Ponto Verde	150,00	10/24th/2013	0,588	2,106	6,82	6,44	61	21	40	16,25	39	2	9	0,07	0,12	<0,001	0,12	34	3
rio Cachoeira bridge	209,63	10/24th/2013	0,313	3,582	6,71	7,7	27	19	8	18,42	39	3	10	0,06	0,13	<0,001	0,1	30	0
F24 Cachoeira outlet	289,22	10/24th/2013	0,313	3,582	6,94	13,2	76	64	12	28,63	47	4	16	0,09	0,11	<0,001	0,11	14	5
Intervention Cancan	2,01	10/24th/2013	0,91	0.009	7,02	5,54	24	2	22	47,22	40	3	13	0,08	0,07	<0,001	0,09	194	0
Reference Cancan	1,26	10/24th/2013	0,816	0.006	7,13	2,36	62	49	13	42,81	22	2	11	0,06	0,03	<0,001	0,49	272	5
F30 Cancan outlet	97,00	10/24th/2013	0,447	0,951	7,12	24,6	53	45	8	38,13	63	3	19	0,12	0,16	<0,001	0,11	8,40E+05	3,4E+3

APPENDIX B – Primary data from field campaings in Jaguari, Cachoeira and Atibainha subbasins, period Oct.2013-May 2014 (cont).

Sub-basin	Drainage area (km^2)	Sampling date	Mean velocity ($m.s^{-1}$)	Flow ($m^3.s^{-1}$)	pH	Turbidity (NTU)	Total solids (mg/L)	Fixed total solids (mg/L)	Total volatile solids (mg/L)	Electric conductivity (µS/cm)	Apparent color	DBO (mg/L)	DQO (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Nitrogen ammonia (mg/L)	Total coliforms (UFC/100 mL)	*E. coli* (CFU/ 100 mL)
Intervention Moinho	3,10	10/25th/2013	0,075	0,001	6,69	9,47	32	25	7	34,48	12	1	4	0.05	0.02	0.004	0.03	6,5E+05	2,4E+3
Moinho outlet	16,92	10/25th/2013	0,102	0,081	6,84	3,9	43	30	13	51,12	23	<1	6	0,08	0,18	0,005	0,13	517	517

ANNEX A - Gauging stations with observed data from 2004 to 2014.

Source	Type	Code	City	State	Period	Latitude	Longitude
USP/EESC	Field campaigns	Montante	Extrema	MG	Dec/2012-May/2014	-22.879	-46.247
USP/EESC & ANA	Field campaigns	Médio ANA -62584500	Extrema	MG	Dec/2012-May/2014	-22.867	-46.244
USP/EESC & ANA	Field campaigns	Exutório ANA - 62584600	Extrema	MG	Dec/2012-May/2014	-22.833	-46.231
USP/EESC	Field campaigns	Exutório Salto	Extrema	MG	Dec/2012-May/2014	-22.838	-46.218
USP/EESC	Field campaigns	Alto Jaguari	Extrema	MG	Dec/2012-May/2014	-22.820	-46.154
USP/EESC	Field campaigns	Parque de Eventos	Extrema	MG	Dec/2012-May/2014	-22.853	-46.325
USP/EESC & SABESP	Field campaigns	Bairro dos Tenentes F-23	Extrema	MG	Jan/2004 - Jul/2014	-22.827	-46.314
USP/EESC	Field campaigns	Cachoeira dos Pretos	Joanópolis	SP	Dec/2012-May/2014	-22.968	-46.171
USP/EESC	Field campaigns	Chalé Ponto Verde	Joanópolis	SP	Dec/2012-May/2014	-22.964	-46.181
USP/EESC	Field campaigns	Ponte Cachoeira	Joanópolis	SP	Dec/2012-May/2014	-22.968	-46.171
USP/EESC & SABESP	Field campaigns	Exutório F-24	Joanópolis	SP	Jan/2004 - Jul/2014	-22.983	-46.244
USP/EESC	Field campaigns	Intervenção (Jesuíno)	Joanópolis	SP	Dec/2012-May/2014	-22.912	-46.225
USP/EESC	Field campaigns	Referência (Domithildes)	Joanópolis	SP	Dec/2012-May/2014	-22.886	-46.222
USP/EESC & SABESP	Field campaigns	Exutório F-30	Joanópolis	SP	Jan/2004 - Jul/2014	-22.935	-46.212
USP/EESC	Field campaigns	Intervenção (Bertolino)	NazaréPaulista	SP	Dec/2012-May/2014	-23.222	-46.325
USP/EESC	Field campaigns	Referência (Ronaldo Santal)	NazaréPaulista	SP	Dec/2012-May/2014	-23.232	-45.323
USP/EESC & SABESP	Field campaigns	Exutório	NazaréPaulista	SP	Dec/2012-May/2014	-22.848	-46.327

ANNEX A - Gauging stations with observed data from 2004 to 2014 (cont.).

