Year : 2023

Production, circulation and application of scientific knowledge: forest hydrology and policy-making in Chile

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Faculté des géosciences et de l'environnement

Institut de géographie et durabilité

Production, circulation and application of scientific knowledge: forest hydrology and policy-making in Chile

Thèse de doctorat

Présentée à la

Faculté des géosciences et de l'environnement
de l'Université de Lausanne

pour l'obtention du grade de
Docteur en sciences de l'environnement

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Lausanne, 2023

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Madame Astrid OPPLIGER URIBE

Titulaire d'un
Master of Science en Gouvernance des risques et des ressources
de l'Université de Heidelberg

intitulée

PRODUCTION, CIRCULATION AND APPLICATION OF SCIENTIFIC KNOWLEDGE: FOREST HYDROLOGY AND POLICY-MAKING IN CHILE

Lausanne, le 21 février 2023

Pour le Doyen de la Faculté des géosciences et de l'environnement

Professeure Marie-Elodie Perga

Para Chile y mi amado Ewoud Lauwerier.
Mis amadas Celeste Estella, Madre y abuelitas Ella y Adriana.
Con amor a mi padre, y mis abuelos W. Uribe, y Tata Cesar.

Mit Liebe und Dankbarkeit für alle meine schweizerischen
und deutschen Vorfahren.
A todos mis ancestros del sur y el norte.

Source: author, 2020. Old-growth *Eucalyptus* forest, in Victoria, Australia.

Abstract

Forests and plant communities play a key role in regulating the hydrological cycle. During the last decades, forest plantations of *Eucalyptus* species – or *Pinus* and *Acacias* – have become predominant in the landscapes of many countries and raised concerns about their detrimental effects on water availability. The phenomenon has become a controversial subject. Such is the case in Chile, where, despite the existence of a wide range of international and national forest hydrology studies, the issue remains somehow contested. As scientific knowledge plays a key role in the development of societies, by providing, for example, the basis of knowledge for decision or policy-making, the science of forest hydrology – which studies how water flows through forests and vegetation communities – might help to understand such contestations of environmental knowledge.

This investigation was initiated to understand the science of forest hydrology, and whether or not in its social production, circulation and application of knowledge it was possible to find reasons for these water and forest contestations. To address this, the investigation draws on three bodies of literature: (1) forest hydrology science, (2) science studies and (3) political ecology. Empirically, this research is based on three field campaigns in Chile, South Africa and Australia. The research method is structured in three phases. First, it draws on a systematic literature review on *Eucalyptus* trees – from forest hydrology studies of these three countries. The second and third phases of the research focus on Chile. Inspired by works interconnecting science studies and political ecology, the research operationalises the 'field theory' and the 'advocacy coalition framework' as theoretical tools to analyse the social production, circulation and application of scientific knowledge of forest hydrology, its governance, and policy-making. In this regard, the forest hydrology science and policy of 'the Forest Plantation Protocol (FPP)' in Chile are taken as a case study.

Results are presented in three chapters. First, results demonstrate that most scientific studies confirm that *Eucalyptus* trees have higher water use rates than other land covers such as native forests or scrublands, agriculture, grassland, wetland vegetation, and other plantation tree species such as *Pinus radiata* or *Acacias*. These hydrological results hold irrespective of whether the *Eucalyptus* trees are present as native or non-native trees. The review suggests that

variations and nuances in these findings may result from variations in the study design. Second, the investigation on the production and circulation of knowledge in the forest hydrology field reveals the presence of knowledge producers from academia, government and forestry companies. These actors contribute to and contest scientific knowledge and its legitimacy in different ways. Some senior governmental actors, for instance, claim that there are no studies, or that they are not aware of the existence of (or relevant) forest hydrology research in the country. Other researchers for their part, acknowledge the existence of several forest hydrology studies and the effects of forestry plantations on water resources, but some challenge the legitimacy and scientific authority of these forest hydrology studies in different ways. The investigation shows the existence of two scientific trends or approaches within the forest hydrology field: the ecosystem approach and the forestry hydrogeology approach. It also demonstrates that external political-economic relations within which the field is embedded, shape the production and circulation of the forest hydrology knowledge, and some of its practices challenge its relative autonomy. Third, the research on the circulation and application of forest hydrology knowledge in the policy-making of the FPP demonstrates that the knowledge listened to is a combination of forestry hydrogeology and ecosystem science approaches. Both approaches correspond to two opposing coalitions on water and soil regulation issues in the FPP: forestry industry versus governmental actors, and their respective allies. Most of the invited academics supported the industrial coalition, as did some governmental actors. It is demonstrated that some academics are sometimes inconsistent in their statements, and might generate doubt on certain issues of forest hydrology. Nonetheless, it is also demonstrated that scientific knowledge played a modest role in the policy production through the circulation and the application of scientific articles to support the policy outputs. Paths to policy change are a combination of external events (fires in 2017), some learning, and mostly a process of negotiation where socio-economic criteria are applied. The research also shows that external events can relatively shift the balance of negotiation powers, as well as that previous policy or agreements can strategically establish negotiation margins for the policy outcomes. Finally, this study suggests that the practices of contestation of the existence or non-existence of studies, the delegitimisation of existing research, and the stated inconsistencies, among others, have very likely contributed to building controversy over the field of forest hydrology and the knowledge it holds on plantation forestry and its effects on water resource and its reductions in the country.

This theoretical and empirical investigation contributes to the literature in three ways. First, it contributes to understanding forest hydrology discussions. Second, it empirically and geographically furthers research in political ecology and sciences studies working on production, circulation and application of environmental knowledge. Third, it contributes to the work of political ecology and science studies by operationalizing the concepts of 'the field theory' and the 'advocacy coalition framework', highlighting the role of scientific knowledge, its governance and role in policy-making.

Résumé

Les forêts et les communautés végétales jouent un rôle clé dans la régulation du cycle hydrologique. Au cours des dernières décennies, les plantations forestières d'espèces d'*Eucalyptus* – ou de *Pinus* et d'*Acacias* – sont devenues prédominantes dans les paysages de nombreux pays et ont suscité des inquiétudes quant à leurs effets sur la disponibilité de l'eau. Le phénomène est devenu un sujet de controverse. C'est le cas au Chili, où, malgré l'existence d'un large éventail d'études internationales et nationales sur l'hydrologie forestière, la question reste contestée. Comme la connaissance scientifique joue un rôle clé dans le développement des sociétés, en fournissant, par exemple, la base de connaissances pour la prise de décision ou l'élaboration de politiques, la science de l'hydrologie forestière – qui étudie comment l'eau s'écoule à travers les forêts et les communautés végétales – pourrait aider à comprendre ces contestations de la connaissance environnementale.

Cette recherche a été initiée afin de comprendre la science de l'hydrologie forestière et pour savoir si, dans sa production sociale, sa circulation et son application de la connaissance, il était possible de trouver des raisons à ces contestations de l'eau et de la forêt. Pour ce faire, l'enquête s'appuie sur trois corpus de littérature : (1) la science de l'hydrologie forestière, (2) les études scientifiques et (3) l'écologie politique. Empiriquement, cette recherche se base sur trois campagnes de terrain au Chili, en Afrique du Sud et en Australie. La méthode de recherche est structurée en trois phases. Premièrement, elle s'appuie sur une revue systématique de la littérature sur les *Eucalyptus* dans ces trois pays, relevant pour la science de l'hydrologie forestière. Les deuxièmes et troisièmes phases de la recherche se concentrent sur le Chili. Inspirée par des travaux interconnectant des *sciences studies* et l'écologie politique, la recherche opérationnalise la 'théorie du champ' et le '*modèle des coalitions de cause*' en tant qu'outils théoriques pour analyser la production sociale, la circulation et l'application des connaissances scientifiques de l'hydrologie forestière, sa gouvernance et son utilisation dans l'élaboration des politiques. A cet égard, la science de l'hydrologie forestière et la politique du "Protocole de Plantation Forestière (PPF)" au Chili sont prises comme étude de cas.

Les résultats sont présentés en trois chapitres. Premièrement, les résultats démontrent que la large majorité des études scientifiques confirment que les *Eucalyptus* ont des taux d'utilisation de l'eau plus élevés que d'autres couvertures terrestres telles que les forêts ou arbustes sauvages, l'agriculture, les prairies, la végétation des zones humides et d'autres espèces

d'arbres de plantation telles que *Pinus radiata* ou *Acacias*. Ces résultats hydrologiques sont valables indépendamment du fait que les *Eucalyptus* soient présents en tant qu'arbres indigènes ou non indigènes. L'examen suggère que les variations et les nuances dans ces résultats peuvent résulter de variations dans le design de l'étude. En deuxième lieu, la recherche sur la production et la circulation des connaissances dans le domaine de l'hydrologie forestière révèle que les académiciens, l'État et les entreprises forestières sont des producteurs de connaissances. Ces acteurs contribuent et contestent les connaissances scientifiques et leur légitimité de différentes manières. Certains acteurs gouvernementaux de haut niveau par exemple, affirment ne pas être au courant de l'existence (ou de la relevance) de la recherche en hydrologie forestière dans le pays. D'autres chercheurs, pour leur part, reconnaissent l'existence de plusieurs études sur l'hydrologie forestière et les effets des plantations forestières sur les ressources en eau. Mais certains d'entre eux remettent en question la légitimité et l'autorité scientifique de certaines études d'hydrologie forestière de différentes manières. Elle montre l'existence de deux tendances ou approches scientifiques dans le domaine de l'hydrologie forestière : l'approche écosystémique et l'approche hydrogéologique forestière. L'investigation démontre également que les relations politico-économiques externes dans lesquelles le domaine est intégré, façonnent la production et la circulation des connaissances en matière d'hydrologie forestière, et que certaines de ses pratiques remettent en question son autonomie relative. En troisième lieu, la recherche sur la circulation et l'application des connaissances en hydrologie forestière dans l'élaboration de la politique du PPF, démontre que les connaissances prises en compte sont une combinaison d'approches d'hydrogéologie forestière et de science des écosystèmes. Ces deux approches correspondent à deux coalitions opposées sur les questions de régulation des eaux et des sols dans le PPF : l'industrie forestière et les acteurs gouvernementaux, et leurs alliés respectifs. La plupart des académiciens invités ont soutenu la coalition industrielle, et certains acteurs gouvernementaux l'ont également défendue. Il est démontré que certains académiciens sont dans certains cas incohérents dans leurs déclarations et peuvent génèrent le doute sur certains thèmes d'hydrologie forestière. Malgré cela, il est démontré que la connaissance scientifique a joué un rôle modeste dans la production de la politique par la circulation et l'application d'articles scientifiques pour soutenir les résultats de la politique. Les voies du changement politique sont une combinaison d'événements externes (feux de forêt en 2017), d'un certain apprentissage et surtout d'un processus de négociation où des critères socio-économiques sont appliqués. La recherche montre également que les événements externes peuvent modifier relativement l'équilibre des pouvoirs de négociation, et que la politique ou les accords précédents peuvent établir stratégiquement les marges de négociation des résultats politiques. Enfin, cette étude suggère que les pratiques de contestation de l'existence ou de l'inexistence d'études, de délégitimation des recherches existantes et d'incohérences déclarées, entre autres, ont très probablement contribué à la controverse dans le domaine de l'hydrologie forestière et ses connaissances sur la foresterie de plantation d'espèces exotiques et ses effets sur les ressources en eau et leur réduction dans le pays.

Cette étude théorique et empirique contribue à la littérature de trois manières. Premièrement, elle contribue à la compréhension des discussions sur l'hydrologie forestière. Deuxièmement, elle approfondit empiriquement et géographiquement la recherche en écologie politique et en études des sciences travaillant sur la production, la circulation et l'application des connaissances environnementales. Troisièmement, il contribue à enrichir le travail de l'écologie politique et des études scientifiques en opérationnalisant les concepts de 'théorie du champ' et de 'cadre de coalition de plaidoyer', en soulignant le rôle de la connaissance scientifique, sa gouvernance et sa fonction dans l'élaboration des politiques.

Resumen

Los bosques y las comunidades vegetales desempeñan un papel fundamental en la regulación del ciclo hidrológico. En las últimas décadas, las plantaciones forestales de especies de *Eucalyptus* – o *Pinus* y *Acacias* – se han hecho predominantes en los paisajes de muchos países y han suscitado la preocupación por sus efectos sobre la disponibilidad de agua. El fenómeno se ha convertido en un tema controvertido. Tal es el caso de Chile, donde, a pesar de la existencia de una amplia gama de estudios internacionales y nacionales sobre hidrología forestal, la cuestión sigue siendo controvertida. Dado que el conocimiento científico juega un papel clave en el desarrollo de las sociedades, al proporcionar, por ejemplo, la base del conocimiento para la toma de decisiones o la formulación de políticas, la ciencia de la hidrología forestal – que estudia cómo fluye el agua a través de los bosques, plantaciones y diversas comunidades de vegetación – podría ayudar a entender estas contestaciones del conocimiento ambiental.

Esta investigación se inició para entender la ciencia de la hidrología forestal, y si en sus fases sociales de producción, circulación y aplicación del conocimiento era posible encontrar razones para estas impugnaciones sobre el agua y las plantaciones forestales. Para ello, la investigación se basa en tres cuerpos de literatura: (1) la ciencia de la hidrología forestal, (2) los estudios sobre la ciencia y (3) la ecología política. Empíricamente, esta investigación se basa en tres campañas de campo en Chile, Sudáfrica y Australia. El método de investigación se estructura en tres fases. En primer lugar, se basa en una revisión bibliográfica sistemática sobre los eucaliptos en estos tres países, relevantes para la ciencia de la hidrología forestal. La segunda y tercera fase de la investigación se centran en Chile. Inspirada en trabajos que interconectan los estudios de la ciencia y la ecología política, la investigación operacionaliza la 'teoría del campo' y el 'marco de las coaliciones de causa' como herramientas teóricas para analizar la producción, circulación y la aplicación del conocimiento científico de la hidrología forestal, su gobernanza y utilización en la elaboración de políticas. En este sentido, se toma como caso de estudio la disciplina científica de la hidrología forestal y el caso de la política forestal del 'Protocolo de Plantaciones Forestales (PPF)' en Chile.

Los resultados se presentan en tres capítulos. En primer lugar, los resultados demuestran que la vasta mayoría de los estudios científicos confirman que los eucaliptos tienen tasas de uso de agua más altas que otras coberturas terrestres como los bosques o matorrales nativos, la agricultura, los pastizales, la vegetación de los humedales y otras especies de árboles de

plantación como el *Pinus radiata* o las *Acacias*. Estos resultados hidrológicos se mantienen independientemente de que los eucaliptos estén presentes como árboles nativos o exóticos. La revisión sugiere que las variaciones y matices en estos resultados pueden ser el resultado de las variaciones en el diseño del estudio. En segundo lugar, la investigación sobre la producción y circulación del conocimiento en el ámbito de la hidrología forestal revela la existencia de productores procedentes del mundo académico, del gobierno y de las empresas forestales. Estos actores contestan de diferentes maneras el conocimiento científico de la hidrología forestal y su legitimidad. Algunos actores gubernamentales del alto nivel central declaran que no hay estudios o de no saber de la existencia de investigación científica (o relevante) en hidrología forestal en el país. Otros investigadores, por su parte, reconocen la existencia de varios estudios de hidrología forestal y los efectos de las plantaciones forestales en los recursos hídricos. Pero algunos cuestionan la legitimidad y la autoridad científica de los estudios en hidrología forestal de diferentes maneras. Se demuestra la existencia de dos tendencias o enfoques científicos dentro del campo de la hidrología forestal: el enfoque ecosistémico y el enfoque hidrogeológico forestal. También se demuestra que las relaciones político-económicas externas en las que se inserta el campo de la hidrología forestal, están transformando la producción y circulación del conocimiento de la hidrología forestal, y algunas de sus prácticas están desafiando su relativa autonomía. En tercer lugar, la investigación sobre la circulación y la aplicación de los conocimientos de hidrología forestal en la elaboración del PPF, demuestra que los conocimientos que se consideran son una combinación de enfoques de 'hidrogeología forestal' y 'ecosistémico'. Ambos enfoques fueron usados por dos coaliciones opuestas en cuestiones de regulación del agua y el suelo en el PPF: la industria forestal y los actores gubernamentales, y cada uno de sus aliados. Sin embargo, la mayoría de los académicos invitados apoyaron la coalición industrial, y algunos actores gubernamentales también abogaron por la industria. Se demuestra que algunos académicos son en ciertas ocasiones inconsistentes en sus declaraciones y que pueden generan dudas en ciertos temas de la hidrología forestal. A pesar de esto, se demuestra que el conocimiento científico jugó un papel modesto en la producción de la política del PPF a través de la circulación y la aplicación de artículos científicos que apoyaron los resultados del PPF. Los caminos para el cambio político, son una combinación de eventos externos (los incendios forestales de 2017), algunos aprendizajes y sobre todo un proceso de negociación donde se aplican criterios socioeconómicos. La investigación también muestra que los acontecimientos externos pueden cambiar relativamente el equilibrio de los poderes de negociación, así como que las políticas o los acuerdos anteriores pueden establecer estratégicamente los márgenes de negociación de los resultados políticos. Finalmente, este estudio sugiere que las prácticas de impugnación sobre la existencia o inexistencia de estudios, la deslegitimación de las investigaciones existentes y las incoherencias declaradas, entre otras, han contribuido muy probablemente a crear controversia sobre el campo de la hidrología forestal y sus conocimientos sobre plantaciones forestales de especies exóticas y sus efectos sobre los recursos hídricos y su reducción en el país.

Esta investigación teórica y empírica contribuye a la literatura de tres maneras. En primer lugar, contribuye a la comprensión de los debates sobre hidrología forestal. En segundo lugar, enriquece empírica y geográficamente la investigación en los estudios de ecología política y estudios de la ciencia que trabajan en la producción, circulación y aplicación del conocimiento medioambiental. En tercer lugar, contribuye al trabajo de la ecología política y los estudios de ciencia al hacer operativos los conceptos de la teoría del campo y del marco de la coalición de defensa, al destacar el rol del conocimiento científico, su gobernanza y su función en la elaboración de políticas.

Acknowledgements

Thanks to all the professors who – in one way or another – helped me to learn, to understand and to mature, many of the findings of this research. Thanks to Professors René Véron and Michael Handke, who were present from the beginning, accompanying me and giving their recommendations. Many thanks to Professor David Richardson, who with his strength helped me to open many paths. Also, thanks to Professor Rodney Keenan. I learned a lot. Many thanks to Professor Javiera Barandiarán for her interest in my research. Many thanks to my supervisor, Professor Christian Kull, who by his example taught me a lot throughout the years of my research. Thanks Christian, I learned a lot.

Many thanks to all the forest hydrologists, foresters and scholars who shared their knowledge and experiences with me. Professors Antonio Lara, Carlos Oyarzún, Andres Iroumé, Julia Jones, James Bathurst, Pablo Donoso, Luis Gonzalez, Andres Plaza, Mauricio Galleguillos, Sergio Donoso, José Luis Arumi, Rafael Rubilar, Christian Echeverria, Alejandra Stehr, Mauricio Aguayo. To Pablo Ramirez, Oscar Mardones, Christian Little, Victor Vargas, Fernando Raga, Guillermo Barrientos, Trevor Walter, Patricio Rutherford, and many others in Chile. Professors Jan Bosch, David Le Maitre, Peter Dye, David Scott, Dirk Versfeld, Mark Gush, Alistair Clulow, Roland Schulze, and others in South Africa. Professors Helena Bender, Lu Zhang, Richard Silberstein, Robert Vertessy, Alice Brown, Albert van Dijk, Leon Bren, Richard Benyon, Gary Sheridan, Patrick Lane, Richard Harper, Brett Bennett, and many others in Australia. Thank you all.

Especial agradecimiento y amor para mi familia. Mi madre, Celeste Estrella, Mónica Caro, mi Ellita Hermosa, mi Tata César, mi abuelo Wensceslao, y mi gatuna Ayarauca Blanca. Gracias a mi aquerida tía Luz. Dank je mijn liefste Ewoud Lauwerier en heel je familie. Vielen dank Cousin Jaime Uribe und alle meine liebe Familie Uribe. Gracias a todos los profesores, personas y amigos que, de una u otra forma, también han contribuido en mi camino para llegar hasta aquí. Don José Luis Buitano y todo el A.P.R. de Mashue. Mi tío abuelo Erich Oppliger y tía Sonia Negrón de La Unión. A Michael Hantke D. A los Profesores Hugo Romero A., Johanna Höhl, Andrea Cabezas, y Rocio Urrutia. A Alberto

Dufey, Nadine Chuat, Patricia Schifferli y Lincoyan Nehuen. Thanks to Ross Shackleton. Merci Flore Lafaye de Micheaux, Barbara Beck, Marcia Curchod and to the professors and colleagues of the Institute of geography and sustainability. Thanks Maria Amaya, Annalisa Soncini, Nuria Sanchez, Emanuele Politi, Amal Zayed and Jad Moawad. Gracias a todo Génesis n° 5 G.L.F.Ch. A la bella Valeria Ravera. Merci à Daniel Bally et Inés Gomez. And to so many others who in one way or another listened to, shared a book, gave some advice, encouraged to continue, shared joy and tried to understand what this PhD was all about for me.

Gracias a la vida, a todes mis antepazades, y por todas las sincronias. These last 5 years have been the most wonderful and the most horrible – with their nuances – of my life. During the process of this investigation, I indeed learned a lot. Many thanks to all those whom I met during this investigative journey and who taught me a lot.

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Chapter I

Introduction

This chapter provides an overview of the thesis. Section 1.1 introduces the background of the investigation. Section 1.2 identifies gaps in society and existing research. Section 1.3 presents the objectives of the investigation. Section 1.4 presents personal motivations for developing the research. Finally, section 1.5 provides an outline of the structure of the thesis.

1.1 Background

Forests play a key role in global, regional and local hydrological cycles. Run-off and infiltration from natural forests support many of the world's largest river systems and supply drinking water for nearly half of the world's largest cities (UN-Forests 2021) as well as to small rural villages (Oppliger et al. 2019). Moreover, climate change has made water scarcity a key global concern (UN-Water 2021) and availability and access to water is a primary issue among different water users (Oppliger et al. 2019). Therefore, understanding the role of forests in hydrological processes has become a crucial aspect of water management (Lane et al. 2010; Melbourne Water 2021; CSIR 2021). This is particularly the case for tree species planted extensively around the world and associated with high use of water rates, such as eucalypts trees.