Source	Type	Code	City	State	Period	Latitude	Longitude
SABESP	Discharge	F-23	Extrema	MG	Jan/2004 - Jul/2014	-22.827	-46.314
SABESP	Discharge	F-24	Joanópolis	SP	Jan/2004 - Jul/2014	-22.996	-46.241
SABESP	Discharge	F-25B	Extrema	MG	Jan/2004 - Jul/2014	-22.875	-46.369
SABESP	Discharge	F-28	Camanducaia	MG	Jan/2004 - Jul/2014	-22.832	-46.123
SABESP	Discharge	F-30	Joanópolis	SP	Jan/2004 - Jul/2014	-22.935	-46.211
SABESP	Discharge	F-34	Piracaia	SP	Jan/2004 - Jul/2014	-23.095	-46.264
SABESP	Rainfall	BRA	NazaréPaulista	SP	Jan/2004 - Jul/2014	-23.174	-46.393
SABESP	Rainfall	BRC	Piracaia	SP	Jan/2004 - Jul/2014	-23.050	-46.319
SABESP	Rainfall	P-10	BragançaPaulista	SP	Jan/2004 - Jul/2014	-22.923	-46.421
SABESP	Rainfall	P-11	Camanducaia	MG	Jan/2004 - Jul/2014	-22.685	-46.183
SABESP	Rainfall	P-12	Camanducaia	MG	Jan/2004 - Jul/2014	-22.864	-46.049
SABESP	Rainfall	P-13	Camanducaia	MG	Jan/2004 - Jul/2014	-22.795	-46.053
SABESP	Rainfall	P-14A	Sapucaí-Mirim	MG	Jan/2004 - Jul/2014	-22.755	-45.837
SABESP	Rainfall	P-3	Mairiporã	SP	Jan/2004 - Jul/2014	-23.310	-46.447
SABESP	Rainfall	P-4	Joanópolis	SP	Jan/2004 - Jul/2014	-22.941	-46.121
SABESP	Rainfall	P-5	NazaréPaulista	SP	Jan/2004 - Jul/2014	-23.021	-46.170
SABESP	Rainfall	P-6	NazaréPaulista	SP	Jan/2004 - Jul/2014	-23.261	-46.394

ANNEX A - Gauging stations with observed data from 2004 to 2014 (cont.).

Source	Type	Code	City	State	Period	Latitude	Longitude
SABESP	Rainfall	P-7	Joanópolis	SP	Jan/2004 - Jul/2014	-22.994	-46.242
SABESP	Rainfall	P-8	Camanducaia	MG	Jan/2004 - Jul/2014	-22.779	-46.180
SABESP	Rainfall	P-9	Extrema	MG	Jan/2004 - Jul/2014	-22.775	-46.275
INMET	Weather	83075	Guarulhos	SP	Jan/2004 - Jul/2014	-23.430	-46.460
CPTEC/INPE	Weather	83721	Campinas	SP	Jan/2004 - Jul/2014	-23.000	-47.140
CPTEC/INPE	Weather	83829	São José dos Campos	SP	Jan/2004 - Jul/2014	-23.220	-45.870
CIIAGRO	Rain and Temperature	at	Atibaia	SP	Jan/2004 - Jul/2014	-23.083	-46.560
CIIAGRO	Rain and Temperature	bj	Bom Jesus dos Perdões	SP	Jan/2004 - Jul/2014	-23.131	-46.450
CIIAGRO	Rain and Temperature	br	BragançaPaulista	SP	Jan/2004 - Jul/2014	-22.949	-46.525
CIIAGRO	Rain and Temperature	ex	Extrema	MG	Jan/2004 - Jul/2014	-22.852	-46.326
CIIAGRO	Rain and Temperature	nz	NazaréPaulista	SP	Jan/2004 - Jul/2014	-23.177	-46.397
IGAM	Water quality	PJ001	Extrema	MG	Oct/2011 - Jul/2014	-22.832	-46.123
IGAM	Water quality	PJ024	Extrema	MG	Oct/2011 - Jul/2014	-22.830	-46.314
IGAM & SABESP	Water quality	PJ021 e F-28	Camanducaia (Monte Verde)	MG	Oct/2011 - Jul/2014	-22.826	-46.129