Eucalyptus and the closely-related genus *Corymbia* (hereafter "eucalypts") contain more than 700 species that dominate native forests and shrublands in Australia (Booth et al. 2015). Many species of eucalypts and their hybrids are cultivated in forest plantations around the world (Whitehead and Beadle 2004). Eucalypts are appreciated for their high growth rates and adaptability to a wide range of environmental conditions (Vargas, et al., 2018). They can be grown on short rotations of 5 or 15 years to produce multiple products of value for local people (firewood, construction), and for forest-based industries (Forrester et al. 2010). This has made eucalypt-based forestry an important renewable and profitable industry in many countries, with its products mainly destined for pulp mill production (paper) (King 1978) and recently for forest fiber (polymer, textiles) production due to an increasing global demand for biodegradable products (Väisänen et al. 2016). Although generally less invasive than other tree genera that are widely planted as non-natives globally (notably *Acacia* and *Pinus*), at least 45 eucalypt species are naturalized somewhere in the world (Rejmánek and Richardson 2011) and several are important invasive species (Rejmánek and Richardson 2013; Hirsch et al. 2020).

Despite being a renewable resource and providing multiple benefits, job and important revenues (King 1978; Väisänen et al. 2016), *Eucalyptus* have long been criticized for their effects on water availability, due to their high water use (Barros Ferraz et al. 2019). As a result, the nexus between water resources and eucalypts has been a subject of worldwide debate, including among public and private actors, forest hydrologists and other scientists (Calder 1999; 2004; Dye and Versfeld 2007; Doody et al. 2011; Albaugh et al. 2013; White et al. 2016). In this context, the science of forest hydrology, which is the science that studies how water moves through forests (Jones et al. 2009), has helped to understand the interactions of water and forests.

This is the case in Chile, where at least since the 1960's, there have been many environmental debates about the nexus between exotic forest plantations and water depletion. In Chile, *Pinus* and *Eucalyptus* trees were introduced since the end of 19th century, but its production was dramatically increased - by at least double - since 1974, and have become the main trees used in the country's forestry industry. Up to today, *Eucalyptus* trees are becoming more predominant and expanding their production in Chile. Putting the country forestry production in perspective, in South America, Chile is the country with the second-largest expanse of forest plantations after Uruguay (Jones et al. 2016), and with 861,000 hectares (INFOR 2017b) *Eucalyptus* is one of the most important exotic tree species used in the forestry industry. Since the 1990s, Chile has been one of the ten largest exporters of forest products in the world (Jelvez et al. 1990), and currently, some Chilean forestry companies are among the largest pulp mills in the world (LaTercera 2017). This is an important source of development for Chile, where the forestry sector contributed 1.9% of the national GDP in 2017 (INFOR 2020; Cardemil-Winkler 2021).

However, Chile has faced an unprecedented 'mega drought' from 2010 to 2018 with only a partial recovery anticipated in the next decades (CR2 2015; Garreaud et al. 2020). Water scarcity has become one of the country's most important environmental problems (Bachelet 2015), and some members of civil society living in rural areas associate the increase of water depletion with the introduction of neighbouring exotic forestry plantations (Palma et al. 2013; INFOR 2013; Torres-Salinas et al. 2016; CONAF 2017a). Furthermore, in Chile it is well known that in diverse regions characterised by the presence of extended tree plantations with high rate of water use (e.g. *Eucalyptus*, *Pinus*, *avocados,* etc.), the rural inhabitants living near such plantations are depending on emergency water supply mechanisms such as water tankers to overcome water scarcity problems (Torres-Salinas et al. 2016; Fragkou et al. 2022).

Inspired by this national debate, in 2017 the Chilean State through the Ministry of Agriculture sought to address, for the first time at the national level and collaboratively with academics, companies, and civil society organisations, the nexus between water scarcity and exotic forest plantations by creating the Forest Plantations Protocol (FPP). This Protocol seeks (among other topics) to safeguard water and soil resources through the development of water protection buffer-zones (CONAF 2017b). The Forest Plantations Protocol (2017) is part of the new Forest Policy of Chile (2015-2035). The protocol was developed through a governance approach, in which forest hydrologists, forestry companies, policy-makers and representatives of social organizations were summoned to jointly negotiate the Protocol design. Nevertheless, as in many environmental discussions or policy production processes, the science underlying the discussions appeared contested.

Inspired by these issues, this Ph.D. thesis aims to shed light on the state of knowledge of forest hydrology interactions, and the production and circulation of forest hydrology scientific knowledge, and its application (or not) in forest hydrology policy-making. It does so, especially, through the case of Chile, by looking at its scientific field of forest hydrology, its debates and contestations on forestry plantations and water reductions, and the elaboration of a policy: The Forest Plantations Protocol (FPP) in 2017. Moreover, this investigation also contributes to review and historically contextualise the forest hydrology scientific knowledge evolution of South Africa and Australia, where many *Eucalyptus* species originate and which have important trajectories in the development of forest hydrology science and its policy-making. By doing so, this research also helps to understand and globally contextualise, the evolution of the forest hydrology science in Chile.

1.2 Research gaps

There are three main reasons that make the study of forest hydrology knowledge a timely topic. First, the interactions between water and forests have been widely studied around the world by multiple scientific disciplines, which have acknowledged the crucial role of forests and vegetation communities in the regulation of water resources (Bosch and Hewlett 1982; Calder 1999; Zhang et al 2001a; Jones et al. 2016; Alvarez-Garreton et al. 2019) among other fundamental aspects of the planet's environmental cycles and as underpinnings of human development. Countries such as South Africa, the United States and Australia have been pioneers in forest hydrology studies. However, despite this extensive body of research, in several countries where eucalypts forestry plantations are widely grown (and invade), the nexus between water reduction effects and eucalypts remains contested in ways that can have important influences on forestry and water resources policy debates (Doody et al. 2011; Albaugh et al. 2013; White et al. 2016). Therefore, as a first step it is necessary to analyse the scientific evidence to understand the current state of knowledge on the effects of trees on water, and that could help on understanding these forest hydrology debates.

Second, there is room to study the forest hydrology field and its contestations, from a social dimension – that is usually less visible and analysed – to address the production of this scientific knowledge, its circulation and application in the elaboration of an environmental policy. To our knowledge, there are no previous studies from a social or human-geography perspective on the forest hydrology field in Chile. For this reason, this Ph.D. project is a contribution for advancing on these matters. The study of the phases of production, circulation and application of environmental knowledge, are topics of interest to political ecology and sciences studies, and there is a call for increased collaboration between these bodies of literature (Goldman et al. 2011). In this sense, there is a call to explore and expand the application of theoretical tools to enrich understandings of the processes of production, circulation and application of environmental knowledges (Goldman et al. 2011).

From the point of these analyses, often less attention has been paid to the social production of scientific knowledge (Robertson 2016; Duvall 2011). An analytical framework used to reveal the social relations of the production and circulation of science has been Pierre Bourdieu's widely-known theory of "the field" (Bourdieu 1975). A field is a socially constructed (Bourdieu 2004) space with dynamic borders, without components but formed by agents and institutions that occasionally face struggles (Bourdieu 1988). Bourdieu's concept of the field has been applied by many disciplines and scholars (see e.g. Schmitz et al 2017; Bühlmann et al. 2017; Sapiro 2016; Lizardo 2011). Among these scholars, the social geographer Lave (2012) applies Bourdieu's field concept as an analytical framework for bridging together science studies and political ecology, to assess the external political-economic relations of production, circulation and application of science and scientific expertise. She uses the field concept focusing on the 'Rosgen Wars' in the stream restoration field in the United States, for analysing social structure, scientific habitus, legitimacy and autonomy aspects of the field's production. By operationalising the field concepts in Chile, I aim to conceptually and geographically expand the field theory' concepts (Bourdieu 1975; Lave 2012) operationalisation to understand the multiplicity of social and political-economic relations in the production and circulation of forest hydrology science.

Third, the study of environmental science and policy-making interactions, has tended to insufficiently address analyses of *governance* – understood as a descriptive tool in this research and defined as a network of governmental, market and societal actors, agents, organisations and institutions who negotiate, create and implement public policy (Cornea et al. 2017 ; Lemos & Agrawal 2006; Arts and Visseren-Hamakers 2012; Hansen et al. 2020) – and its inclusion has been recognized as an important challenge and a research gap in political ecology analyses (Forsyth 2003; Goldman et al., 2011). In particular, political ecology has not usually inquired into the process of policy-making and its governance. This inclusion of governance implies the analysis of diverse actors and institutions to understand how scientific knowledge is circulated and applied in policy-making, to discern which scientific expertise is listened to and how it can change policy production.

Currently, the inclusion of governance in social domains of analysis is challenging because of the wide flexibility that the concept of 'governance' offers (Jessop, 2009). An analytical frame used to study policy-making governance while paying attention to the role that scientific or technical information plays in policy design, is Paul A. Sabatier's well-known

Advocacy Coalition Framework (ACF) (Sabatier 1988). The ACF highlights that information, knowledge or expertise in a domain is required by policy actors (coalitions) to modify the public policy (policy outputs) (Sabatier and Weible 2007). In addition, ACF also recognises that the political system is influenced by external factors such as changes in public opinion (e.g. the Chilean Mega-Fires), socio-economics or the political sphere, among others (Sabatier and Weible 2007). For these reasons, I argue that ACF is a useful framework that brings governance lenses to science and policy studies, while helping to explain the application and circulation of scientific knowledge in policy production.

The integration of ACF lenses as a theoretical tool into the STS and political ecology studies is pertinent, because ACF studies also have recognized the need to "expand our understanding of science and policy analysis in the policy process" (Ma et al. 2020, p.12). In this way, there is a dialectical enrichment between these frameworks. Finally, this research also seeks to contribute to closing the gap of the minority of ACF studies that have been done in South America in comparison with countries in the northern hemisphere (Pierce et al. 2017; Weible et al. 2009; Ma et al. 2020).

In this way, this research seeks in general to enrich the studies focused on production, circulation and application of environmental knowledge (Goldman et al. 2011) by operationalising field theory' and ACF' concepts as theoretical tools in the analyses of political ecology and science studies. These concepts enrich these analyses by analysing how expert knowledge is socially produced and contested, what experts or scientific knowledges are listened to and legitimated in the process of policy production, and how expert or scientific knowledge can change (or not) a policy-making process. The above are all topics of interest for political ecology, and sciences studies or science and technology studies (STS), which share the attention for issues of the production, circulation, and application of scientific knowledge in policy making-processes.

1.3 Overall research aims and relevance

This research draws upon the literature of Forest Hydrology Science (chapter 5), and the social analysis from Science Studies and Political Ecology (chapters 6 and 7). The social study (chapters 6 and 7) is inspired by the phases of production, circulation and application of environmental knowledge (Goldman et al. 2011).

As a whole, the aim of the research is to analyse how the production, circulation and application of the forest hydrology knowledge can influence the interrelations (practices) in environmental science and policy-making in Chile. To address this, I have explored three main bodies of literature: (A) forest hydrology, (B) field concept (Lave 2012a; Bourdieu 1975), and (C) advocacy coalition framework (Sabatier 1988b). First, I have engaged with forest hydrology literature to explore in-depth (through more than 200 reviewed articles) the state of art in this field about the effects of forests on water resources, as well as some of the internal aspects of their study design. Second, I have applied Bourdieu's field concept adapted by Lave (2012) to analyse the production and circulation of the forest hydrology field. Third, I have engaged with Sabatier's advocacy coalition work to understand the circulation and application of science in policy-making governance (Sabatier, 1998; Sabatier & Weible, 2007).

This theoretical and empirical research aims to contribute in three ways to the scientific literature. First, this research seeks to deepen the understanding on the Chilean forest hydrology debates. Second, it intends to geographically expand and theoretically enrich social studies working on the phases of production, circulation and application (Goldman et al. 2011) of scientific knowledge in policy-making, through the inclusion of 'field' analysis (Bourdieu 1975; 1994) and 'Advocacy Coalition Framework' (ACF) (Sabatier and Weible 2007a) as theoretical tools. Additionally, with the inclusion of ACF as a theoretical tool, this research also aims to contribute to the inclusion of governance lenses in the analysis of environmental science in environmental policy-making.

The research is carried out through three main phases, aiming to answer the following questions in three different results chapters: questions 'A', 'B', and 'C' (below), which are answered in chapters 5, 6 and 7 respectively.

General question: How can the production, circulation and application of the forest hydrology knowledge influence the interrelations (practices) in environmental science and policy-making in Chile?

A. What are the areas of consensus and nuances regarding eucalyptus-water interactions?

A1. How are the effects of eucalypts on water quantity at different stages in the hydrological cycle, during evapotranspiration, in soils, in streamflow and in groundwater?
A2. How are the effects of eucalypts on water quantity for different types of forests and species, type of land cover and changes, treatment comparisons and bio-environmental conditions?
A3. How can the context and study design explain nuances?
A4. What are the knowledge gaps regarding eucalyptus-water interactions?

B. How does the production and circulation of science in the forest hydrology field happen in Chile?

B1. How have the forest hydrology field and their agents evolved over time?
B2. How are the schemes of perception, the choice of objects, approaches and the evaluation of possible solutions?
B3. How are the scientific capitals of the field composed by different claims of legitimacy, power and authority?
B4. How do external political-economic relations shape production-circulation within the forest hydrology field?

C. How has forest hydrology science been applied and circulated in the Chilean environmental policy production?

C1. What scientific knowledge has been heard and what are the actors' coalitions in the policy-making governance?
C2. How have the relative stable parameters influenced the forest hydrology decision-making?
C3. How have the external system events influenced the forest hydrology policy-governance?
C4. How has the scientific knowledge been applied and what have been the paths to policy change?

1.4 Personal motivation

The motivation for this research came after my Master of Science degree at the University of Heidelberg in Germany. In search of a research topic for my Ph.D., I was inspired by a concern that arose during my master's fieldwork, and fieldwork experiences in Chile. In relation to the effects of forestry plantations on water resources, I frequently encountered representatives of the government and forestry companies, who expressed different explanations or avoided talking about it. While rural communities – facing water scarcity and being supplied by cistern trucks for years – pointed out the occurrence of water reductions after the massive arrival of *Pinus* and *Eucalyptus* plantations, among other factors. On the other hand, I knew about the existence of some scientific studies in Chile that showed how forestry plantations do reduce water levels in comparison with other land covers. However, I had not done an extensive review of this scientific field, and I wondered why this issue was so contested and uncertain in Chile. So confusing was this forest hydrology issue that no one could explain why, in what scientific topics/aspects uncertainties emerged, or what precisely these uncertainties were that did not allow common understanding among the various forestry actors. This called my attention and I wondered if scientific research on this could help me understand and find answers. Moreover, as I was interested in further research on governance issues, I needed a concrete case study that included all forestry actors and helped me to delimit this broad topic. By coincidence, at the end of 2017 – and just months before starting my PhD in Lausanne – for the first time a policy-document was published in Chile which addressed the issue of forestry plantations and water reductions at the national level in Chile. This was the Forestry Plantations Protocol.

1.5 Structure of the thesis

Figure 1. Structure of the thesis

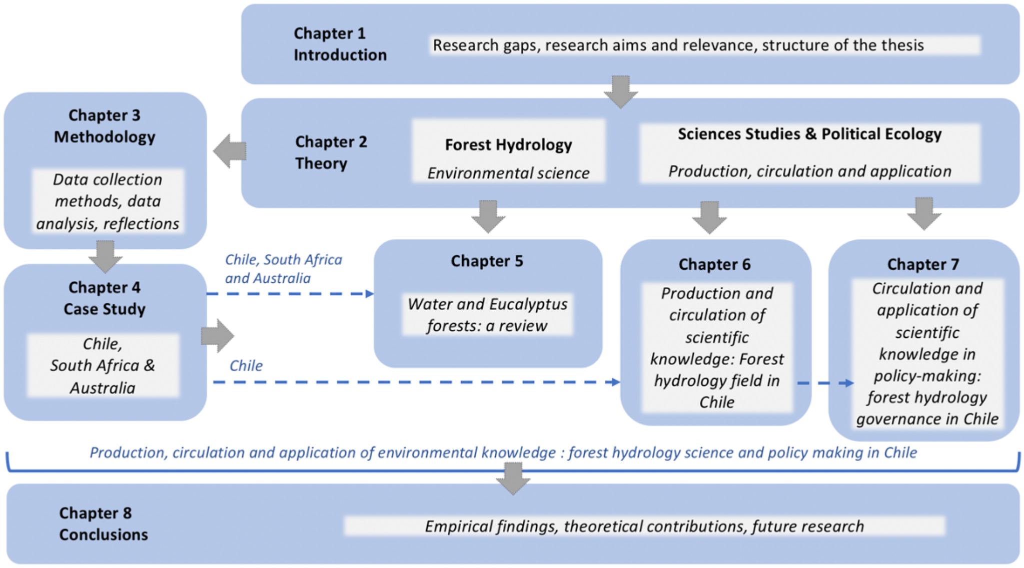


Figure 1 presents the structure of the thesis. The thesis is composed of 8 chapters. Chapter 1 provides an overview of the thesis, its relevance, research gaps and objectives. Chapter 2 introduces the three bodies of literature in which this research is address. This is composed by three main scientific fields: 1) forest hydrology, 2) sciences studies and 3) political ecology. Sciences studies and political ecology focus on the production, circulation and application of environmental knowledge. Chapter 3, presents the general methodological strategy of the thesis. It presents the methods of data collection, and the diverse methodologies of data analysis applied to provide answers in chapters 5, 6 and 7. It also presents methodological reflections on the research process.

Chapter 4 introduce the case study. This is composed by three countries: Chile, South Africa, and Australia. Nevertheless, the main analyses of this investigation focus on Chile. This chapter is organized in two main sections. Firstly, it introduces the origin and first forest hydrology studies in the world, to contextualize the relevance of the forest hydrology studies de South Africa, Australia and Chile. It reviews the forest hydrology field and main contributions in South Africa, Australia and Chile. This contextualizes the origins and evolution of the forest hydrology field, and how its knowledge has been considered in policy-making processes in each of these countries. Secondly, it focuses on Chile, as the main case study of this research. This provides an overview of the Chilean forestry history, geography and environment, forestry sector economy, water and forest policy, as well as introduces the main actors involved in the Chilean case.

Chapters 5, 6 and 7 present the main results of the investigation. Chapter 5 reviews the science of forest hydrology with particular focus on the effects of *Eucalyptus trees* on water quantity at different stages in the hydrological cycle: during evapotranspiration, in soils, in streamflow and in groundwater. The review is based on the available literature in three southern hemisphere countries with active forest hydrology research programmes on *Eucalyptus*: Australia, Chile, and South Africa. Results show that most studies confirm that eucalypts have higher rates of water use than other land covers such as agriculture, grassland, native forests, native scrublands, wetland vegetation, and other plantation tree species such as *Pinus radiata*. These results hold irrespective of whether the eucalypts were present as native or non-native trees. Our review also suggests that studies that did not support these findings generally do not contradict them but add nuance, and deviations may result from variations in the study design. The review closes with an overview of knowledge gaps in forest hydrology.

Chapter 6 analyses the production and circulation of forest hydrology knowledge, based on interviews with prominent forest hydrologists doing research in Chile. This chapter contributes to sciences studies and political ecology studies working on the production and circulation of environmental knowledge. It argues that these could benefit from the theoretical concepts of 'the field'. This theory suggests to look at four elements – structure, habitus, capital and autonomy – that underpin scientific production and its circulation of knowledge. The investigation shows how the use of different research objects and concepts may move the trend of scientific production in different research directions and towards different possible solutions. It also reveals the development of different claims for legitimacy and authority in those ongoing scientific debates. Drawing upon on Lave's operationalisation of Bourdieu's 'field' theory which evaluates the production and circulation of science, this chapter also shows that external political-economic relations within which the forest hydrology field is embedded, have shaped the production and circulation of scientific knowledge and autonomy of the field.

Chapter 7 investigates how scientific knowledge is mobilized and applied in environmental governance, specifically in a process where the State, academics, the private sector, and civil society actors produce a policy in Chile. This is analysed through the phases of circulation and application of forest hydrology knowledge, in order to expand understanding of the role of scientific knowledge in policy-making. Taking the case study of the Forest plantation Protocol (FPP), it is argued that Sabatier's advocacy coalition framework (ACF) can enrich social studies focused on the application and circulation of scientific/expert knowledge in environmental governance and policy-making/change. The research reveals that the scientific knowledge listened to in policy-making is a combination of forestry hydrogeology and ecosystem science approaches. Both approaches correspond to two opposing coalitions on issues concerning water and soil regulation in the FPP: forestry industry and governmental actors. The research also demonstrates that while scientific knowledge played an important role in policy production by providing scientific knowledge to advance the policy outcomes, the paths to political change were a combination of external system events, forest hydrology learning, and a process of negotiation, where forest hydrology publications, but also some socio-economic aspects were considered in policy-outcomes. Additionally, it shows that environmental shocks can be an opportunity to partially shift the balance of negotiation powers, and that relative stable parameters (previous policies and agreements, etc.) can establish the negotiation margins of policy-outcomes.

Chapter 8 provides the main conclusions of this research by summarising the theoretical and empirical contributions of the study. It shows the contributions derived from a thorough understanding of the forest hydrology science, as well as from the social research on production, circulation and application of environmental knowledge; environmental governance; and policy-making in Chile. The diverse theoretical contributions and practical findings of this thesis not only help to understand the debates on forest hydrology in Chile, but it also contributes to a deeper understanding of diverse contested or controversial environmental subjects. The Chilean case and its controversy about effects of forestry plantations of *Eucalyptus* or *Pinus* on water resources, suggest that there can exist a 'controversy', which not necessarily is based on a scientific basis, despite the complexities and uncertainties proper to science. It highlights the 'field theory' and 'advocacy coalition framework' as useful theoretical tools for deepening political ecology and sciences studies for these environmental analyses.

Chapter 2

Concepts and existing literature

This chapter provides the theoretical basis for the questions addressed in this research. Section 2.1., provides an overview of the forest hydrology science. Additionally, chapter 5 will review the state of the art of forest hydrology in Chile, South Africa and Australia in order to answer questions A.1-2-3-4 of this investigation.

Section 2.2. reviews the previous contributions of science studies and political ecology as theoretical considerations. This review focusses on scientific and environmental knowledge in broad terms, but especially on the topics of forests, forestry and water. At the same time, this review addresses previous learnings about contested environmental and scientific knowledge in governance and policy-making. Furthermore, this section also addresses why political ecology and sciences studies or science and technology studies (STS), have been interconnecting in order to investigate the production, circulation and application of environmental knowledge. Section 2.3. refers to the theoretical tools used as a general approach in this research to build a bridge between science studies and political ecology.

Finally, section 2.4 presents the specific theoretical anchors of this research to analyse the production, circulation and application of forest hydrology knowledge and policy-making in chapters 6 and 7. Section 2.4.1. reviews the theory of the 'field' (Bourdieu 1975; Lave 2012) which will be operationalised as a theoretical tool in order to answer questions B.1-2-3-4 in chapter 6. The framework of the 'field' is mobilised to investigate the production and circulation of environmental knowledge in the forest hydrology field. Section 2.4.2. presents the 'advocacy coalitions framework' (ACF) (Sabatier 1988a; Sabatier and Weible 2007a) which will be used to answer questions C.1-2-3-4 in chapter 7. This theoretical tool is harness to investigate the circulation and application of forest hydrology knowledge in the governance of policy-making and policy-change.

2.1. Reviewing the forest hydrology science

Given the broad water and eucalypts concerns (Calder 1992, 1999, Dye and Versfeld 2007, Doody et al. 2011, Albaugh et al. 2013, Morales et al. 2015, White et al. 2016), several reviews have investigated the issue. There is general consensus that planting trees at large scale reduces streamflow (Bosch and Hewlett 1982; Smakhtin 2001; Brown et al. 2005; Jackson et al. 2005). However, the hydrological response to changes in land cover depends strongly on the initial state of the ecosystem (Jones et al. 2016). Land cover change from agriculture crops or grasslands to forest plantations (which can include many different species of trees) generally results in increased evapotranspiration and reduction in streamflow (Bonnesoeur et al. 2019; Jones et al. 2016; van Dijk and Keenan 2007; Farley et al. 2005; Whitehead and Beadle 2004; Zhang et al. 2001; Bosch and Hewlett 1982). Reviews indicate that, compared with native forests or shrubs, catchments with large areas of non-native eucalypt and pine plantations have lower water yields (Bonnesoeur et al. 2019; Filoso et al. 2017; Jones et al. 2016; Balthazar et al. 2015). The inverse is also true: removing trees increases streamflow (Hewlett et al. 1969; Bosch and Hewlett 1982; Sahin and Hall 1996; Smakhtin 2001; Brown et al. 2013; Zhang et al. 2017). However, if deforestation is not permanent, this increase only occurs during the first years after harvesting because water use by tree regrowth reduces streamflow (Brown et al. 2005).

Other important factors to consider are the geographical scale of analysis: relatively small increases in forested areas have a small hydrological impact when the analysis concerns a large scale catchment, while the inverse is true as well (Brown et al. 2007; Zhang et al. 2017). Also, there can be gaps in knowledge in forest hydrology that may lead to differing understandings (Scarascia-Mugnozza et al. 2000).

At the same time, trees are complex and dynamic living beings, so measuring how they consume water is challenging. From studies in forest hydrology we know that through their roots, trees consume water stored in soil (Dye 1996, White et al. 2000, Sudmeyer and Hall 2015), from aquifers (Morgan and Barton 2008, Nolan et al. 2018, Zolfaghar et al. 2017) and in some cases from water flowing to rivers (Hervé-Fernandez et al. 2016). For those reasons, considering root depths (Dye 2013b, Zhang et al. 2001) and preserving the structure of soils is important since soils are water reserves (Barrientos and Iroumé 2018) that also allow the recharge of rivers and aquifers throught infiltration (Nimmo et al. 2006). The water consumed by trees is then mobilised it through the trunk and released through the leaves during day and at night as transpiration (Mitchell et al. 2009, Pfautsch et al. 2011). But there are also other natural water losses in the hydrological cycle, such as evaporation of water from soil due to the sun. It is for this reason that forest hydrology studies have focused on studying different parts of the hydrological cycle to evaluate the effects of trees in evapotranspiration, streamflow, soil, or groundwater.

Despite an extensive body of research existing since the 1980s, in several countries where eucalypts are widely grown (and invade), the nexus between water effects and eucalypts trees remains highly contested in ways that can have important influences on policy debates about forestry and water resources (Doody et al. 2011; Albaugh et al. 2013; White et al. 2016). Consequently, as a first step of the analysis, it is essential to review in depth the scientific knowledge on the eucalypts forest hydrology, which can contribute to better understanding the eucalypts forest hydrology debates. This is addressed in depth in chapter 5.

2.2. Science studies and political ecology frameworks

2.2.1. Scientific knowledge

Science is a social activity of human beings, acting and interacting, where their knowledges, techniques and statements are fundamentally a social knowledge, produced by a historical process that involves human (and non-human) actors in a place and time (Mendelson, 1977). In this way, science is recognized as socially constructed (Jasanoff 2012). Disciplinary scientific knowledge is a highly developed process of thinking in pursuit of knowledge, organised through experience and experimentation (Kuhn 2011), and a product of current and previous construction, revision and establishment of methods, techniques, and theories through various mechanisms of peer-review and dissemination (Farrall 1975; Sorenson and Fleming 2004).

For that reason, the development of scientific knowledge is a process of reconstruction of knowledge, where the internal and external contextual dimensions are not analytically divorced (Knorr-Cetina, 1981). According to Van Den Daele (1977), there are two explanatory approaches to scientific development: the internal and external dimensions. On the one hand, the internal approach analyses the internal history of intellectual transformations in the development of scientific knowledge through their scientific structures, objects and its dynamics – like sciences studies or sciences and technology studies do. The external approach, on the other hand, seeks to understand the development of scientific knowledge through the broad historical layers behind, and interlinks these with those social, economic, political, material and technical transformations of society at that time – like political ecology does.

2.2.2. Science studies and political ecology, and their interrelationships

The social analysis of this research combines science studies and political ecology. On the one hand, Sciences Studies have become an interdisciplinary and innovative field that studies 'science' itself and the way knowledge is produced (Sismondo, 2010). While studies of science have a wide range of streams – e.g. Science Studies; Science, Technology and Society; or Science and Technology Studies (STS) – which over the years have evolved in parallel and in tandem (Moyal 1978; Goldmand et al. 2011; Felt et al. 2017) – in this research they are simply referred to as 'science studies' or 'science and technology studies' (STS). One of the major contributions of sciences studies to the study of scientific knowledge is to recognize science and technology as historical products of human labour, choices, investments and designs (Felt et al. 2017), because it recognizes that different groups of producers, are shaped by circumstances of science, society, and history (Hackleett et al., 2008). According to Jasanoff (2012), scientific knowledge is produced only if its findings are developed in accordance with prior agreements over theories, methods, techniques, review and validation processes, which are done through continual processes of negotiation among scientific agents and institutions. In this regard, sciences studies have focused their attention on how scientists use the material world in the production of knowledge through different networks (Sismondo, 2010).

On the other hand, political ecology studies have focused on analysing social, cultural, political and economic power relations (Swyngedouw 2009; Bustos et al. 2015) that define distribution and access to resources (Ribot and Peluso 2003) and how all these dynamics produce environmental changes that impact groups and individuals (Robbins 2011). Political ecologists have also recognized that environmental knowledge is shaped by social, political, economic and historical contexts of power (Bixler 2013). In this sense, political ecologists have identified that science "is itself a product of both political economy and the changing environment in which it is practiced" (Peet et al., 2011, p.39), as well as that these political, economic or institutional powers can "produce structured gaps in knowledge" (Ottinger, 2013, p.253), through the access or exclusion of knowledges. For these reasons, political ecologists have started to adopt the STS framework and methods (Forsyth 2003) to explore contested knowledge (Sismondo, 2010; Budds 2013; Budds 2013), where often less attention has been paid to the production of that knowledge (Robertson 2016; Duvall 2011). In the same way, STS scholars have sought to incorporate elements of political ecology, seeking to address more comprehensively aspects of the production, circulation and application of environmental knowledge (Goldman et al., 2011); interconnecting and enriching in this way both bodies of literature.

2.2.3. Insights on environmental knowledge

In the following sub-sections, the combined theoretical contributions of political ecology and sciences studies are reviewed. They present relevant literature related to environmental knowledge, forests, forestry plantations and water, by revising literature on (i) contestations or controversies over scientific knowledge, (ii) production, (iii) circulation and (iv) application of environmental knowledge in governance and decision making. In this way, insights about environmental knowledge are provided as a general background. These previous contributions also demonstrate the pertinence of operationalising the 'field' and 'ACF' frameworks to answer the social questions of this investigation in Chapters 6 and 7. The 'field' and 'ACF' frameworks are subsequently presented in sections 2.3.1. and 2.3.2. respectively.

2.2.3.1. Contestations or controversies over scientific knowledge

This thesis emerged inspired by an environmental controversy, more specifically contestations about forest hydrology scientific knowledge regarding forestry plantations influencing (or not) water reductions. Researcher from political ecology, science studies, and philosophy of science have made a number of useful contributions about contestations of scientific knowledge or controversies (Martin and Richards 1994; Harker 2017; Sharman

2015; Clapp and Mortenson 2011; Supran and Oreskes (2021). In this respect, five pertinent contributions and characteristics are presented.

First, Martin and Richards (1994) review scientific and public controversies involving discrepancies in scientific issues (on topics such as the greenhouse effect, fluoridation, etc.) in the United States, observing that these are becoming more and more common in public discussions, and often have profound social, economic and political implications. These disputes between experts generate challenges to decision makers and policy making around the issues discussed. Well-documented cases have shown experts or consultants to be active participants on the one or the other side of these discussions. This situation has called into question who holds expertise and generated a growing demand for greater public participation in decision making (Martin and Richards 1994). By revising diverse science studies working on controversies, they come to suggest multiple advantages of using holistic analytical approaches that analyse 'internal' and 'external' dimensions of these disputes that confront multiple interests. Similarly, they caution that a multi-perspective analysis does not presume that there is a single 'best way' to explain these debates. As an example, they propose and analyse in levels the case of disputes between dentists, fluoridation, and sugar industries. First by understanding the technical debate. Second, by reviewing the social dimension of arguments and decision making that were polarised. Third, by looking at the credibility dispute between opponents. Afterwards, they found that there were powers that denied publications, blocked funding, disassociated dentists, among other techniques of power control. Additionally, they found that there was a path of resistance in the context of powerful corporations, expressed in a fluoridation campaign to prevent tooth loss. They conclude that the discussions on fluoridation in the US can be understood as a power struggle on a number of levels. Suggesting that for integrated analyses it is beneficial to combine different approaches in a perspective that uses a diversity of conceptual tools (Martin and Richards 1994). In this way, they argue that a more realistic understanding of scientific knowledge and its use in decision making can be presented. This input suggests a series of three multi-level analytical levels and combining various theoretical tools to understand a controversy. In the same way, they call us to be cautious since there is no single path in these complex matters.

For philosophers of science like David Harker (2017), controversy over certain scientific knowledge can be created and proceed from misconceptions or inconsistences of/over knowledge which produce doubt and public confusion. In broad terms ‘constructed controversy' or 'manufactured scientific controversy' is understood as the construction of doubt for the general public by magnifying uncertainty – since all scientific studies live with some uncertainty – and/or by undermining/denying the existence of a well-supported body of knowledge (Harker 2017). Contestations or controversy over scientific knowledge has been studied and commonly associated with interest groups. For instance:

> *"Rather than ignoring the science, or denying it absolutely, cigarette companies promoted doubt, and thereby helped undermine the idea [in the public / citizens] that there existed a scientific consensus [about tabaco effects on human health]. If the strategy was successful, then laypersons could no longer turn to science for answers about the connection between cigarettes and lung cancer, because the cigarette industry would create the impression that the science was hopelessly unsettled." (Harker 2017, p.251).*

In this respect, Harker (2017) identifies that one of the consequences have been the generation of public doubt about particular issues which actually are scientifically uncontested, or the creation of the appearance that an issue is more scientifically contentious than it is. In this sense, the affected audience of a created controversy is a less well-informed public and controversy is amplified from misconceptions (Harker 2017). His contribution highlights that controversies on certain scientific topics can be created by interest groups and amplified by the misconceptions or inconsistences of knowledge on a given topic. It also highlights the existence of other strategies which have been identified as contributors of controversy, such as the installation of doubt, confusion, uncertainty amplification, denialism, undermine, etc. which challenge demonstrated scientific knowledge but without consistent evidence base.

Complementarily, the work of Sharman (2015) on the impacts of the controversy on the production of scientific knowledge, highlights that the construction of consensus has been particularly challenging in contexts where scientific authority is delegitimized as a discourse. Taking the case of scientists working on climate change in New Zealand and the United Kingdom, she argues that the particular characteristics of a scientist, her/his discipline, or their level of public commitment, are usually contested issues under conditions of controversy. The foregoing is relevant given that contestations over researchers can influence scientific knowledge production in different ways. For instance, through interviews and a literature review of cases, she conceptualizes the reactions of scientists when working under controversial or contested conditions. She identifies a gradient (see table 1). It goes from researchers reacting in a defensive manner, defending their work or that of colleagues, or blaming other factors/colleagues (rebuttal); over phases such as reflection; resistance; revision; retraction; to - in extreme cases - a "chilling effect" (removal), where the researcher abandons her/his research project or scientific career. The latter, then, has implications for the 'non-production' or marginalization of certain types of knowledge. Sharman (2015) closes her analysis by stating that "*further research is required to provide more concrete examples of the impact of controversy on the policy decision-making process, particularly as regards specific contexts and settings*." (p.23). This contribution highlights the diversity of concrete implications that the existence of controversies may have on the scientific production of those working on contested topics. Likewise, her contribution invites us to explore what kind of implications a controversy may have on decision-making over contested issues.

Table 1. Scientists' potential responses to controversy

	Potential response to controversy	
Offensive engagement	Rebuttal	→ Speak out in defence of own or colleagues' work (Hilgartner, 1990) → Shift blame for shortcomings to other factors (Negru, 2013)
↑	Reflection	→ Increased attention to accuracy in scientific practice → Clarity in public communications to avoid misinterpretation → Increased transparency (Russell, 2010)
	Resistance	→ Actively (or passively) ignore controversy (Oliver, 2001) → Unwilling to share data (particularly when requesters are deemed troublesome or with an ulterior motive) (Swallow and Bourke, 2012) → Boundary work (Gieryn, 1983; Gieryn, 1999)
	Revision	→ Increased caution or hedging in scientific process or public communication → Adopt discourses that shape choice of scientific enquiry ("seepage") (Lewandowsky et al., 2015) → Changes to overarching professional norms (Boykoff and Boykoff, 2007)
↓	Retreat	→ Reduction in public engagement activities → Unwillingness to discuss personal/institutional attacks for fear of further incidents (Illman, 2005) → Change research behaviours or topics that are "forbidden" so that they become "nonknowledge" (Kempner et al., 2011)
Defensive avoidance	Removal	→ Abandon research project/research career via the "chilling effect" (Kempner, 2008)

Source: Sharman (2015, p.18).

Clapp and Mortenson (2011), analyse the socially contested environmental planning process of the old-growth forests in the central coast of British Columbia, Canada. This region host the largest temperate forest remnants in the world and more than half of the population is indigenous, First Nations peoples such as Heiltsuk, Nuxalk, Kitasoo, and Oweekeeno, among others (Clapp and Mortenson 2011). The authors explore how scientific information was used in the planning debates between forestry companies – interested in harvesting and commercialize old-growth forests – and environmental and indigenous groups seeking forest cultural and biodiversity conservation. To resolve these diverse interests, the environmental planning process included a team of experts – the Coast information team (CIT) – from the Canadian state, who invited scientists and technicians from the various stakeholder groups to reach joint decisions. In their analysis, Clapp and Mortenson (2011) focus on understanding the strategy applied in the CIT that facilitated the conflict resolution among parties in the central coast planning process. As Clapp and Mortenson (2011, p.908-906) explain:

> *"This team [CIT] combined aspects of independent scientific review with a collaborative interest-based model incorporating dependent scientists and technicians, and emerged as a boundary organization regulating the science–policy divide. This boundary organization aided in conflict resolution in the short term, and in the long term created a boundary object that facilitates the collaborative production of science and social capital".*

The CIT process involved two phases of negotiation. In Phase I (between 1997-2001), industry and conservation groups sought to justify or challenge current forestry practices with scientific information. Phase II (2001-2003), generated smaller and more expert working groups that sought to combine the review of scientific information between independent and dependent scientist groups. In this stage, the CIT agreed to conduct analyses on spatial ecosystem and socio-economic aspects; as well as to develop an ecosystem management framework to address them. The CIT sought to legitimize the application of science nationally and internationally, so all experts were asked about their independence from their employers, interest groups or to disclose relevant influences on their work. Even so, the process was not exempt of challenges about legitimacy over scientific information. For instance, issues of access to information were also contested. While there was more spatial information for the development of maps on environmental and economic aspects, there was a lack of spatial information on social and cultural aspects which provided frustration to First Nations who felt pressure to make decisions without complete information. In addition, issues of scientific uncertainty about the information also arose without being resolved. Despite all these issues, the actors had to make decisions according to deadlines (Clapp and Mortenson 2011).

Based on Star and Griesemer (1989) analysis of 'boundary objects', Clapp and Mortenson (2011), argue that GIS mapping work acted as a boundary object that facilitated the coexistence of contested interests and enabled cooperation between actors without necessarily reaching absolute consensus:

> "*Overlays of the ecosystem mapping and the timber harvesting land base enabled the negotiators to evaluate candidate protected areas for the volume, species composition, and accessibility of its timber, as well as its old-growth habitat, rare ecosystem types, and landscape connectivity. Without a common database of ecosystem types and timber volumes, it would have been much more difficult to split the difference, as bargainers sometimes must do to reach agreement.*" (p. 913).

Through this case they conclude that the strategy of providing actors with a common set of information such as cartography, and separating the scientific information-based discussions from the negotiations on the implications of the scientific information, helped the CIT to develop agreements for the measures to consider in the plan operationalized in 2004. Likewise, they conclude that the explicit recognition of science as an – inevitably – socially constructed aspect, helps the transparency of the environmental governance process. And, with the openness to different voices, it gives greater legitimacy to the planning process (Clapp and Mortenson 2011). This contribution highlights that the construction of a common database (boundary object), might aid communication and conflict resolution for decision-making. It also highlights the usefulness of separating discussions about scientific data and information from discussions and negotiations about the implications of scientific data/information (e.g. in discussion phases or spaces).

Supran and Oreskes (2021), scholars from Harvard University's history of science department, analyse the framing of ExxonMobil's climate change communications. By 'framing' they mean the selection of certain language aspects that make a communication more salient. In this regard, communications (news, papers, reports, documents, social media, etc.) are relevant to investigate since this fossil fuel industry has invested billions of dollars in various communications and "has used language to subtly yet systematically frame public discourse about climate change" (p.696). They define this as the "subtle micro-politics of language to downplay its role in climate crisis and to continue to undermine climate litigation, regulation and activism" (p.696). Their computational analysis of the fossil fuel industry's narrative and framing – based on internal industry documents, peer reviewed papers, and advertorials in the New York Times, among others public documents corroborates the results of previous qualitative discourse analysis studies on the interests of the fossil fuel industry. Their results show 'scientific uncertainty' as one of the 3 main rhetorical frames mobilized, and suggest it is used to prolong climate change regulation and litigation, and to downplay the role of the fossil fuel industry in climate change.

> "*Rhetorical frames: Frame package analysis leads us to identify three dominant frames in ExxonMobil's advertorials, which we name (1) Scientific Uncertainty, (2) Socioeconomic Threat, and (3) Fossil Fuel Savior (FFS) (for details, see S4, supplemental information).* ***The Scientific Uncertainty frame*** *presents AGW* [anthropogenic global warming] *as unproven and advocates additional climate Science research.* ***The Socioeconomic Threat frame*** *argues that binding climate policies (such as the Kyoto Protocol) are alarmist and threaten prosperity, urging voluntary measures instead.* ***The FFS*** **[Fossil Fuel Savior]** ***frame*** *describes AGW as the inevitable (and implicitly acceptable) risk of meeting consumer energy demand with fossil fuels for the foreseeable future, and presents technological innovation as the long-term solution."* (Supran and Oreskes 2021, p.702).

The authors state that these rhetorical patterns resemble those from the tobacco industry, which in its response to the scientific consensus that tobacco use is harmful to human health, presented a rhetorical shift from a focus on uncertainty to something like tobacco consumption is a 'risk factor' but it is not a 'proven cause'. In this way framing relies on the power of language rather than falsehood. Other examples constitute word choices such as 'potential', 'may', 'more research', 'risk' etc. that do not necessarily deny or delay, because such terms are co-opted from academia, journalism, etc. As for the 'Scientific Uncertainty Frame' in particular, the authors point out that anthropogenic climate change is presented as unproven and more research is required before any policy-making action can be taken (see more in Supran and Oreskes (2021b). Finally, they conclude that during the mid-2000s:

"Exxon-Mobil's public AGW communications shifted from explicit doubt (a Scientific Uncertainty frame) to implicit acknowledgment couched in discourses conveying two frames: a Socioeconomic Threat frame, and a Fossil Fuel Savior (FFS) frame". (Supran and Oreskes 2021, p.712).

This contribution, highlights the identification of certain communication strategies of 'framing', with which the fuel industry in particular contests climate change and environmental challenges for the sector. It demonstrates the existence of three discursive strategies of this fuel industry. It also highlights 'the power of language' as a strategy to contest and diminish the proven causes of climate change, to prolong discussions, policy production and actions.

2.2.3.2. Knowledge Production and Environment

Previous contributions have been made by scholars of political ecology and sciences studies when investigating the production of environmental knowledge (Gibbons et al. 1994; Turner 2011; Beck et al. 2017). As a general consideration in this regard, since the 1990s it has been broadly recognized that knowledge production systems are changing. In their work, Gibbons and colleagues (1994), recognize the emergence of new modes of knowledge production. They define these as Mode 1 (classic) and Mode 2 (new), and although these constitute different modes of knowledge production, both interact with each other. In Mode I, problems are defined and governed in a broadly academic context, with the interests of a specific disciplinary community. In Mode 2, the production of knowledge is conducted and governed in a context of application of that knowledge. In this sense, Mode 2 is transdisciplinary. As Gibbons et al. (1994) explain:

"Mode 2 knowledge is thus created in a great variety of organizations and institutions, including multinational firms, network firms, small hi-tech firms based on a particular technology, government institutions, research universities, laboratories and institutes as well as national and international research programs" (p.6). (…) "Some of them have gone into government laboratories, others into industry, while others have established their own laboratories, think-tanks and consultancies" (p.10).

For Gibbons et al. (1994), in Mode 1 the production, legitimization and dissemination of knowledge must follow a cognitive phase and social norms defined by academia. In Mode 2, the usefulness of knowledge production in the context of application (social, economic, or political) becomes a relevant factor in this kind of production. Work in the context of the application increases sensitivity to the implications of what scientists or experts are doing, and brings new implications for universities, industrial laboratories or governments (Gibbons et al. 1994). Among these implications, Gibbons and colleagues emphasize that communication in Mode 2 becomes crucial. Such communication is partially maintained through strategic alliances, collaborative agreements or through informal electronic communication networks (Gibbons et al. 1994), making its study difficult. They also highlight the challenge of language in the context of transdisciplinary, which is especially difficult when describing nature in the natural science domains. This way, Mode 2 is also creating new challenges for governments, as national institutions become more permeable and governments through their policies can promote changes in these directions (Gibbons et al. 1994). This contribution shows some changes present in the forms of production of expert knowledge during the last two decades, and invites to be aware of these aspects.

Turner (2011), writing about the production of environmental knowledge, points out that how scientists, citizens, or developers use, transform, or protect the environment is shaped by how they understand it. He states that human understanding and knowledge about the environment is transformed by external forces. Forces such as the complexity of aspects/objects studied, the historical-geographical contexts, the human dimension of environmental analyses, and the applicability or policy-oriented of many environmental analyses. For him, all these forces and complexities, make it difficult to separate the aspects of the production, circulation and application of environmental knowledge. He also recognizes that these processes are not exempt from clashes between diverse interests and perceived needs. This contribution invites us to explore the multiple external layers that transform environmental knowledge and understandings, as well as to recognize that the divisions between production, circulation and application of knowledge is a challenging ideal.

According to Beck et al. (2017), STS investigates the production of global environmental knowledge by exploring, for instance, who constructs that knowledge, using what frameworks, and what types of infrastructures, concepts or models. For Beck and colleagues, such elements of study bring uncertainties that hold significant implications for global environmental governance. They mention as an example of a global environmental monitoring and modelling expert organization, the case of the Intergovernmental Panel on Climate Change (IPCC). Currently, the IPCC is the leading organization with global scientific authority on climate change and has acquired political authority as well. Talking about this case - which has not been exempted from scientific consternations – they indicate that different modes of environmental knowledge have framed the issue of global change in different ways. Through this case, they also explore the relevance of scientific legitimacy and authority. Indicating that scientific credibility or legitimacy provides authority over environmental knowledge that could be circulated and applied in political decision-making. Because "*who gets to participate in defining which knowledge matters, through what processes, and at what times. These choices shape how knowledge is generated and subsequently adopted into policy*" (Beck et al. 2017, p.1067). The authors end by emphasizing the need to investigate how different societies, scientific expertise, and political expertise in different communities and cultures organize to gain legitimacy and authority in different jurisdictions (Beck et al. 2017). This contribution demonstrates the relevance of investigating how legitimacy and scientific authority are constructed and applied in different social settings, given that they may influence what knowledge is used, circulated, applied (or not) in the production of environmental policy.

Ibarra, O'Ryan and Silva (2018) analysed the interface between scientific knowledge and decision-making on arsenic in Chile, taking the case of the FONDEF 2-24 project that involved local science production and its communication and use to policy-makers. In their analysis, they focus on understanding the governance of knowledge and rules of the process (Ibarra et al. 2018). At that time, the regulation of arsenic gained relevance in the country due to the increasing awareness of the dangers of arsenic for human health and the challenges posed by the international mining market (Ibarra et al. 2018). Arsenic in Chile derives from natural causes of volcanic production and human activities linked to mining. The scientific evidence of arsenic health impacts is long-standing in Chile, with an extensive production dating back to the late 1960s (Ibarra et al. 2018). Arsenic contaminates water, soil and air and its exposure is linked to cases of cancer (Ibarra et al. 2018).In the 1980s, US mining companies petitioned the International Trade Commission to accuse Chile of environmentally dumping copper (Ibarra et al. 2018). This put Chile under international pressure to improve its environmental standards in terms of pollutants impacting human health (Ibarra et al. 2018). In this regard, the mining sector in Chile "claimed that copying standards from WHO or EPA [Environmental Protection Agency] would imply closing down most copper facilities. (…) [and that] using the EPA approach required scientific evidence on the local baseline conditions" (Ibarra et al. 2018, p.117). In 1994, Chile's national environmental authority (CONAMA) was created by law 19.300 and became the main body responsible for the development of environmental standards and regulations. CONAMA had the political will to regulate arsenic based on knowledge but with minimal resources for research (Ibarra et al. 2018). For that reason:

> *"CONAMA suggested that researchers apply to the FONDEF public grant program. The FONDEF program was founded in 1991 to foster scientific and technological development to promote economic competitiveness and improved quality of life for Chilean citizens. It was run by the National Agency for Science and Technology (CONICYT), which depended on the Ministry of Education. It was thus independent of any of the parts in conflict. The funding application was supported by the Ministry of Mining. This proposal would become the FONDEF 2-24 project, entitled "Protection of the competitiveness of Chile's mining products: antecedents and criteria for environmental regulation of arsenic" which was undertaken between 1994 and 1996."* (Ibarra et al. 2018, p.118).

Ibarra, O'Ryan and Silva (2018) show that the civic epistemology – social, cultural and political governing rules – of parts of Chilean society in the 1990s was characterised by profound political and social changes of a military dictatorship between 1973 and 1989 (Ibarra et al. 2018). In the 1990s Chile was taking its first steps on the return to democracy, and in a context of still marching military power in policy-making, which created a so-called "democracy of consensus" and displaced environmental policies as subordinate to economic development (Ibarra et al. 2018). The decision-making process involved only the State and selected experts. Despite this, Chile considered itself an exceptional country in the region for its stable institutions (Ibarra et al. 2018).

The Chilean knowledge system in the 1990s considered international actors as a reference of authority (credibility) in knowledge (Ibarra et al. 2018). The participation of multiple actors to represent multiple interests in the decision-making process was seen as an element that added salience – relevance for action – and credibility to the process (Ibarra et al. 2018). Legitimacy – "*legitimacy considers whether it is fair to all stakeholders involved*" (Ibarra et al. 2018, p.116) – of the process was understood as achieving "*consensus and equilibrium between economic development and other values*" (Ibarra et al. 2018, p.120) in the post-dictatorship context.

The intervention of the FONDEF 2-24 project in the science-policy interphase of arsenic regulation in Chile and its communication practices, focused on mediation and negotiation (Ibarra et al. 2018). To produce results that were credible, researchers (in their own words) 'had to win the blessing of the EPA'. Finally, the project results determined significant and less significant ranges of health effects from arsenic limitations (Ibarra et al. 2018). The FONDEF 2-24 project also considered the costs, risks, technical feasibility of meeting these new standards and multiple scenarios, and thus "proposed a specific emissions standard for each of the seven smelters in the country, rather than a uniform ambient standard (FONDEF2–24, 1997)" (Ibarra et al. 2018, p.121), thus promoting heterogeneity over uniformity of future arsenic policy. The companies needed time to adapt to future regulation and the project intervention provided the time required for the policy adaptation that came into effect in the late 1990s (Ibarra et al. 2018). Today, after more than 20 years, the standards of the first airborne arsenic law in Chile have not changed significantly (Ibarra et al. 2018).

This contribution shows part of the structures of scientific production and its intersections with decision-making and policy production in Chile in the transition period from dictatorship (1973) to democracy (1990). This demonstrates part of the mindset and work dynamics involved in the processes of legitimisation of scientific knowledge in policy-making in the post-dictatorship period. Furthermore, this contribution also shows a science-policy interface deeply rooted in consensus-building dynamics that, in this case, weighed the economic costs to industry against the health benefits to humans.

2.2.3.3. Circulation of Environmental Knowledge

Science studies and political ecology scholars have made a number of useful contributions about circulation of environmental and scientific knowledge, and showed that communication (or not) in governance systems are key to the circulation of knowledge (Tsing 2015; Hohenthal et al. 2018; Irwin 2008; Undurraga, et al., 2022). Four relevant contributions can be mentioned here. In her book '*The mushroom at the end of the world*', Tsing (2015) explores the production and circulation of scientific knowledge about the matsutake mushroom, highly valued on international markets (Tsing 2015). Her main argument is that cosmopolitan science is composed of a diversity of patches of scientific knowledge that give it richness. To exemplify this, she analyses the forestry sciences about the matsutake mushroom developed in Japan (where it originates) and in the United States. During her research, she noticed that the mushroom scientific experts in both countries did not communicate. This had not always been the case – these two forestry schools having been born together in the post-World War II period, through commercial and scientific exchanges – but over time, both approaches took distance, producing segregated patches of scientific knowledge and practices. As Tsing (2015) explains:

> "*Furthermore, scientists in Japan and in the United States tend to use contrasting investigative strategies — particularly on issues of site selection and scale. This removes the possibility of direct comparisons across their respective results. In this process, segregated patches of knowledge and research practice are formed. That divergences matter is particularly evident when alternative sciences arrive in the same place*". (p.219).

She attributes these scientific divergences to the different scale and site selection in which the production of the valuable matsutake mushroom was sought to be enhanced in each country, and which were reflected in the different management approaches in which the U.S. and Japanese forestry institutions had to promote the mushroom. The matsutake is a mushroom that grows in symbiosis with Japanese pine. That is, for this mushroom to grow, it needs this particular pine. In Japan, for the production of the mushroom, scientists pay attention to the site and advise the thinning (disturbance) of other tree species to open new spaces in the forest to allow the reproduction/revitalization of the Japanese pine – reduced in number – and consequently the revitalization of the mushroom. If the forest is a neglected (degraded) one, more thinning is recommended. For Japanese scientists, matsutake forests are managed with very little human disturbance. For U.S. scientists, matsutake forests are managed with a high human disturbance as the U.S. forestry approach prefers to conserve trees, without thinning. In this way, she argues that "*alternative performances of 'nature' are at stake. Consider their different takes on human disturbance*" (Tsing 2015, p.218). Furthermore, she found that the scale of the work was also a differentiating feature between these two approaches:

> "*What was the block? One Pacific Northwest researcher told me that Japanese studies are not very useful because they are 'descriptive'. In untangling what 'descriptive' might mean, and what is wrong with it, the cultural and historical specificity of U.S. forestry research comes into focus. Descriptive means site-specific, that is, attuned to indeterminate encounters and thus non-scalable. U.S. forestry*

researchers are under pressure to develop analyses compatible with the scalable management of timber trees. This requires that matsutake studies scale up to timber. Site selection in Japanese research follows patches of fungal growth, not timber grids" (Tsing 2015, p.221). (see also figure 2 for a representation of small patches of fungal growth).

Thereby, the different scales also reflect different units, methods and human needs. For example, Japanese scientists focus on understanding site ecology and the interrelationships of minerals, soil, trees and fungus. Instead, in the U.S., the basic forestry unit is the stand or timber landscape, and they consequently work on building models to upscale mushroom production to a timber regionalization (Tsing 2015). This contribution evidences that cosmopolitan science is produced and circulated by diverse patches of knowledge. Science can have different strategies or trends, according to different needs. These different strategies can generate gaps in the circulation of knowledge between different performances of environmental knowledge. In the same way, this research demonstrates the importance of scientific exchange to avoid the construction of knowledge gaps. It also invites us to be aware that different scientific approaches respond to different contexts and human needs, and to understand the units or scales of analysis as translations of those knowledges.

Figure 2. Schematic representation of the sites with the mastsutake mushroom by a Japanese researcher

Source: Tsing (2015, p.216).

Drawing on a political ecology approach, Hohenthal, Räsänen and Minoia (2018) analyse the diverse ecological knowledge in discussions about *Eucalyptus* plantations and water between local communities and government decision-makers in Taita Hills, Kenya. They recognize the existence of a plurality of ecological knowledge systems and perceptions concerning environmental resources that are socially constructed and power-laden. They argue that in Taita Hills, the bureaucrats' discourses around *Eucalyptus* reproduced colonial power structures that positioned local people as subordinate in environmental management, as they did not recognise local arguments as valid ones for decision-making. These bureaucrats based their power on professional knowledge, but the environmental governmental system had internal inconsistencies, and unclear policies on the issue. The bureaucrats also appealed to the lack of valid evidence on the hydric effects of eucalyptus, and promoted the planting of eucalyptus to meet national timber demands. Local people, for their part, based their knowledge and perceptions on their experiences with *Eucalyptus* and water reductions. Similarly, local people's discourses related *Eucalyptus* not only to water, but also to historical injustices in relation to their cultural relationship with the land. As a result, the problems surrounding the *Eucalyptus* planting policy in the area are largely incongruent due to disagreements between actors, and they continue to replicate colonial structures without incorporating participatory mechanisms (Hohenthal et al., 2018). For Hohenthal et al. (2018), the Taiti Hills case demonstrates the challenges of communication and collaboration between state actors and local people in contexts of power asymmetry. This insight from political ecology points out the existence of diverse knowledge systems and power asymmetries around environmental discussions.

Irwin (2008) states that scientific governance – understood by him as the relationship between scientific expertise and policy makers – is not fixed and is open to multiple framings of problems and definitions. He states that it is necessary to include a broad spectrum of actors, such as industry, scientific organisations, public groups, the market and its consumers, etc., in governance analyses. In this way, the assemblies of power are decentralised, and the multiple activities of governance can be broadly appreciated. Taking the European case, Irwin evidences the existence of a new growing scientific governance. Focusing on the need to reinforce the legitimacy and credibility of regulatory institutions, this new approach calls for broad engagement with the public. In this respect, Irwin takes the example of the United Kingdom and the debate on crop genetic modification. He mentions that although the debate received over 37.000 feedbacks on one website - recorded as the largest public engagement exercise in the country - the overall process was not rated as successful. The major flaw of the debate was that it did not engage with a broad spectrum of citizens and the social-media debate was limited to particular social and academic groups. However, he also calls for caution in approaching claims of this new governance, and invites to understand it also as another social category of construction. This contribution reveals the versatility and flexibility of the concept of governance, and invites us to understand the various forms of communication between scientists and decision-makers.

Undurraga, Güell, and Fergnani (2022) analyse the politicisation in the media over the socio-natural disaster of the forestry fires that affected Chile in 2017. This fire event was a macro-context in which the Forest Plantations Protocol (FPP) policy analysed in chapter 7 of this thesis was developed. In their media analysis Undurraga et al. (2022) argue that the media transformed the event into political drama framed by previous macro-political disputes. Specifically, there were different contents in the media about the fires, but all of them had in common a single dominant frame in opposition to the government of the day (eg. Supertanker – a water airplane - is a hero, the government a villain) (Undurraga, et al., 2022). In this way, media diverted the public attention away from structural discussions arising from the fires, such as the expansion of the forestry sector and its role in the 2017 fires, or the unmitigated issue of climate change (Undurraga, et al., 2022). The authors argue that these issues were avoided given the context of power struggles between the opposition and the government. In this sense:

> "*Politicization, in this case, served to steer coverage away from these highly relevant issues, fostering what is arguably a partial public understanding of the fires, their causes, and what it would mean for government to assume responsibility for mitigating and managing such catastrophic events in the future*" (Undurraga, et al., 2022, p.18).

This contribution shows a media politicisation as a way to divert attention from highly relevant issues of the mega-fires of 2017 (e.g. such as causes, effects, possible future solutions as a society, etc.). This can also be understood as a promotion of public sensationalism and partial understanding, instead of knowledge discussions in media communications.

2.2.3.4. Application of environmental knowledge

The application and circulation of environmental knowledge – especially on water resources – with its material, social, political and economic dimensions have been widely explored by political ecologists and SS scholars in Chile (e.g. Bauer 2004; 2012; 2015; Budds 2012; 2013b; Prieto 2015; Palomino-Schalscha, Leaman-Constanzo, and Bond 2016; Budds 2020). In this respect, four important contributions are presented (Budds 2009; Bakker 2015; Barton and Román 2012; Barandiaran 2018), which also introduce relevant considerations for the understanding of expert/scientific knowledge and environmental governance in Chile. Political ecologist Jessica Budds (2009), for instance, was inspired, among other things, by the contestations over water and its reduction and distribution among different water users in the La Ligua and Petorca watersheds in Chile. She analyses how the Chilean State, represented by the Direccion General de Aguas (DGA) uses scientific-technical knowledge in the environmental management and allocation of groundwater rights. She demonstrates the social influences of a scientific-technical approach within a neoliberal political-economic regime in Chile (Budds 2009). She demonstrates the limitations of focusing on a predominantly hydrogeological model for the estimation of groundwater abstraction effects, which does not recognise the various social relations at stake. Budds (2009)'s findings are relevant, as they demonstrate how the hydrogeological assessment of the DGA was used selectively in accordance with their own interests, and thereby reproducing "unequal patters of resource use and configuring uneven waterscapes" (Budds 2009, p.418). She also discloses legitimation and information asymmetries between 'local knowledge' and 'expert knowledge', the ignoring of social concerns, and the prioritization of top-down decision-making. She proposes the concept of the hydrosocial cycle "to further critically engage with environmental science" by recognising the various social relations embedded in water's materiality (Budds 2009, p.418). In this sense, Budds (2009) understands science as socially constructed and applied. This research demonstrates that the Chilean state's approach to groundwater allocation, knowledge generation and decision-making is deeply influenced by asymmetric social relations that are re-produced and applied throughout the materiality of water. It also warns about the existence of social influences on assessments of hydrogeological models for groundwater allocation in Chile. Theoretically, this case invites us to inquire into the social relations behind the legitimisation, distribution and application of expert knowledge in Chile.

In a similar vein, Karen Bakker (2015) has studied the neoliberalisation of nature, and in particular of water, in various countries around the world, of which Chile has been one. For Bakker (2015), in her global analysis of neoliberalisation, Chile constitutes a 'radical' case where neoliberalism was widely adopted and applied in various policies. She describes the neoliberalisation of nature as one of the most controversial contemporary issues in environmental governance and management. In her work (Bakker 2015), she reviews recent political ecology contributions into this debate, by exploring the environmental outcomes following the inclusion of private actors and markets in the environmental governance. In this sense, she distinguishes between the concepts of neoliberalism and neoliberalisation. She understands the former as a doctrine that recognises commercial exchange as the guide for all human actions. Neoliberalisation, on the other hand, is a process that seeks to implement neoliberal ideology. For this reason, neoliberalisation processes are highly variable and diverse, according to specific historical and geographical contexts. Nonetheless, for Bakker, the process of neoliberalisation consists of three aspects that can be generalised. First, neoliberalisation seeks to establish conditions for the accumulation of capital and to provide, restore, or reinforce the power of economic elites at various scales. Second, for setting these conditions, a combination of strategies is used, including deregulation and re-regulation; marketisation; the re-scaling of governance mechanisms; or privatisation, among others. Third, the process of neoliberalisation discursively legitimises the reforms and implementation of neoliberalism. As an example, she takes the case of South America, which in the 1990s experienced neoliberal reforms that marketised and privatised land, forests, water, fisheries, and other previously public elements. In this context, she describes neoliberalisation as an inextricably environmental project (Bakker 2015). In South America, neoliberalisation has generated controversy and promoted the emergence of counter-projects. Among these counter-currents, environmental concerns have been one of the most powerful. As an effect, a 'liberal environmentalism' has been progressively developed, which seeks compatibility between economic growth, market and environmental concerns. At the same time, in liberal environmentalism some general strategies have been observed. First, an intense phase of resource accumulation by dispossession. Second, cost reduction through the globalisation of environmental externalities, for example, by moving industries to places or countries with weaker (or without) legislation. Third, the development of new technologies or businesses to transform externalities into a profitable resource (e.g. transform waste into bio-energy). Fourth, the search for new socio-natures, from new climates, to geographies, or genes (Bakker 2015). As a consequence, Bakker argues that the neoliberalisation of nature should be understood as (1) an accumulation of capital that redefines and co-produces socio-natures; and (2) as a mode of political-economic regulation congruent with neoliberalisation. This contribution highlights neoliberalisation as an essentially environmental process embodying primarily economic ideals. As a process that manifests itself through a diversity of strategies. As a process of political-economic regulation, which co-produces environments and legitimises them. In this sense, Chile constitutes a radical case of neoliberalisation in the world.

Barton and Román (2012) examine three moments of social movements making demands for socio-ecological justice around the Chilean forestry sector in Chile. The forestry sector in Chile has been associated with multiple macroeconomic growth effects, but at the same time has been widely criticised by various social organisations for its social and environmental impacts (Barton and Román 2012). They demonstrate the existence of power asymmetries in the sector, in which forestry actors mainly from the companies Arauco and CMPC (also the smaller company Masisa) constitute the mainstream actors with the greatest power of influence in the decision-making processes (Barton and Román 2012). Meanwhile, actors from different social movements, such as unions, NGOs and indigenous groups remain marginalised from the decision-making processes (Barton and Román 2012). In this sense, social organisations fail – as it is often difficult for them – to make their claims heard due to their unsystematic organisational nature (Barton and Román 2012). In terms of political influence in policy making, the forestry sector represented by CORMA (Coorporacion de la Madera) seeks to influence the high hierarchies of ministries and state agencies such as the Ministry of Agriculture, the Ministry of Economy and the National Forestry Corporation (CONAF) (Barton and Román 2012). While marginalised organisations often seek to influence the Ministries of Social Development, Environment, and Regional Government Secretariats (SUBDERE) (Barton and Román 2012). However, social organisations face different geometries of power and their diverse alliances are 'fluid' and vary in space and over time (Barton and Román 2012). Moreover, "*the State and the forestry sector (CORMA) — as mainstream actors — manage each challenge separately and concede the minimum* [in decision making] *to avoid damage to productive interests and social unrest*." (Barton and Román 2012, p.882). As a consequence, the contemporary State in Chile struggles for legitimacy in the face of globalisation processes (Barton and Román 2012). This contribution highlights the existence of power asymmetries between social organisations and companies in the forestry sector. The forestry sector is powerful in Chile and has the capacity to influence decision-making and to minimise socio-ecological policy-changes in order to prevent damage to its economic and productive interests. Meanwhile, the Chilean State is struggling for legitimacy.

One of the major STS contributions relevant to this study is the work of Javiera Barandiarán (2018) on the circulation and application of scientific advice knowledge in the Chilean environmental impact assessment (EAI) system. In her book, *Science and Environment in Chile. The politics of expert advice in a neoliberal democracy*, this author analyses what neoliberalism in Chile has meant for the production, legitimacy and public utility of scientific knowledge.

Inspired by several cases reported in the United States where scientists have seen their science influenced by the interests of their funders, she takes the Chilean case to investigate environmental governance in the context of a State agency that lacks an authoritative body of scientific knowledge for decision making (such as the U.S. or other European countries have). She looks at the role of scientific knowledge and its autonomy in the face of the challenges of a State that tries to evaluate and legitimize large industrial projects, at how various actors promote or challenge this, and at disputes over expert knowledge when scientists attempt to participate in decision making. To investigate this, she focusses in particular on the period of transition from dictatorship (1973) to democracy in the 1990's, and analyses four case studies and economic sectors (mining, pulp & mill, aquaculture, and hydroelectric sectors) that provide geographic and cultural representativeness to her analysis.

Barandiaran concludes that under its democratic governments, the Chilean State has not invested in scientific capacities (laboratories, monitoring, follow-up). Their capacities are therefore limited and lacking in analytical and scientific skills. Science in this neoliberal State has been transformed into a market commodity. For Barandiaran, the State in Chile is an 'umpire State' where "*the State can only do what it is expressly allowed to do, while the private sector can do anything not explicitly forbidden*" (p. 191), and its governance summarises neoliberal ideals where the market is the only legitimate way of organising society and knowledge. In other words, what counts as science, who can participate, who can provide evidence or not, and the idea that good science is expensive, are all aspects regulated by free market mechanisms (Barandiaran 2018). In terms of knowledge for decision making, the Chilean neoliberal State denigrates or denies expertise in its governance: "*Chile's ideal umpire State, in which the denial of expertise and objective knowledge results from as well as reinforces the denial of the possibility of collective* *goals*" (p. 200). This was evidenced by noticing how objective information or questions were often ignored or banalised in the EIA's discussions:

> "*Straightforward questions, such as those left unanswered by HidroAysén's seemingly exhaustive EIA – for example, would the Baker River still be navigable if the dams were built? – become obfuscated by posturing for and against the dams*" (Barandiaran 2018, p.201).

This, Barandiaran also notes, has consequences for how the State works with information and public servants. For instance, in her research she found that many servants were afraid or felt censured to speak the truth to their hierarchy or other powerful institutions. This constitutes a challenge for State officials to discern legitimate information from misleading one. In this way, Chilean scientists and experts are challenged, as neither the State nor the market provides them with opportunities to show their autonomy (Barandiaran 2018). However, on certain occasions, Barandiaran found that agents of the State could challenge some ideas of this 'umpire' State or more powerful actors, by introducing new concepts or tools that sought to strengthen the standards of EIA. Similarly, in these four case studies, the knowledge of international experts seemed to be perceived by citizens as a more autonomous science – compared to local science – from the interests of the market or the State agencies (Barandiaran 2018).

In one of the three case studies in her book, Barandiaran (2018) investigates a pulp and mill industry in Chile. This industrial case provides relevant insights for the forest hydrology case carried out in this doctoral thesis, and for this reason, it is extensively reviewed in the following paragraphs.

In 2004, residents near a pulp mill industry in Valdivia were affected by a cloud of foul odours that caused eye irritation and nausea. The community was shocked when black swans – endemic to the area – began to fall from the sky into their gardens. Within a short period of time, the mortality of the swan community increased, and questions about what could be the cause of the losses fell on the newly opened pulp mill. "*For the next eight years, rival teams of scientists fought in court over alternative standards of evidence to prove or disprove that toxic pollution from the paper and pulp mill had destroyed the swans' food*" (Barandiaran 2018, p.93). On this occasion, the institutions faced in court were CONAMA – the State environmental agency in charge of the environmental impact assessment process – and the paper and pulp mill of the Celco

Arauco company. Both institutions hired different scientific experts, as Barandiaran (2018, p.94-95) explains:

> "*In response to the crisis, CONAMA and the company that owns the mill, Celco Arauco, each hired scientists to determine if pollution from the mill had caused a toxic effect on the swans or luchecillo* [main swan' food]. *The scientist that CONAMA and Celco Arauco hired differed in many ways, such as by their disciplinary training, in the questions they were asked to research, and in the resources they had access to. They differed also in their places of work and residence. CONAMA's scientists worked at Austral University, located in Valdivia on the banks of the Cruces River, which runs through the wetland sanctuary. Celco Arauco's scientists instead worked at the Catholic University of Chile in the nation's capital, Santiago. They also reached opposite conclusions. While the Austral University scientists found the paper and pulp mill responsible for polluting the wetland sanctuary, the Catholic University scientists argued the proofs by their Austral Colleagues were inconclusive. One thing both teams of scientists had in common is that they were hired as scientific advisers through ad hoc, market-like channels. For that reason, each group was accused of producing 'special interest science'* ".

Eight years later, in July 2013, the first civil court of Valdivia found Celco Arauco guilty. The company accepted the verdict and began a multimillion-dollar remediation plan at the sanctuary, but now, with partners from the Universidad Austral and local NGOs.

Equally interesting are the lessons on the contested legitimacy and authority of the Chilean scientific experts from this case. In particular, the discourses used in the contestations of the scientific legitimacy of the institutions are noteworthy for the similarities observed with the present study on the Chilean forest hydrology field. According to Barandiarán, on the side of the State agency, arguments were inconsistent and erratic over time. In first instance, the arguments from CONAMA to justify the environmental permit for the operation of the industry were vague and lacked technical justifications. Likewise, the CONAMA reports contained statements that denied or relativized/minimized toxicity problems. These situations affected the State's credibility in front of the industry's neighbours. Subsequently, in the face of growing citizen protests against CONAMA, the State agency initiated to carry out its own investigation, for which it would hire academics from the Austral University, some of whom were also neighbours affected by the industry. In this sense, citizens were sceptical about the possible conclusions of the research groups from Universidad Austral and

Universidad Católica, and some citizens even sabotaged their attempts at environmental monitoring. Doubts about the autonomy of both groups of researchers were directed towards possible conflicts of interest linked to the funders of the research.

On the scientific expert side, both groups of scholars have different profiles. The first difference between the teams concerns funding. Arauco hired ninety-one experts – mainly from abroad – compared to twenty-four experts called in by the State. Additionally, academics from the Universidad Austral had participated in the baseline studies of the plant in 1994 and 1995 – some of them as resident neighbours of the pulp mill site - and a few had raised an early alarm about the potential impacts. For their part, academics from the Universidad Católica resided in Santiago – 900 km away from the site – and some of them had strong ties to the Angelini economic group owners of Celco Arauco. Thus, both groups of researchers were deeply involved in the project, and their scientific legitimacy was contested from different actors and perspectives.

The work strategies were also different in the two academic groups. The Universidad Austral team – mostly characterized by its disciplinary background in ecology – focused on the study of swans. Their study, based on less than 10 monitoring points, concluded that the pulp mill was most likely responsible for the swans' death by contamination. Additionally, they concluded that contaminants from other sources – such as surrounding agriculture, etc. – were too small to be toxic. However, there was a prevalent gap in the Austral argument. The researchers had not been able to determine what type of element had caused the toxic shock to the swans. For their part, the Universidad Católica researchers' strategy focused on identifying the gaps and uncertainties in the Univeridad Austral study, and raising doubts about the accuracy of the Austral study. The researchers hired by Arauco accused the Austral report for not providing conclusive answers, and said it was not possible to determine the effects with any certainty at all. The Universidad Católica researchers did not conduct alternative monitoring, but raised their voice against the ecological monitoring methods, and their failure to consider possible alternative explanations. In this way, the credibility of the Austral study was contested and in short, many alternative hypotheses and debates in the media arose.

Later, in response to criticisms, Arauco, however, began to conduct its own water quality monitoring program. Yet, Austral researchers would denounce the accuracy of Arauco's measurement methods. It would later be demonstrated that the Arauco's instrument for measuring conductivity – an important indicator of pollution – was broken, and that as a result the company was using incorrect measurement methods, underestimating the amount of acids and recines deposited in the river, and overestimating the river's capacity to contain pollutants. One thing that both groups of academics agreed on was that the peer-review system was the best way to validate scientific studies, in which the Universidad Austral de Chile was in the lead (Barandiaran 2018).

Over the years, mutual accusations about lack of autonomy of researchers from the interests of their employers would follow. In 2005, the Chilean Ecological Society and the Chilean Biological Society held a conference with a special session aimed at building consensus and friendship between researchers from Austral and Catolica. However, accusations of credibility continued. Some accused Austral of having overstepped its bounds and of transforming its research into a political judgment. Others accused the Católica researchers of acting as a think tank of consultants to Arauco. In this way, the conference failed in its objective to bring closer the groups of researchers, and discussions about legitimacy would continue even in court. As Barandiaran (2018, p.116) expands:

> "*The judge did not disqualify any scientist because, legally speaking, a conflict of interest requires direct pecuniary gain (ibid, verdict article 9). Yet for those suspicions of the private sector, signs of Celco Arauco's financial influence were everywhere. Celco Arauco's scientists presented evidence that was expensive to obtain or produce: satellite images, isotope tests, and sampling campaigns that government-paid scientists could never afford. Austral's original report, for instance, contained results from 5 sediments samples, while consultants working for the company tested 139 samples with much more sophisticated methods. On the witness stand, Austral's scientist in charge of sediments was blunt: if in 2005 they had had US$250.000 more, they could have analyzed sediment records to challenge Celco Arauco's claims*".

For their part, Arauco researchers in the court used 'ignorance' as one of the most common defensive strategies against accusations about credibility and autonomy in their investigation. This was evidenced in statements such as from the subdirector of the Universidad Catolica's ecology institute, who stated that he "*supposes that there is some funding (from Celco arauco) to the university but (he) does not know anything about it*" (CDE v. Arauco 2013, 9971 – in Barandiaran 2018, p.114). Before court, Arauco group continued to criticize the Austral study, arguing that ecological methodologies have nothing to say about pollution impacts. They also appealed to the relativity that exists in nature as well as in physical science studies, and the uncertainties of knowledge. These accusations about the credibility of the Austral team exhausted them personally through the years, "*and it ultimately undermined Austral scientists' confidence in their own knowledge of the wetland*" (Barandiaran 2018, p.107). This was evidenced by testimonials in court that differed from the initial – more categorical – studies that the Austral team had reported about. As the years passed by, the scientific claims of Austral's scientists adopted a defensive tone and began to take over and reinforce Arauco's idea that 'science does not produce truths but rather probabilities. This is exemplified by the testimony of an Austral researcher in court: "*I have previously sustained that science has no monopoly on the truth and therefore there are no absolute explanations*" (Barandiaran 2018, p.117). This also undermined the State agency's confidence in the Austral study and diminished the State agency's authority to act. In addition, it was legally impossible to carry out surprise inspections of the industry for water monitoring, and the State agency had to rely on samples and information provided by the company. Nonetheless, between 2004 and 2005 CONAMA reported 19 infractions against the pulp mill, including the construction of an unauthorised waste pipeline, the construction of the pulp mill with a higher capacity than authorised in its EIA permit (300.000 tonnes more per year), and that the mill would consume more water and produce more waste than authorised in its EIA, among others (Barandiaran 2018). Yet another limitation to CONAMA's came from the legal definition of pollution (Barandiaran 2018). In this context, the verdict finding Arauco guilty in 2013 was historic.

> "*the judge argued that although the Austral scientists could not rule out natural causes, they provided evidence that natural causes by themselves would not have produced the observed ecological collapse. The evidence pointed to release of a high volume of wastes that more likely than not, produced a toxic reaction that would not have otherwise occurred*" (Barandiaran 2018, p.120).

According to Barandiaran (2018), this Chilean case provides evidences that in the face of environmental crises, scientists are generally not considered as a legitimate and authoritative source, and the debates can take years of discussion. At the same time, Barandiaran argues that this case shows some divergences from the literature usually found in science studies. First, the suspicion that scientists may have conflicts of interest with their funders affected industry' and State' researchers alike. Second, there is a strong belief in Chile that good science is expensive. These ideas influenced other scientists' perceptions about the legitimacy of the Austral study, which was modest in its funding and this was reflected in the extend of the research, applied technologies, etc. For example, many researchers believed the arguments of Arauco's lawyers that Austral's scientists were invested in the local cause, as some were neighbours also affected by the industry. In this regard, Austral's scientists were ineffective in demonstrating their autonomy. In addition, the open uncertainty about what substance, in what quantities and under what conditions, also affected the credibility of the Austral study. While the Catholic scientists effectively blurred the borders between scientists and consultants, the Austral scientists had difficulties in showing the value of their science to society. For their part, Arauco developed a strategy that made its science credible. Arauco had a plan to show its scientific credibility to the public, unlike CONAMA. For Barandiarán, what it sought to portray as a neutral EIA, was and remains highly contested in Chile.

Barandiaran (2018)'s theoretical contribution demonstrates some of the ongoing discursive strategies on scientific legitimacy in Chile, such as issues of scientific autonomy, the role of the State, and the influences of the neoliberal approach to science and decision-making on environmental issues in the country. The case study on the pulp and mill industry, in turn, is closely involved with actors in the Chilean forestry sector analysed in this research, so that the empirical considerations of this case are equally relevant to this investigation. The following section briefly presents the strategic approach that inspires this research for the integration of science studies and political ecology in the social analysis of the interrelationships in environmental science and policy-making in Chile.

2.3. Bridging sciences studies and political ecology: production, circulation and application of knowledge as a social analysis approach on environmental knowledge

To combine political ecology's and sciences studies' theoretical frameworks, this investigation is inspired by Goldman et al. (2011) in its focus on the phases of production, circulation and application of environmental knowledge (see figure 3) to deepen understanding of the interconnections between environmental science and policy-making. At the same time, this approach recognises that the dimensions of environmental knowledge production, circulation and application are difficult to separate since they are intrinsically interconnected (Goldman et al. 2011).

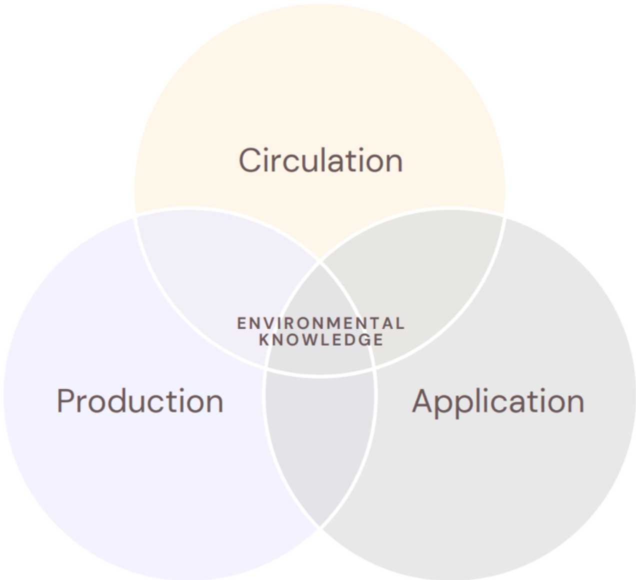
In this context, the review of previous insights and contributions on environmental knowledge (section 2.2.3) of political ecology and science studies, can be summarized as follows: Regarding contestations or controversies over scientific knowledge, the relevance of analysing contested knowledge across multiple levels and tools (Martin and Richards 1994) lies in the fact that these can affect the production, circulation, and application of knowledge (Supran and Oreskes 2021; Sharman 2015). In other cases, contestations or controversies over scientific knowledge or its legitimacy may be framed by using strategic language or rhetorical elements. This, among others, may promote misconceptions, inconsistences, doubt, denial, misunderstanding, confusion, or divert attention away (or ignore), etc. on certain well-established scientific knowledge on a topic (Harker 2017; Supran and Oreskes 2021). And sometimes it can downplay responsibilities, prolong discussions and delay policy-making and action (Supran and Oreskes 2021). In this context, the legitimacy and autonomy of scientific knowledge can also be challenged on contested knowledge issues and in policy making (Martin and Richards 1994; Clapp and Mortenson 2011; Sharman 2015; Harker 2017; Javiera Barandiaran 2018; Supran and Oreskes 2021).

Furthermore, the existence of multiple trends of knowledge production, conceptualisations, theories, models, infrastructures, etc., are also a product of multiple and diverse historical, environmental, social, economic and political layers (Gibbons et al. 1994; Turner 2011; Beck et al. 2017). Additionally, neoliberalism is the prevailing contextual setting for the production, circulation and application of knowledge, especially present in the Chilean contemporary reality of scientific production, expert knowledge and policy-making (Budds 2009; Bakker 2015; Javiera Barandiaran 2018). Moreover, the production, circulation and application of environmental expert or scientific knowledge in environmental assessment, may respond, among others, to different social contexts and human needs (Irwin 2008; Tsing 2015; Budds 2009; Bakker 2015; Javiera Barandiaran 2018). Also, scientific assessment practices may sometimes be asymmetric, re-produce social structures, or facilitate the generation of knowledge gaps (Hohenthal, Räsänen, and Minoia 2018; Tsing 2015; Budds 2009).

The Chilean case in particular stands out because of the presence of a process of transition from a military dictatorship to a post-dictatorial State (recovery of democracy) that has profoundly transformed the country's society, policy, economy, environment, and science.

These transformations have highlighted neo-liberalism as a dominant regime of knowledge governance (Budds 2009; Bakker 2015; Ibarra et al., 2018). This form of governance in Chile has been characterised by a 'democracy of consensus' and has positioned environmental issues as subordinate to economic development (Ibarra et al., 2018). In order to be carried out, it also implied the exclusion of citizens from decision-making (Budds 2009; Barton and Román 2012). In this neoliberal Chilean context, the production of scientific knowledge in its legitimacy and authority for policy production has been transformed into a search for consensus, mediation or negotiation between economic development and any other interests (Ibarra et al., 2018). In particular in the forestry sector, it highlights the important asymmetries of power in which private forestry companies constitute the mainstream actors capable of influencing decision and policy-making in the country (Barton and Román 2012). The circulation of forestry information in the Chilean media has been politised and served to divert public attention from the underlying understanding (knowledge) on issues, causes, consequences, etc. of events such as the mega fires of 2017 in Chile (Undurraga, et al., 2022). In this Chilean neoliberal context, scientific knowledge has become a commodity which undermines its credibility/legitimacy, and leaves the Chilean State as an ‘umpire State’ in a seemingly neutral role (Barandiaran 2018).

Figure 3. general conceptual approach on production, circulation and application of environmental knowledge



Source: author. Inspired from Goldman et al. (2011). Figure 3 outlines the phases of production, circulation and application of environmental knowledge, which are the focus of the social analysis in chapters 6 and 7 of this research.

These previous theoretical contributions and their empirical considerations make it relevant to apply 'field' theory, and 'ACF' frameworks as theoretical tools in this investigation. Because while the 'field' theory addresses concepts such as *social structure*, *habitus*, *capital* and *autonomy* – which are related to the production and circulation of scientific knowledge, their institutions, practices, struggles of legitimacy, authority and scientific autonomy – 'ACF' mobilises concepts such as *stakeholder coalitions (core beliefs and resources), relative stable parameters, external system events, and pathways to policy change* – which are related to the circulation and application of environmental knowledge in policy-making, their agents and institutions, policy structure, socio-economic and environmental events that may play part. Thus, making it possible to address and advance on previously theoretical and practical issues demonstrated by STS and political ecology scholars when investigating contestations of knowledge and production, circulation and application of environmental knowledge.

Both frameworks and their theoretical concepts are explained in detail in the following section 2.4, which presents the specific theoretical background used for the analyses of the production, circulation and application of forest hydrology knowledge in Chile in chapters 6 and 7.

2.4. Building a production, circulation and application framework for the forest hydrology field

The following sections 2.4.1 and 2.4.2, respectively present the frameworks of 'the field' (Bourdieu 1975; Lave 2012), and the 'advocacy coalition framework (ACF)' (Sabatier 1988; Sabatier and Weible 2007) to answer the questions B.1.2.3.4. and C.1.2.3.4. of this research. By operationalising these two frameworks as theoretical tools, this investigation seeks to contribute to the social understanding of the phases of production, circulation and application of scientific knowledge in forest hydrology policy-making in Chile in chapters 6 and 7.

2.4.1. Field theory: analysing the production and the circulation of scientific knowledge

An analytical framework used to reveal the social relations of the production and circulation of science, arts or bureaucracies, has been Pierre Bourdieu's widely-know theory of 'the field' and its concepts (Bourdieu 1975; Lave 2012). Bourdieu, who is today recognised as one of the foremost sociologist of the twentieth century (Grenfell 2008), developed the theory of the field in books like *Homo academicus* (1988) where he explores the social structure of the university, its faculties and body of agents and their social relations, to study the production and circulation of knowledge. As mentioned before, many scholars, such as environmental geographer Lave (2012) have operationalized it (see figure 4).

According to Bourdieu, a *field* is a potentially open space with dynamic borders, without components but formed by agents and institutions which occasionally face struggles (Bourdieu 1988). A field is socially constructed (Bourdieu 2004), and in this way, it can cautiously be compared to a game between players (Bourdieu and Wacquant 1992).

A field is structured at any given moment. This *structure* is defined by the distribution of power among the participants (people or institutions); that is, by the distribution of specific capital, which is objectified into agents or institutions who participate in the field (Bourdieu 1975). In this sense, for Bourdieu (1993) the strategies of participants are a function of the amount and structure of their *capital* (legitimacy and authority) and *habitus* (objects, practices, solutions thought, etc.) which evolve over time (trajectory). Thus, the dynamics of a field are based on the structure, asymmetries and gaps among the forces (capital) of participants (Bourdieu and Wacquant 1992).

According to Bourdieu, the structure of the field is organized around two poles which he defines as the *autonomous and heteronomous* poles (Bourdieu, 1994), and which allow to explore political-economic interactions (Bourdieu & Wacquant, 1992). The *autonomous pole* is understood as the space where scientific production is mainly shaped and controlled by the internal capital and dynamics within the specific field in which agents and institutions play a part. In contrast, the *heteronomous pole* is understood as the space where scientific production is mainly shaped and controlled by outside forces (Lave 2012), such as in the case of science performed in the private sector (Lave 2015). In other words, the heteronomous pole tends to be favourable to "those who economically and politically dominate the field", and the autonomous pole tends to be favourable to those who are identified "with a degree of independence from economy" (Bourdieu & Wacquant, 1992, p.101).

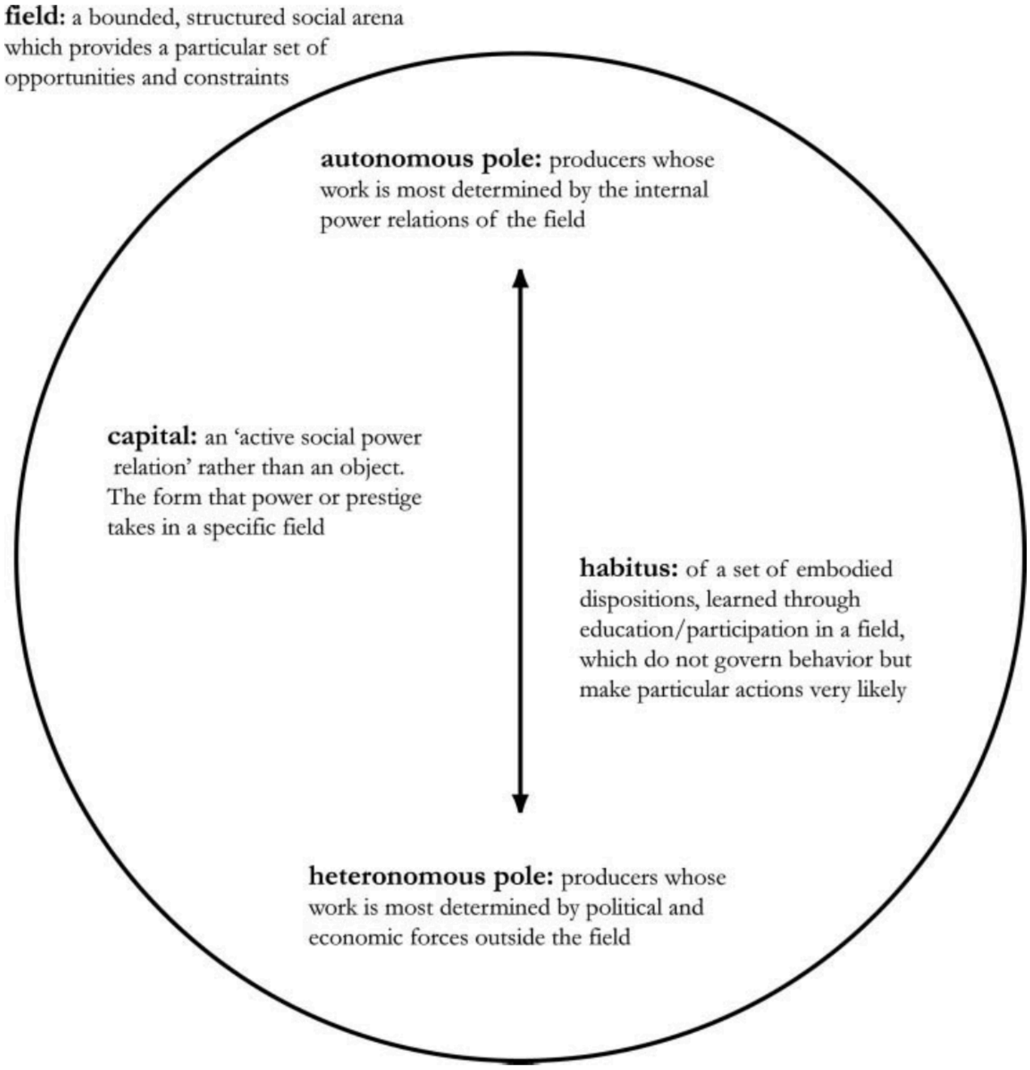
By *scientific capital*, Bourdieu (1975) refers to the amount of scientific resources accumulated in the field. Such capital can be economic, cultural, social, physical force, informational or symbolic (Bourdieu & Wacquant, 1992; Bourdieu, 1994). In this sense, for Bourdieu (1975) the struggle for scientific authority and legitimacy (social capital) gives power to the agents in a field, which subsequently can be transformed into other capitals. In this context, the present research focuses on scientific capitals composed by different claims of legitimacy, power and authority (Lave 2012). These capitals can take diverse forms according the dynamics and structures of a society at a given time.

Habitus on the other hand, refers to "a set of embodied dispositions, learned through education/participation in a field, which do not govern behaviour but make particular actions very likely" (Lave 2012, p.368). The habitus is composed of two interconnected functions (Lave 2012). The first one can be understood as the subconscious and subjective aspects, involved in a *practical sense* of choices and practices. The second function is understood as the socially constructed dispositions aimed at practical functions acquired through practice, such as educational training or personal experiences. In other words, habitus can be understood as both subconscious and conscious practices. Thus, habitus constitute a "systems of generative schemes of perception, appreciation and action, produced by a specific form of educative action, which make possible the choice of objects, the solution of problems, and the evaluation of solutions" (Bourdieu 1975, p.30).

One of the characteristics that most differentiate fields is their relative *autonomy* (Bourdieu 2004). Bourdieu (1975) defines the degree of autonomy in a particular scientific field in relation to external social demands, determinations and arbitrariness of the dominant agents or institutions over a field. Thus, in an academic context, autonomy can be measured by the way in which an external agent or institution can impose its own norms and sanctions on one or more producers in a field (Bourdieu, 1993). In other hierarchical institutional contexts (e.g. governmental or other institutions) the presence of hierarchy will imply some interdependence between different levels of the organisation (Tabary 1991; Harley 1999), and in these contexts some obedience to internal laws is to be expected (Tabary 1991) (although some individual agency may always be expected as well). For these contexts of diversity and complexity of production, the degree of autonomy is relative and it "varies considerably from one period and one national tradition to another, and affects the whole structure of the field" (Bourdieu, 1993, p.40). In other words, autonomy is also relational, because an individual and a field are always subject to the historical conditions and social determinisms of the social being, proper to humanity (Bourdieu 1975; Bourdieu 2004; Friedman 2013).

In this way, *relatively autonomy* is understood as an external political-economic practice that shapes the production or circulation of scientific knowledge on one or more producers in a field (Lave 2012; Bourdieu, 1993). To address it under a neoliberal system of scientific practices (like in the U.S. and Chilean cases), Lave (2012, p.376) recognizes three main characteristics that shape and influence scientific production and circulation in neoliberal research regimes: (i) the increasing privatization in the field, (ii) "a shift toward applied research to meet market and agency demands", and (iii) "the creation of metrics to enable market-based environmental management". To look at Lave's neoliberal aspects is very pertinent to the Chilean forest hydrology field because as many authors have demonstrated, the neoliberal economic policy has profoundly impacted contemporary Chile and its scientific production and technocracy (see e.g. Budds 2009; Moore et al. 2011; Tironi and Barandiarán 2014; Barandiaran 2018), and these neoliberal forces should be analysed as situated practices (Tironi and Barandiarán 2014).

Figure.4. Field concept diagram.



Source: Lave (2012, p.368).

2.4.2. The Advocacy Coalition Framework (ACF): tracking the circulation and application of scientific knowledge in policy-making

Paul Sabatier's 'advocacy coalition framework' (ACF) has been a framework used to study the circulation and application of scientific or expert knowledge in a policy-making, governance process or policy change (Sabatier 1998b). As such, it is well-known among policy scholars (Sabatier 1998b).

ACF has been widely applied to analyse how policy production is governed and changed (Sabatier 1988; Jenkins-Smith and Sabatier 1994; Sabatier 2007). This work is especially interested in understanding the role that scientific or technical information plays in the public policy-making process (Sabatier, 1998; Sabatier & Weible, 2007; Weible et al. 2009). ACF assumes that policy-making is complex and that participants must specialize if they want to be successful in changing the policy system, given that knowledge is recognised as an important power for policy-change. For that purpose, it seeks to analyse how and what kind of knowledge from scientists, among other experts, plays a role in the policy-making work (Sabatier and Weible 2007; Sabatier 2007). In this way, Sabatier's theoretical tools can be used to enrich the analysis of governance in the phases of the application and circulation of scientific knowledge in policy design.

ACF is composed of 3 mains analytical elements: (i) a policy subsystem (see figure 5), (ii) relative stable parameters; and (iii) external system events that influence these. The policy subsystem is understood as a field of competing relations among advocacy coalitions (Sotirov and Memmler 2012). Each of the coalitions can be composed of governmental and non-governmental actors who have common beliefs and share collective actions (Sabatier 1998a; Jenkins-Smith and Sabatier 1994). In the policy subsystem, different coalitions try to make their beliefs prevail through scientific and technical information. It is in this process of policy design that policy-decisions are debated and taken up by the coalitions to change the policy outputs (Sabatier and Weible 2007).

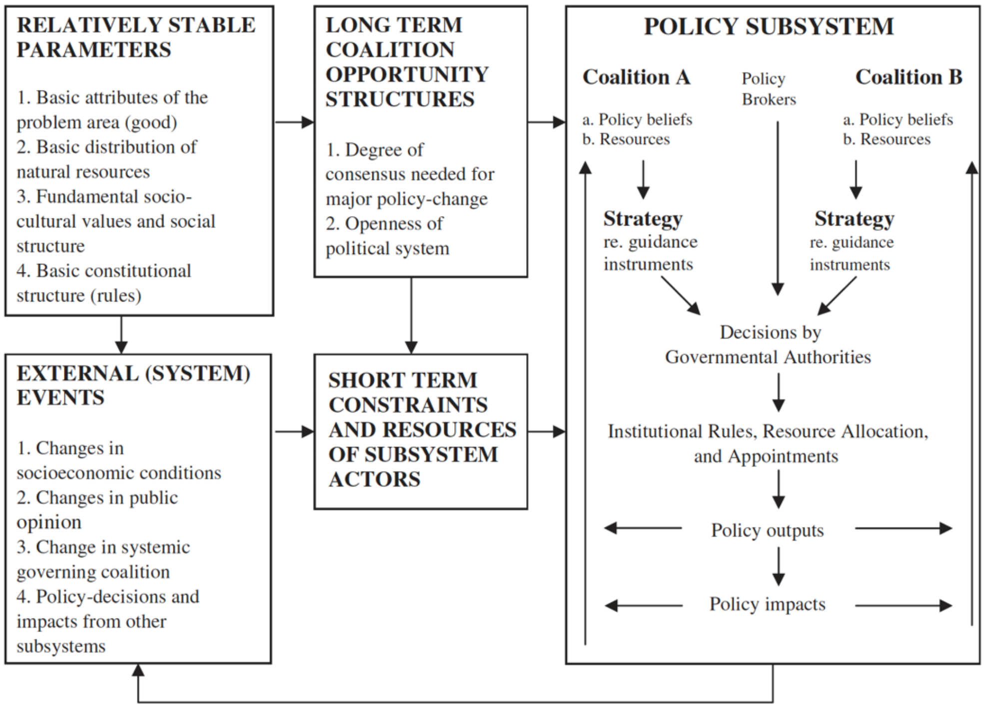
One strategy to study the actors in the policy subsystem is through their core beliefs (Weible and Nohrstedt 2012). Sabatier & Weible's (2007) analysis conceptualises three levels of core beliefs. First, *deep core beliefs* involve very general normative and ontological understandings, such as human nature or fundamental values (Sabatier & Weible, 2007). Deep core beliefs are difficult to change because they are mostly developed in childhood. Second, *policy core beliefs* represent a coalition's basic normative commitments and perceptions in the policy domain or subsystem (Jenkins-Smith and Sabatier 1994). Third, *secondary beliefs* are more, empirically-based, (Weible et al. 2009) scientific or technical approaches. They have a narrow scope and may include rules, or applications in a specific context (Sabatier & Weible, 2007) (e.g. forest hydrology science). In this way, based on the characteristics of this case study, the research mainly focuses on the identification of policy core beliefs, because they help to identify forming coalitions and minor policy changes following changes in secondary beliefs (Sabatier & Weible, 2007; Weible et al. 2009; Pierce et al. 2020). In this way, they help to analyse what kind of scientific expertise was heard in the policy process.

Regarding coalitions, ACF looks at policy participants trying (a) to circulate their beliefs within a policy making process, (b) to seek allies with people who hold similar beliefs, and (c) to engage in a certain degree of coordination (Sabatier & Weible, 2007). In this sense, advocacy coalitions are groups of actors that share core beliefs and coordinate their behaviours or strategies to change the policy-making process (Pierce et al. 2017; Ma et al. 2020). Coordination in an advocacy coalition means working together or jointly pursuing behaviours for achieving similar actions or objectives (Sabatier & Weible, 2007). The framework assumes that the incorporation of expert knowledge and subsequent learning into policy making is instrumental and that coalition members seek to understand the world in order to advance their objectives (Sabatier 1988).

Simultaneously, the advocacy coalition framework recognizes that the policy system (internal policy dimension) is affected by two sets of exogenous factors: *external system events* and *relatively stable parameters*. The relatively stable parameters rarely change during a decade, while the dynamic external factors can change faster and include changes in socioeconomic conditions, in the governing coalition, and/or in policy decisions from other subsystems. Furthermore, stable system parameters help to mediate the behaviour of coalitions (Sabatier and Weible 2007).

Finally, the ACF recognises four main pathways for policy change in the policy sub-system (Weible et al. 2009). The first path corresponds to external subsystem events (Pierce et al. 2020). These external events can change faster (Sabatier and Weible 2007) and may also constitute 'shocks'. They include changes in public opinion, in the government of countries, in socio-economic conditions and in other sub-systems, or disasters (e.g. earthquakes, tsunamis, fires, etc.). A second path is policy-oriented learning. Policy-oriented learning is defined as alterations in behaviour or thinking through new information or experience, and have to do with the revision of policy objectives (Weible et al. 2009). However, the ACF recognizes that new scientific and technical information may facilitate learning at a level of secondary beliefs, but is unlikely to affect deep or policy core beliefs (Sabatier and Weible 2007). The third path is internal subsystem events (Sabatier and Weible 2007) such as policy failures, scandals, fiascos or crises in the present subsystem (Pierce et al. 2017; Weible et al. 2009; Pierce et al. 2020). The fourth path is negotiated agreements between two or more coalitions (Weible et al. 2009), "where 'professional forums' provide an institutional setting that allows coalitions to safely negotiate, agree, and implement agreements" (Weible et al. 2009, p.124). Learning and negotiation pathways to policy change may occur between two or more coalitions (Pierce et al. 2020).

Figure 5. The Advocacy Coalition Framework Diagram.



Source: Sabatier & Weible (2007, p.202).

Chapter 3

Methodology

This chapter presents the general research strategy. The chapter is structured as follows. Section 3.1 describes the general strategy and case study selection. Section 3.2 presents the general organisation of the three field visits carried out in Chile, South Africa and Australia. Section 3.3 summarises the different types of training I underwent to carry out the research. Section 3.4 gives an overview of the different methods of data collection. Section 3.5 explains the different methods of data analysis in order to answer the three main research questions in chapters 5, 6 and 7; and finally, Section 3.6 critically reflects on methodological issues of the research.

3.1. Introduction

In order to understand the contestations on the knowledge of forest hydrology, and to follow its production, circulation and application of knowledge in Chile, as a first step, a deep and wide learning about the knowledge of forest hydrology and its science was necessary. For this reason, the research has a mixed-methods approach (Creswell 2014), which is primarily qualitative oriented.

The research is carried out through extensive empirical inquiry and is based on sound theoretical considerations. For example, Chapter 5 develops an in-depth and comprehensive literature review of forest hydrology literature over the last 40 years. However, for the development of this review, the knowledge obtained through multiple interviews and exchanges with forest hydrologists during my academic visits in Chile, South Africa and Australia, was key to the understanding of terminologies, processes, or methodologies specific to the field, which subsequently facilitated the study. Chapter 6 and 7 intertwines an empirical analysis and a theoretical literature review focused on Chile. In this respect, scientific literature on the production and circulation of environmental knowledge, and its application in policy-making processes were sought to complement and help to understand

and analyse the information that emerged from the interviews or fieldwork with the various actors in Chile. In these ways, the combination of empirical elements with the theory was an interactive process that enabled the evolution of this investigation through the years.

The three case studies were chosen for reasons of relevance and synchronicity around the theme of forests and water. Regarding the case of Chile, although I have Swiss origins and nationality, I was born and raised in Chile, so the language and knowledge of its environmental and socio-political reality was familiar to me. As for South Africa, already on my arrival in Switzerland and during the process of designing my research, I met a South African colleague from the Stellenbosch University who worked with my supervisor, and who introduced us to the South African long-term forest hydrology studies. Later, in my first fieldwork in Chile, my interviews corroborated that the South African case was widely recognised and frequently mentioned or cited in the forest hydrology literature in Chile. Subsequently, through my literature review I verified that "*South Africa has carried out some of the most detailed and definitive studies of water use from forests and commercial eucalypt plantations of any country in the world*" (Calder 2002, p.37). Therefore, its choice for field research was very pertinent. As my literary review progressed, I became aware of the vast amount of literature that exists in the forest hydrology field. This made the planned review of chapter 5 very challenging to organise and required a strategy that would allow the research to be bounded and feasible to carry out over a four-year period. Also, I was inspired by the fact that my supervisor was studying Australian tree species around the world, and that during my fieldwork in Chile, I noticed that the country was undergoing a landscape transition from *Pinus* plantations to *Eucalyptus* plantations. We then, together with my supervisor, decided to limit the review to *Eucalyptus* species only, while *Pinus* – also planted in Chile – among others, would be studied tangentially. In this way, through the choice of *Eucalyptus* species, the Australian case – where *Eucalyptus* trees are native – proved to be relevant. Additionally, this country has developed a vast amount of research in forest hydrology. Moreover, during my fieldwork in Chile, I found that senior researchers from the biggest forestry company were advised by Australian consultants on the development of their forest hydrology programme and publications. Hence, the Australian case gained relevance for the Chilean field as well. This added to the fact that all three countries have globally relevant and active forest hydrology programmes. Moreover, all three countries are in the southern hemisphere, sharing a Gondwanan geological past and current geographic feature ranging from latitude, *Eucalyptus* species planted, and wide rainfall gradients present in those countries. In these ways, the three countries of Chile, South Africa and Australia proved to be relevant to analysing their forest hydrology studies as a whole. This last is in line with the insights of renowned Australian forest hydrologists, Bren (2015), who in one of his books addressing the question "what's different about Australian forest hydrology?" explains:

> "*Probably the best answer is that there is nothing in Australian forest hydrology that is not found elsewhere, but that Australia commonly exhibits more extremes – longer droughts followed by large floods and greater inter-annual variability than many countries. The hydrology of other parts of the world – particularly settled agricultural districts in Western Europe and Eastern USA – looks ordered and predictable compared to Australian hydrology. And perhaps, because of this, Australian hydrology issues have been much more in the political spotlight (mainly due to drought, flood, and fire) than is the case in other countries. Having said that, relationships developed between rainfall and streamflows using Australian data appear to sit very well with worldwide relationships*" (Bren 2015, p.20)

Subsequently, many external events happened which modified my research. Among which the COVID-19 pandemic triggered globally in 2020, just as I was planning my return from Australia to Switzerland. I managed to get back to Switzerland before the border was closed, but my second planned field trip to Chile in 2020 had to be cancelled for good. With this, the questions of the last results chapter had to be adapted as well. As a result, together with my professors, we decided to refocus the research on other aspects. Given the large amount of information collected and considering the timeframe of the research, it was decided to focus the research in the sixth and seventh chapter only on the Chilean case. The following table shows an overview of the distribution between case studies, questions and databases. Further details are presented in the following sections.

Table 2. Overview of case study data types

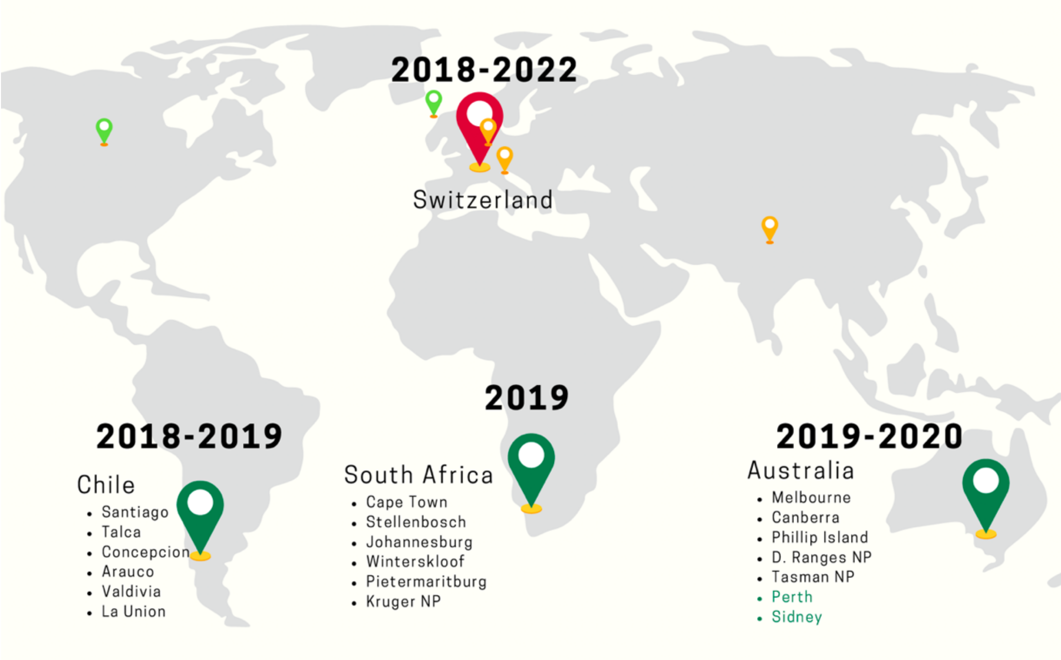
Chapter	Case studies	Research aims	Databases
Chapter 5	Chile, South Africa and Australia	A.1, A.2., A.3., A.4.	Scientific peer-reviewed journals on *Eucalyptus* forest hydrology
Chapter 6	Chile	B.1, B.2, B.3, B.4.	Chilean interviews
Chapter 7	Chile	C.1., C.2, C.3, C.4.	Chilean interviews, and policy-documents of the Forest Plantation Protocol (FPP) (e.g. related policies, minutes of policy-meetings, etc.)

The following section provides general background details on the different data collection methods.

3.2. Fieldwork organization: Chile, South Africa and Australia

The research is based on fieldwork, carried out in Chile, South Africa and Australia. The fieldwork had three main stages during 2018, 2019 and 2020 and had a total duration of more than 8 months (figure 6). The fieldwork in Chile took place between the end of October 2018 and the end of January 2019. The research visit in South Africa took place between the end of August and the end of October 2019. I was based at Stellenbosch University and hosted by Professor David Richardson, director of the Centre of Excellence for Invasion Biology. The research-stay in Australia took place between early November 2019 and early February 2020. I was based at Melbourne University, School of Ecosystem and Forest Sciences and hosted by Professor Rod Keenan. The constant exchanges and constructive criticism from both academics contributed greatly to the revision and improvement of chapter 5 of this research. Both academics were contacted through my supervisor's contacts. The list of the various locations visited during my three fieldwork missions are shown in figure 6.

Figure 6. Case study locations: doctorate time-map



Source: author. Figure 6 shows a representational map of the different case studies, locations visited and general timelines of this research. The three big green locations show the countries and case studies of Chile, South Africa and Australia and the years of their visits. In the red-top location, the research base in Switzerland is shown. The light green locations show the locations of forestry hydrologists who were contacted online for logistical reasons, including in Canada, England, and Perth and Sydney in Australia. Locations in yellow-minor show other places visited as part of my doctoral training, such as Germany, Italy and Nepal.

Fieldwork in Chile had two main orientations. First, the objective was to deepen my knowledge of Chilean forest hydrology, its diverse themes, contents, methodologies, and gaps, and to elucidate the actors involved. Interviewees were consulted to help me to understand what at that time I thought to be a scientific controversy around the issue of forests and water. Second, I sought to understand the circulation of the field's knowledge, and its application in the construction of forest policy. In that regard, my research focused specifically on the case of Chile's Forest Plantation Protocol (FPP), elaborated in 2017. In order to do so, the fieldwork had two main strategies: identify, interview and interact with forest hydrology producers in Chile, as well as the institutional and political actors who participated in the elaboration of the Forest Plantation Protocol.

In the Chilean case, I was not based at any university or institution directly or indirectly linked to my research. To develop my work autonomously, I rented a shared office space at Nube Cowork in Valdivia, located at that time between Serrano and Cochrane streets. In this city, I had to conduct most of the interviews with forest hydrologists, and my first encounter with them was at my presentation at the Forest and Water Conference, hold in Valdivia.

South Africa's field campaign was oriented towards working with the leading forest hydrology experts. The South African forest hydrologists who were interviewed were trained in the long-term studies that I started to review during my South African and Australian fieldworks for the development of chapter 5. Similar to the Chilean case, the South African case also had the objective of deepening my knowledge in the field of forest hydrology. Although this fieldwork mainly focused on the understanding of production of forest hydrology knowledge, aspects of its circulation and application of knowledge in the South African forest hydrology policy making were also asked.

The work in Australian had a strategy similar to the South African case. The main objective of the visit was to deepen my understanding of the process of scientific production of Australian forest hydrology. Through this, I also sought to understand what phenomena in forest hydrology could generate different hydrological responses or a potential controversy around the issue of water use from natural *Eucalyptus* forests or their forestry tree plantations. But also, I asked questions related to the circulation and application of hydro-forestry knowledge in Australian policy regulations.

Once back in Switzerland, after each of my three periods of fieldworks, presentations with preliminary findings were given to colleagues and professors at the IGD institute during so-called 'Bouillon d'idées' meetings. The report of the preliminary findings from the field in Chile was presented in February 2019. The presentation of the fieldwork report in South Africa and Australia took place in March 2020. The comments obtained at these occasions helped to enrich the subsequent analyses.

3.3. Scientific training on forest hydrology field

In addition to my multiple fieldworks, field observations, formal interviews and informal talks with various experts in forest hydrology from around the world, and in particular with forest hydrologists from Chile, South Africa and Australia, I carried out an extensive literature review on *Eucalyptus* forest hydrology, which from a list of more than 1700 articles, led me to review more than 200 of them. In particular for the development of Chapter 5, this intense work was constantly revised and improved through exchanges with the Professors Rod Keenan, Dave Richardson and Christian Kull, as well as by comments from the editor and an anonymous reviewer of the *Forest Ecology and Management* journal. Over a period of more than 4 years, all these experiences as a whole, trained me directly and indirectly in a wide phenomenological, theoretical and methodological knowledge of the forest hydrology field.

3.3.1. The VIU Graduate Seminar

In addition to the training mentioned above, in July 2019, and prior to the development of my fieldworks in Australia and South Africa, I attended a seminar training on "hydrogeophysical inversion and data assimilation for the characterization and monitoring of coastal aquifers". The seminar was developed under the guidance of the Venice International University, University of Lausanne, and Università di Padova in Venice, Italy. In order to participate in the seminar, I had to pass a personal interview with the coordinator of the University of Lausanne, since my background was different from doctoral students from geophysics institutes. I had to explain the objective of my research and why I thought it relevant to my research to train myself in groundwater dynamics. The seminar lasted 5 days and included classes, readings, working groups, a field visit in a place artificially drained to avoid salinization in a farmland on the continental coast of Venice, and the design, presentation and discussion of a final poster. I must confess that the experience was very challenging. Indeed, I lacked programming knowledge in which the other Doctoral students from geology or physical geography were already familiar. However, the seminar lectures, readings and the multiple conversations with the professors, helped me to deepen my knowledge on aquifer basic dynamics, especially in coastal areas, where fresh waters interact with saline marine ones. Furthermore, in a very interesting conversation with a Swiss professor, I became aware of the literature on Australian groundwater, *Eucalyptus* and salinization problems. In this way, the knowledge acquired in the seminar not only contributed to my general understanding on groundwater and methods of analysis, but also helped me to prepare myself for my fieldwork in Australia, where the largest number of studies on aquifers and forest plantations have been carried out.

3.4. Data collection methods

3.4.1. Interviews: Chile, South Africa and Australia

Semi-structured interviews were used in order to answer questions about production, circulation, application of forest hydrology knowledge and policy-making. Given that the main focus of knowledge was centred on scientific knowledge produced in different contexts and circulated and applied in the production of policies. The target audience tended to be diverse groups of expert actors from the scientific-university based, business world and high-level policy or governmental experts. In this context, the interview method was selected, because:

> *"Interviews are often used for studies in which participants are 'experts' from whom you hope to learn how certain practices, experiences, knowledge, or institutions work – or at least, how your participants talk about these things working."* (Secor 2010, p.199).

Interviews proved to be one of the most efficient methods to collect in-depth experiences of the experts, and at the same time, to connect with each of them with other methods such as focus groups, the meeting of experts is complex to implement (Secor 2010), and a survey or online questionnaire does not provide the richness of personal contact that is capable of conveying other types of information.

According to the characteristics of each question, the use of the interviews varied in each of the chapters developed. For instance, in chapter 5, interviews were not used, although some authors were contacted for clarification on some of the contents of their articles. For chapter 6, interviews were used as a source of substantial information for the analyses. In Chapter 7 the interviews were used to complement the analyses since enough material had already been collected and analysed from secondary policy-sources (e.g., the FPP, its minutes of political meetings, among others).

After the three field campaigns in the years 2018-2019 and 2020, no further interviews or contacts with actors in these countries were conducted. Exceptionally, in 2021 one forest hydrologist was contacted by email communication to ask/clarify specific aspects of a paper relevant to the case of Chile.

3.4.1.1. Selection of participants

The strategy for the selection of participants varied slightly from country to country. This is because knowledge of local culture, language, etc. varied from case to case. In the case of Chile, previous research experiences in the field gave me some names of institutions to start with. Similarly, the development of "the Water and Forests Conference" (WFC) held in Valdivia, in November 2018, was a key event that allowed me to dig into the programme and themes, and review online some names before my arrival in Chile. This conference was used as a starting point for establishing contacts for interviews, as well as for my own training in the field of forest hydrology. A selection of papers was made to attend all sessions where studies on forest hydrology in Chile will be presented. Subsequently, the snowball contact strategy (Sadler et al. 2010) was used to approach further interviewees in Chile.

Four main stakeholder groups were identified in Chile: academics, forestry companies, government institutions and some NGOs (see table 3). Each of these groups had different degrees of relevance for the scientific or policy production aspects that were analysed. For example, in terms of scientific production, actors from academia, industry and government were identified by their participation in the Chilean forest hydrology field, while when analysing the production of the Forest Plantation Protocol (policy), a reduced group of academics, businessmen, government agents and NGOs participated. This led to the specific use of interviews in chapters 6 and 7. Additionally, on a few occasions a 'double participation' of interviewees was found. For instance, in the case of the Forest Plantation Protocol (FPP), an academic was interviewed who at the time of policy development represented an NGO, and a high-level government official was interviewed who at the time of FPP development represented the forestry business sector. In these cases, the affiliations that the actors had when participating in the elaboration of the FPP were considered. In addition, not all FPP participants responded to the invitation letters and their interviews could not take place.

The interviews and observations were carried out in Valdivia, Concepcion, Chillan, Arauco, Talca, La Union and Santiago (see figure 6). Academics were interviewed at the Universidad Austral de Chile, Universidad de Chile, Universidad de Concepción, and Universidad de Talca. In the same way, representatives of different governmental institutions were also interviewed: the National Forest Corporation (CONAF) and the National Forestry Institute (INFOR), as well as the two most influential Chilean forestry companies: Celulosa Arauco y Constitución S.A. (Arauco) and MININCO S.A (CMPC).

The strategies for identifying participants in South Africa and Australia were the same. In South Africa and Australia two strategies were used for stakeholder identification. The first contacts were mainly identified through the contacts of Professors Richardson (in South Africa) and Keenan (in Australia). Subsequently, the snowballing technique was used (Sadler et al. 2010), as well, as my literature review progressed, recurrent names that where identified were also contacted.

This resulted, in the South African case, in visits to the Council for Scientific and Industrial Research (CSIR); the Institute for Commercial Forestry Research (ICFR); former forest hydrology researchers, as well as academics working at the Stellenbosch University and University of KwaZulu-Natal, which are the main universities developing forest hydrology studies in the country. Moreover, I visited many sites of various *Eucalyptus* and *Pinus* research sites and forestry plantations, which are mentioned in figure 6. In the Australian case, visits were made to the Commonwealth Scientific and Industrial Research Organisation (CSIRO); the Melbourne Water Corporation of the Victorian Government; multiple contacts with forestry researchers based at Melbourne University; University of Canberra; University of Sydney; University of Western Australia; University of South Australia; University of Tasmania, as well as Australian forest hydrologists and consultants who work for the Arauco forestry company (Bioforest) in Chile. Additionally, I visited many sites of various *Eucalyptus* natural forests and forestry plantations, which are mentioned in figure 6.

Table 3. List of actors interviewed in each country and remotely

Interviewees	Chile	South Africa	Australia	Total
In person	36	7	10	53
Online	0	3	5	8
Total by country	36	10	15	61

3.4.1.2. Interview design

The research adopted a semi-structured interview approach as the appropriate collection method. This was preferred because in semi-structured interviews, the researcher offers participants the possibility to explore issues that they consider relevant to the topics covered (Longhurst 2003).

In the Chilean case, the interview questionnaire started to be designed in September 2018. Interviewees were asked open-ended questions about the forest hydrology research in Chile. It focused on two main aspects. First, (1) questions linked to forest hydrology itself in its production and circulation of knowledge. For instance, questions related to environmental issues investigated, universities, disciplines, collaborations, projects, certainties, uncertainties, gaps in knowledge, consensus, divergences, methodologies, challenges in research, history, among others. Second, (2) focusing on the Forest Plantations Protocol (FPP). In this case, questions were related to the issues discussed in the FPP, consensuses, disputes, actors, governance, decision-making, and application/role of scientific forest hydrology knowledge on policy.

These ideas and questions related to the semi-structured interview questionnaire for the Chilean fieldwork were reviewed with my Kull team group of colleagues in a private presentation, as well as with university colleagues and professors at the IGD institute during the Bouillon d'idées. With the comments obtained from these two instances, questions were improved and an 'interview guideline' was elaborated and used to undertake the semi-structured interviews in Chile (see table 4). Subsequently, with the experience gained in Chile, the 'interview guideline' was slightly adapted (e.g. language, from Spanish to English, or the non-existence of the FPP in these countries) for interviews in South Africa and Australia. The same interview guideline was applied for both countries (see table 4). Interviews were recorded with audio, video, and/or photographs, always with the consent of those involved.

Table 4. Interview guideline applied in Chile, South Africa and Australia.

<table>
<tr><th>Categories</th><th>Topics</th><th>Questions</th><th>Country</th></tr>
<tr><td rowspan="2">Production*</td><td>· forest hydrology studies

· arguments
- sources of information
- methodologies
- theoretical frameworks
- funding
- network</td><td>How many projects are there?
Which? how? when?

Which ones?
How?
Where does it come from?
Other?</td><td rowspan="2">· Chile
· South Africa
· Australia</td></tr>
<tr><td>· network</td><td>Who? why? when?
Public sector/State?
Private sector/business?
Citizenship?
How is the work dynamic with them?
Other?</td></tr>
<tr><td>Circulation</td><td>· arguments
- topics
- network</td><td>Do plantations/eucalyptus reduce water?
Which ones? environmental context, scales, years of measurement, others?
Consensus? Disagreement?
Uncertainty? complexity?
Gaps?
Where is it going? How? When?
Other?</td><td>· Chile
· South Africa
· Australia</td></tr>
</table>

	· history*	When did/does forestry hydrology appear/start in Chile? When did water reductions in plantations/eucalyptus start to be studied in Chile? Are there milestones? Changes? Other?	
Application	· forest plantation protocol (FPP) - governance - decision-making - development and conservation	What does governance mean? How was the selection of participants? Information asymmetries? Which ones? How? Who? How was the decision-making? Who? Issues of contestation, disagreement? between whom? How do you evaluate the Process? Other?	· Chile
	· water and plantation/eucalyptus policy in the country	Which ones? Did you participate? who? how? when? How were decisions made? Was science used? Were there differences/disagreements? Which ones? Were they resolved? Other?	· South Africa · Australia

3.4.2. Observations: Chile, South Africa and Australia

Observations were the second method used to collect data in this study. This allowed to study actors in their fieldwork environments and to understand 'situations/things' in a broader context of their daily lives (Baker 2006). Observations were carried out in Chile, South Africa and Australia and were crucial to understand the size of each research and its practical strengths and challenges. Observations were registered by written, visual, video and/or audio, and had the consent of those involved. During the field visits it was possible to observe the infrastructures and measurement tools, as well as to discuss in situ with the academics and research managers about their projects.

Field observations in Chile were carried out during visits to three hydrological monitoring sites with associated researchers: two sites of the Universidad Austral de Chile, and one site of the research division of the forestry company Arauco, called Bioforest. The sites of the forest hydrology programs visited were located in (1) the commune of La Union, and (2) in the Periurban Reserve of Llancahue, both located in the Region of Los Rios; and (3) the forest hydrology program of Bioforest, at the latitude of the town Arauco, in the Bio Bio region. The three projects were located on the east or west slopes of the coastal mountain range, with different percentages of land uses of native forests and forestry plantations of pine and eucalyptus. In addition, (4) I participated and took notes at the Second National and International Congress on Forests and Water, held at the Universidad Austral de Chile.

In South Africa, observations were made during (1) a fieldwork visit in the oldest forest hydrology catchments program of the country, started in 1935 in the Jonkershoek Nature Reserve, and located near to the city of Stellenbosch; and (2) a visit to an *Eucalyptus* forestry plantation in company of a forest hydrologist expert in *Eucalyptus* tree species. In addition, (3) contextual and broader knowledge was gained from more casual landscapes observations during diverse outings around the country (e.g. weekend hikes, a solo trip to the Kruger National Park, etc), and upon visiting universities, workplaces, local museums, and diverse neighbourhoods, etc.

In Australia observations were made (1) in national reserves of *Eucalyptus* natural forests and diverse landscapes on the south-west coast, south-east coast, and north-east of the city of Melbourne, in Victoria. These forests usually had the marks of older forest fires that I read about in my parallel bibliographic review of Australian forest hydrology. Moreover, a walking excursion between the Port Arthur and the Tasman National Park, in Tasmania was done. This park is characterised among other aspects, by formations of *Eucalyptus globulus* and *Eucalyptus nitens,* which are tree species widely used in forestry plantations in Chile. Here I carried out a self-exercise of identification of different species of *Eucalyptus* with the support of a field guide of *Eucalyptus* species. The exploratory visit in the Tasman National Park was abruptly interrupted due to the start of the forest fires in Tasmania – which had not started before my arrival on the island. I had to evacuate the park due to the risk of fires in the area, and that same day took a flight back to Melbourne. It was a very impressive experience. By the end of the fire session around February 2020, this had become the largest bushfire on the Australian continent. Furthermore, observations were also made of (2) *Eucalyptus* plantations from roadsides edges, (3) university faculties, workplaces, and local museums, etc.

3.4.3. Other data types: Chile, South Africa and Australia

3.4.3.1. Scientific literature

For chapter 5, peer-reviewed scientific articles published on forest hydrology between 1980 and 2019 were collected from the ISI Web of Science. Databases were searched in both English and Spanish, and focused on reviews of Chile, South Africa and Australia locations. This resulted in over 1700 initial records (76 records for Chile, 129 for South Africa and 1506 for Australia) to be read and subsequently reviewed. Detailed information on this review is provided in section 3.5.1.

For Chapters 6 and 7, diverse topics in the literature were reviewed to complement knowledge on key emerging issues focusing on Chile. These are quoted in these chapters. For example, aspects of drought and climate change in Chile (chapter 6), forest fires of 2017, or neoliberalism in Chile (chapter 7). These themes emerged from the analysis of interviews or policy documents previously reviewed.

3.4.3.2. Email communication

In the course of this research, several authors – forest hydrologists, or other professionals – were contacted via institutional emails in search of supplementary information or clarifications. Actors from Chile, South Africa and Australia were contacted. This information has been authorised for research use by the actors involved. This information was used in a cross-cutting manner to support the development of chapters 5, 6 and/or 7, as pertinent.

3.4.3.3. Policy documents

Several bodies of policy documents were analysed. These mainly focused on Chile, and are used as context (chapter 4) and for detailed analysis in chapters 6 and 7. For instance, Chapter 4, section 4.2.5, provides an overview of the main policy management tools related to forest hydrology in Chile. In the case of Chile, policy-regulations are divided into legislation on water, forests or forestry plantations. This policy review serves as a political-institutional and resource management context for a deeper understanding of the analyses in chapters 6 and 7. Chapter 7 of this research was based on the policy documents of the Forest Plantations Protocol (FPP), its related policy documents, and in particular of the Soil and Water Expert Commission (SWEC).

There are three main datasets that report on the work of the FPP and the SWEC. These constitute a total of more than 48 files reviewed. The first dataset is composed by the Forest Plantation Protocol (FPP) (CONAF 2017a), which is part of the new Chilean forest policy (2015-2035) (CONAF 2015). This first dataset was used to identify the main policy outputs of the FPP.

The second dataset corresponds to a total of 38 documents obtained through the public transparency system of the Chilean State. These documents consist of the minutes of 8 meetings and 18 documents of the "Soil and Water experts commission (SWEC)". The minutes of the 8 sessions provided information about the list of participants, their comments and conclusions. The 18 documents correspond to presentations and complementary documents, submitted by the participants during these 8 sessions held by the SWEC. Additionally, this dataset includes 5 minutes of the TCFPP meetings, and 6 minutes of the Forest Policy Council (FPC) meetings which provide information about the list of participants, their comments and agreements on the FPP. This second dataset was used for the analysis of exogenous factors (relative stable parameters and external system events), the policy subsystem (core beliefs) and for paths to policy change. Regarding the analysis of exogenous factors and particularly relative stable parameter, this was complemented by revising the Decree 82 on soil, water and wetlands regulation, since this was the legal basis (constitutional structure) of the SWEC's work and more particularly, the legal basis for the discussions on the widths of the soil and water protection buffer-zones. As for external system events, these were complemented by reviewing scientific literature, in order to better contextualise the external system event of the forest mega-fires mentioned in the FPP. As for the policy system, the analysis of secondary core beliefs focused on the SWEC scientific discussions on soils and water in plantation forestry, to better understand what science or approaches were listened to (circulated) in the policy making-process. In addition, as a simplification, policy core beliefs are identified as the predisposition demonstrated by actors to increase more or less current regulation standards on soil and water protection, taking the case of protection buffer-zone widths and Decree 82. Finally, regarding the possible pathways for policy change, it focused on identifying changes in the FPP process that have been reflected in the SWEC outputs, and in particular the scientific discussion on widths of the water protection buffer-zones (application).

The third dataset consists of 9 interviews held with participants of the FPP. The interviews were carried out in Chile during three months of fieldwork in 2018 and 2019. Specifically, the cities of Santiago, Talca, Concepción and Valdivia were visited to interview the FPP's participants. Among those interviewed were groups of academics (forest hydrologists), political and technical representatives from forestry government institutions, NGOs and representatives from forestry companies. Two interviews concerned representatives of the forestry industry and a social organisation that participated in the elaboration of the FPP in 2017. When they were interviewed in 2018, their institutional affiliation had changed. One was holding a position representing one of the State forestry institutions, and the other had an academic university-base position; but within their interviews they were considered as an industry - and a social organisation representative since they were asked about their participation in the Protocol process, at which time they indeed represented these sectors. This third dataset was used to complement and deepen the four possible paths for policy change analysis revealed by the minutes analysis of the policy (FPP) production process.

3.4.3.4. Grey literature

In the course of this research, grey literature documents on forest hydrology such as reports, institutional publications, among other documents were occasionally provided or suggested by interviewees, or mentioned in the proceedings of the Forest Plantations Protocol. On these occasions, such documents were identified, reviewed and quoted. This information was used to support the analyses in chapters 6 and 7 as pertinent.

3.5. Data analysis and data management

The previous sections presented the general research strategy, case study selection and data collection methods. The following sections present the methodological procedures used to analyse the data.

To provide answers to questions A of chapter 5, a systematic review of the literature in forest hydrology was developed. To answer questions B, the 'field' concept was operationalised for chapter 6. To answer questions C, in chapter 7, the 'advocacy coalition framework' was employed as a theoretical tool. The detailed analytical and methodological procedures are presented in the following sections.

3.5.1. Forest hydrology review

Chapter 5 is based on a structured literature review, inspired by the protocol of Siddaway et al. (2019) and reported in accordance with Moher et al. (2009). The review sought to identify points of consensus and disagreement regarding the impacts of eucalypts on water quantity. The review did not seek to add new statistical knowledge to the extensive body already existing on the matter. Neither does it provide possible forestry management solutions in this regard. Its contribution focuses on understanding the state of the art on certain forest hydrology topics regarding the genus eucalypts and its diverse effects on water at the different stages of the hydrological cycle. To do so, each study was characterized in terms of bio-environmental factors, land uses, and forestry treatments, based on a review of the conclusions (statements) of the studies.

3.5.1.1. Search protocol and study selection

Peer-reviewed scientific articles published between 1980 and 2019 were collected from the ISI Web of Science. Database searches in both English and Spanish used the logical operators of "eucalypt*" OR "blue gum" AND "country" (South Africa, Chile and Australia separately) AND "water*" OR "runoff" OR "balance" OR "stream" OR "scarcity" OR "drought". This collection was enlarged by (1) searching on Google Scholar, (2) browsing online libraries of journals related to hydrology and forest management, and (3) reviewing the reference lists of Chilean articles to increase access to Spanish language publications. Authors were contacted when articles were not accessible online and a few studies were rejected because the full text was not accessible. This resulted in over 1700 records (76 records for Chile, 129 for South Africa and 1506 for Australia).

After removing duplicates, six filters were applied: first, research data had to come from Chilean, South African and Australian locations; second, the presence of eucalypts was mandatory but the studies could include other land uses (agriculture, grasslands, among others) or tree species (pines, acacias, native trees, etc.); third, the information collected focused on the impact of eucalypts on water, either as streamflow, evapotranspiration, soil water content or groundwater; fourth, studies reported on water quantity (not quality); fifth, books, book chapters, journal opinion pieces, conference proceedings, or research theses were excluded; and sixth, studies had to be either original works or reviews. A first reading of titles and abstracts selected, followed by second round of full textual analysis resulted in a final set of 24 studies in Chile, 34 in South Africa, and 148 in Australia with a final total of 206 articles.

3.5.1.2. Data extraction

After collection, the articles were analysed from the earliest to the most recently published, facilitating the understanding of the historical progression of knowledge. The software Atlas.ti was used to organize information from the articles, concerning the following categories: conclusions/statements regarding forest-water relations; tree species; native or non-native status; land cover types; age of tree stands or forests; changes to land cover (including proportion of the area changed); methodology; area of study (spatial scale); period of measurements (time scale); geographical contexts (climate, soil type and depth of aquifers); and mention of gaps in research.

The identification of conclusions/statements was the core of the coding process. Each statement or conclusion that mentioned an impact of eucalypts on water quantity was codified. In some cases, more than one conclusion on different themes was coded per study. However, in this chapter 'statements' refer interchangeably as 'studies'. Conclusions were also grouped by the portion of the hydrological cycle concerned: evapotranspiration, streamflow, soil and groundwater.

For each conclusion/statement, it was then sought to fill out the categories listed above. In some cases, authors were contacted to clarify missing information. The coding for geographical context focused on climate types, soil types, soil depth and distance to groundwater table. The names of soil groups and their descriptions were often lacking, which made it challenging to group them. Depth to groundwater and aquifers were not mentioned in the Chilean or South African studies, but they often were in Australian studies. Some studies referred readers to more detailed geographical descriptions in other articles; these descriptions were not included. The methodologies and the scale of analysis were frequently mentioned. However, study periods, names and ages of tree species were not always given. Finally, some studies mentioned the existence of unresolved research gaps or suggestions for future research.

3.5.1.3. Analysis of the data

The coded data was exported to Excel, cleaned, categorized and analysed. Coding and cleaning consisted of several rounds with the objective of avoiding repetitions in the analysis. The identification of conclusions/statements was the core of the coding process.

They were first grouped by the part of the hydrological cycle concerned: evapotranspiration, streamflow, soil and groundwater. Then, these statements on eucalyptus were sub-grouped into 3 main categories of investigation: land use, forestry treatments and bio-environmental factors. Additionally, those statements that analysed a land use change were identified (Table 5). Each statement was then categorized regarding whether it investigated natural forests or plantations, and whether the eucalypts were non-native species or native species (where native refers to eucalypt species within Australia, irrespective of finer details of native distribution). The methodologies were organised according to the hydrological factor they studied, and the scales of analysis were lumped into categories (plot, small watershed, large watershed or other scales) to facilitate the general understanding of the statement's analysis. The precipitation data was categorised by precipitations and climate types reported in the studies. Soil data was categorised according to the different soil classifications reported in the studies. Finally, relatively few articles reported the existence of knowledge gaps. For this reason, after the coding of hydrological effects and gaps, a further check of hydrological factors identified any unexplored or insufficiently explored themes.

Table 5. Categories of investigation pertaining to the influence of *Eucalyptus* species on hydrology.

Category	Topics
Part of hydrological cycle studied	Evapotranspiration
	Soil
	Streamflow
	Groundwater
Land cover comparisons	Comparing eucalypts with agriculture
	Comparing eucalypts with grassland
	Comparing eucalypts with other kind of native forests (non-eucalypts)
	Comparing eucalypts with other kind of native shrub
	Comparing eucalypts with wetland vegetation
	Comparing eucalypts with other land covers or mixed land covers
	Comparing eucalypts with other tree species
Forestry treatments	Fire regimes
	Density of plantation
	Distance to body waters
	Irrigation
	Fertilization
	Harvesting
	Thinning
	Defoliation
	Forestry rotation
	Other categories*
Bio-environmental factors	Age of stands
	Seasonality
	Rainfall
	Groundwater
	Flood
	Drought
	Non-saline water
	Transpiration at night
	Insect attacks
	Other categories**
Land use changes	From agriculture to eucalypt (and pine)
	From grassland to eucalypt (and pine)
	From other kind of native forest to eucalypt (and pine)
	From other kind of native shrub to eucalypt (and pine)
	From eucalypt to non-eucalypt trees
	From native eucalypt forest and shrub to agriculture and grassland
	From old eucalypt forest to young eucalypt forest
	From eucalypt to pine
	From eucalypt to acacia
	From willow to eucalypt

(*) Such as restauration, area, coppice trees, etc., or (**) climate change, temperature, etc.

3.5.2. Production and circulation of scientific knowledge

For the analysis presented in Chapter 6, it is operationalized Bourdieu's (1975) field theory, following the example of Lave (2012), to evaluate the external political-economy and internal social relations of the forest hydrology field in Chile. In order to understand this field and how it has evolved and conditioned the production and circulation of knowledge over time, we rely on a variety of sources.

The chapter is based on the collection and analysis of (1) interviews, (2) participant observation and fieldwork visits, and the (3) participation at a conference. As detailed in section 3.4, more than 20 semi-structured interviews of forest hydrology knowledge producers (people or institutions) were consider for this analysis. This resulted in the specific selection of actors and institutions detailed in the section 4.2.1 (overview of actors presents in chapters 6 and 7).

The collected material was analysed using qualitative data analysis software (Atlas.ti) and following the structure of Lave's (2012) operationalisation of Bourdieu's field theory. Specifically, Lave analyses four main aspects (Table 5).

Table 5. Main aspects of field analysis

Concept	Elements sought for datasets analysis
The objective structure of the field	Agents or institutions that participate and collaborate in the field
Habitus	Knowledge specialities, such as choice of research objects, concepts and possible solutions mentioned by participants
Capital	Different claims of legitimacy, power and authority by participants
Autonomy	External political-economic forces of neoliberalism suggested by Lave (2012) that shape the field production or circulation practices

Source: author. Based on 'field' theory (Lave 2012). See theoretical section 2.4.1.

First, the *objective structure* focuses on those who compete for the forms of capital in the field (Lave 2012). Guided by the heteronomous and autonomous poles concept, we identify all those agents or institutions that participate and collaborate in the scientific production in the Chilean forest hydrology field.

Second, the structure of the *habitus* which embodies the practices of participants in the field (Lave 2012) was addressed. We focus on identifying the knowledge specialities which participants learned through a scientific-educational system, such as research objects, concepts used, and solutions considered.

Third, the forms of *capital* that govern the field were explored. In the context of this research, the focus was on scientific capital composed by the participants' different claims to legitimacy, power and authority (Lave 2012). These capitals can take diverse forms according to the dynamics and structures of a society at a given time. Therefore, their identification was an open process based on what the participants themselves mentioned about the legitimacy of forest hydrology studies.

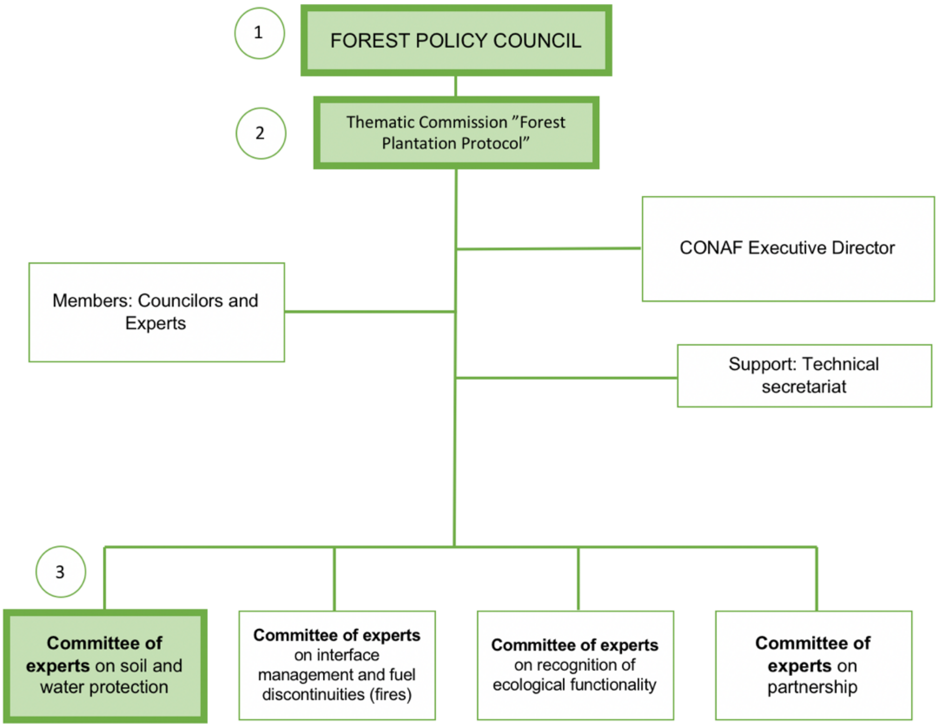
Finally, the relative degree of *autonomy* in the field was addressed, and specifically its focuses on the three external political-economic forces of neoliberalism suggested by Lave (2012). This are: (i) the increasing privatization in the field, (ii) a shift from basic to applied research oriented to market and agency demands, and (iii) market-based environmental management. This is done in order to identify if those forces have shaped (or not) scientific production and knowledge circulation practices in Chilean forest hydrology. Historical accounts of the evolution of the field mentioned by interviewees were complemented by a review of Chilean literature on the same historical issues (chapter 4).

3.5.3. Circulation and application of scientific knowledge

For the analysis presented in Chapter 7, the advocacy coalition framework (Sabatier 1988; Sabatier and Weible 2007) (see section 2.4.2) is operationalized to investigate the circulation and application of scientific knowledge in the policy production in Chile. To analyse the production of the. policy and governance process that addressed the forest hydrology science, the "Forest Plantation Protocol" (FPP) produced in 2017 was taken as a case study. This resulted in the specific selection of professors and institutions that participated in the soil and water discussions of the FPP. The list of actors is detailed in the section 4.2.1 (overview of actors presents in chapters 6 and 7).

The methodological sequence of this analysis mostly follows the chronological progression and working groups that addressed the issue of forest hydrology in the FPP policy-production. This FPP was mandated by the "Forest Policy Council" (FPC) and contained three levels of work in its policy production (CONAF 2017) (see figure 7). First, the FPC itself constituted the highest level of hierarchy; where councillor-representatives of the forestry sectors (forestry State institutions, forestry companies, university deans, and social organisations) were members and voted in plenary sessions on the approval or rejection of the FPP outcomes. Second, there was the "Thematic Commission on Forest Plantations Protocol" (TCFPP). This TCFPP was a temporary commission composed of elected FPC councillors. It constituted the political commission, specifically responsible for the elaboration of the FPP. The TCFPP did not have voting rights but reviewed the progress of the four expert sub-commissions of the FPP, among which was the "Soils and Water experts commission" (SWEC) analysed in this study. Third, this SWEC was the expert commission responsible for discussing the scientific and technical information related to soil and water issues of the FPP. In other words, it was this commission that provided the scientific-technical forest hydrology arguments that supported the policy production of the FPP on soil and water aspects. These experts were nominated by the TCFPP. The invited experts were also able to invite other experts to participate in the SWEC, as long as the meetings were held in front of a member of the Technical Secretariat of the FPC, who supported the coordination of the expert groups and FPP process. Writing the minutes of the meetings was the responsibility of the technical secretariat of the forest policy council.

Figure 7. Governance structure of the Forest Plantation Protocol (FPP) work.



Source: author's drawing and translation based on the FPP (CONAF 2017, p.7). The green boxes represent the various instances that played a role in the elaboration of the FPP and in particular in the SWEC and which were analysed in this research. Box (1) on the forest policy council (FPC), is composed of councillors who are appointed by government sectors (e.g. CONAF, INFOR, DGA, CORFO, etc), forestry companies (Arauco, CMPC, Masisa, CORMA, etc), social organisations (e.g. WWF, Terram Foundation, etc), universities (e.g. Universidad Austral de Chile, Universidad de Talca, Universidad de Concepcion), or other organisations such as FAO. Box (2) corresponds to the commission created under the FPC to specifically develop the FPP. Box (3) corresponds to the expert committee on soils and water that was convened by the members of committee (2). Box (3) constitutes the main group of actors analysed in this research. The four expert committee boxes in figure 7 (line number 3) correspond to the topics addressed by the FPP. This research only reviewed the expert committee on soils and water.

This research was based on the policy documents of the Forest Plantations Protocol (FPP) and its related policy documents. In the case of the FPP this is composed of 48 files reviewed. Composition and organisation of this dataset is presented in detail in section 3.4.3.3.

Following the bodies of analysis of the advocacy coalition framework (Sabatier 1988; Sabatier and Weible 2007) (see figure 5), I focus on two main aspects as methodological steps: (i) exogenous factors (external systems events, and relative stable parameters), and (ii) policy subsystem (see table 6). The content analysis of the different FPP datasets was mainly qualitative (Creswell 2014). The coding process of the datasets was undertaken with the Atlas.ti software and consisted in the identification of emerging themes mentioned by the participants. This review resulted in the identification of 'topics identified and analysed in the FPP', and the operationalisation of datasets (table 6).

Table 6. Main aspects of ACF analysis

Concepts	Elements for analysis	Topics identified and analysed in the FPP	Datasets operationalisation
External system events	Changes in public opinion; socio-economic conditions; in governing coalition; and impacts from other sub-systems (Sabatier & Weible, 2007).	Mega-fires in Chile in 2017.	FPP participants' statements about the fires and their influence on the FPP's governance. E.g. change in the name and process of the commissions, working times defined following the fires, etc. (e.g. Jessop 2003). Registered in the datasets.
Relatively stable parameters	Basic constitutional structure (rules) (Sabatier & Weible, 2007).	Decree 82. Specifically, on widths and water protection buffer-zones.	FPP participants' statements about Decree 82, the protection buffer-zones and their influence in the FPP's governance. Registered in the datasets.
Policy subsystem	Common secondary core beliefs, and presence of coordinated actions (Pierce et al. 2017).	SWEC' scientific backgrounds and approaches, as well as coordinated actions or agreements between actors, specifically on widths and water protection buffer-zones.	FPP participants' backgrounds and statements about hydrological effects of forestry plantations and the role of protection buffer-zones on water resources. Supported by journal, reports, other documents, or their own statements registered in the datasets.
Policy change	Four possible paths for policy change: (a) external subsystem events; (b) policy-oriented learning; (c) internal subsystem events; (d) and/or negotiated agreements (Weible et al. 2009).	External system events, relatively stable parameters and policy subsystem in the Forest Plantation Protocol, especially about widths of water protection buffer-zones.	**(a)** Effects of fire on the FPP governance process and policy changes; **(b)** knowledge approach comparison between previous ACF literature on forestry policy-making (e.g. Arnold 2003) and the current FPP governance process; **(c)** mention of internal system changes that influenced policy-change; and **(d)** mention of agreements for policy-change. Registered in the datasets.

Source: author. Based on ACF (Sabatier 1988), and theoretical section 2.4.2.

Following the review of the three datasets, two topics emerged as the most relevant to the SWEC and FPP forest hydrology analysis. As for policy subsystem (ii) the case of the design of the transversal distance (widths) of *the soil and water protection buffer-zone*, discussed by the forest hydrology experts in the SWEC was identified. This was especially addressed because the buffer-zone issue was finally the most discussed outcome among the SWEC experts, and one of the most discussed issues in the whole policy-making process of the FPP (CONAF 2017n). Additionally, regarding exogenous factors (i) the case of the Chilean mega-fires in 2017 was identified, given the historical and national relevance of this event (see Pliscoff et al. 2020; de la Barrera et al. 2018) that influenced the entire production of FPP. Finally, due to the fact that the experts of the four committees were only focusing on the work of their thematic commissions, and the commissions did not officially interact with each other (CONAF 2017p), the other three commissions of experts on fire, ecological functionality and partnership (figure 7) were not analysed.

3.6. Reflections on the methodology

As with many investigations, the process was not without multiple challenges. The following sections present methodological reflections, and some of the challenges that had an impact on how the research was conducted and adapted.

3.6.1. Changes and adaptations

The research process was not linear and had different phases and adaptations. Of these, chapter 5 was the one that experienced the most adaptations and challenges. Initially, I proposed for the PhD to investigate whether, if any, methodological differences and the design of forest hydrology research could lead to different conclusions. Similarly, this research included a social analysis of the production, circulation and application of forest hydrology knowledge in Chile, South Africa and Australia. This is because my fieldwork in these countries were part of the joint design strategy of chapter 5 and strongly supported by the host professors.

This initial project for chapter 5 and its foundations were developed, shared with, and reviewed by Professors Christian Kull (University of Lausanne), David Richardson (Stellenbosch University), and Rodney Keenan (University of Melbourne), as well as discussed with other professors from the University of Lausanne, prior to my fieldworks in Australia and South Africa. During my stay in these countries and later on, the project was constantly discussed and modified. At the end of my last fieldwork in Australia, and following the suggestions of the professors – who though it too challenging to mix forest hydrology and science studies analyses simultaneously in a single paper – the project of chapter 5 changed its focus from a social-physical study in the field of forest hydrology, to a review of the state of the art of *Eucalyptus* in these three countries, and it was agreed with my supervisor that this study would be a qualitative analysis based on statements. This also resulted in the adaptation that chapters 6 and 7 would only focus on the Chilean case. Indeed, the extent of the literature I had collected and had to analyse in order to develop the ecological analysis of my thesis was extensive. So, in a joint strategy, we decided to limit the five chapter to forest hydrology only. In total, the process of identifying, reading, coding and analysing all the articles in chapter 5took 8 months. The process of writing, and especially revising and responding to the several comments of co-authors, took about 2 years.

In this process, successive adaptations and changes were suggested. Suggestions to change concepts, to re-categorise and re-organise the variables analysed, to reduce the literature included in the analysis, or to focus only on forestry plantations, were some of them. Many of these suggestions were incorporated and improved the work. However, some major structural and methodological changes to the project such as changing the focus of the analysis to forestry management and hydrological solutions, were not feasible to incorporate due to the already advanced stage of the research project at that time. Another big challenge to chapter 5 was the proposal to present quantitative data. Yet, upon much consideration and many exchanges it was decided not to further advance into that direction. Given that the original project was not designed for this, this turned out not to be feasible at that stage.

Another great challenge that modified the research was the COVID-19 pandemic. Due to the lockdown and the closing of the borders, my second fieldwork in Chile had to be cancelled. Chapter 7 would focus on 3 rural localities with the presence of forestry plantations and water problems, to interview rural inhabitants and NGOs. As a consequence of this, the third result chapter had to be adapted and focused only on the Forest Plantations Protocol.

In the final stage of the research a last adaptation was made following requests/suggestions from the jury. Among them, it was suggested to take position on controversy (what is this? clarify it further), and to be more explicit about the multiple interests among actors at stake, and actualize what this work means today in Chile, among others. These useful suggestions were deepened based on the available information already analysed (and written) about forest hydrology discussions. Furthermore, interviews and background documents were revisited to find additional information that could help to further understand, complement, and deepen on these suggestions. As a theoretical reference to do this, additional pertinent Chilean and international literature on controversies over scientific knowledge, STS and political ecology was reviewed and helped to develop these requests. Together this work took almost 4 months.

3.6.2. Investigating sensitive issues in fieldwork

As the investigation developed, I began to observe – in subtle and concrete ways – the existence of multiple sensitivities among the experts on the topic I was researching. I met with multiple reactions. The academics were the most open group of actors, who in a more direct or reserved way – according to the personalities of each one – answered my queries. The vast majority of them accepted the interviews to be audio recorded and filmed. As exceptions in this regard, there were three academics, two in Australia and one in Chile, who during or after the interviews, asked for their names to be anonymized.

Apart from these academics, people and researchers working with forestry companies and the government, manifested greater sensitivities when interviewed. The most exceptional cases were with mid-ranking researchers in the Chilean government. For one key actor of them, it took me 2 months before I could interview him, and when he agreed to do it, he made me understand that without being recorded he could communicate more things. For this reason, we met a second time, and the interview was not recorded. Another key government professional never responded to my interview emails. A third one, a key officer-researcher, was the only actor during all my fieldwork, who requested that I sent him the questionnaire before accepting an interview. The day of our interview, after asking the questions and requesting the institutional forest hydrology information, he suddenly started yelling at me, disqualifying my work. Surprisingly for me too, I managed to get the person to calm down, but the meeting ended quickly. I was confused and found it hard to understand what had happened, or why. Next day, the person contacted me via email. He apologised, and offered me a second interview, to which I agreed only because he was a key actor. However, notwithstanding this person being a key researcher from the government and deeply involved in the history of forest hydrology in Chile, most information on the forest hydrology projects to which I requested access, was provided to me by other academics, who formally and informally, shared information with me. There were multiple other experiences, in which in a concrete and subtle way, I observed how sensitive, uneasy and socially complicated it was to address this topic for most participants – academics, government, business, or NGOs – I met in this research.

3.6.3. Other Challenges in doing research

Upon further research, I found that the world of forest hydrology is a man's field. There were only 2 women in Chile, and 2 in Australia, working in this field. Additionally, being from a geography background and not a forestry background, I found it challenging to develop research in forest hydrology. My knowledge, skills and ethics in the research process were constantly challenged. The more observations I got, the more effort I put into doing the work with the standards of excellence I aspired to. The process was exhausting, but I learned enormously.

Chapter 4

Case study
Forest hydrology research and policy-making

This chapter presents an overview of the case study. There are two main sections in this chapter. First, section 4.1 provides an overview of the first forest hydrology studies around the world and reviews their application (or not) in policy-making processes. This is followed by a review of the cases of South Africa, Australia and Chile. This provides elements that illustrate the relevance of the choice to investigate these three southern countries with active programs in forest hydrology research. Subsequently, section 4.2 focuses on presenting multiple contexts of the main case study: Chile. This section introduces the main actors looked at in Chapters 6 and 7, and reviews the history, geography, environment, economy, and policy related to forestry plantations, forests and water issues in the country.

4.1. Forest hydrology studies

4.1.1. First worldwide forest hydrology studies

According to McCulloch and Robinson (1993), in their review about 'History of forest hydrology' report, the first study on catchment experiments of forest hydrology in the world, was undertaken in Switzerland in 1903. At that epoch, there was concern about flooding risk for the villages. Specifically, the catchments of Rappengraben (31% forest and 69% pasture) and Sperbelgraben (99% forested) in the Emmental, were started to monitor the hydrological response to land uses and rainfall (McCulloch and Robinson 1993). This showed the following results:

> "*From the Sperbelgraben catchment, flood flows and annual water yields were lower, baseflows were higher (Burger, 1943) and erosion, measured as bedload, was half that from the Rappengraben*

pasture catchment; furthermore fewer landslides occurred" (in McCulloch and Robinson 1993, p.193).

The Rappengraben and Sperbelgraben research project in the Bernese Emmental region followed out of the growing concerns about erosion, flooding and adverse climatic effects following the massive deforestation of Europe's natural forests in the mid-1800s (McCulloch and Robinson 1993). But erosion and flooding events appeared even earlier in Europe, and prompted the creation of the first decrees regulating deforestation in the Alpine countries of France, Italy and Austria in the sixteenth century (Kittredge 1948). In Switzerland, for instance, the Federal Constitution of 1874 (para. 24) financed the afforestation and the damming of torrents for flood prevention (McCulloch and Robinson 1993). This also promoted the creation of the first research sites in 1888, to study the yield of Swiss forests (WSL 2020).

While the Swiss-Emmental study was the first, by far the majority of watershed studies have been conducted in the USA (McCulloch and Robinson 1993), where a first paired watershed study was developed at Wagon Wheel Gap, Colorado (Amatya et al. 2011) in 1909 (Neary et al. 2011). Later in Europe, in 1948, the study of two forest hydrology catchments in the Upper Harz mountains, Germany (McCulloch and Robinson 1993) was also started. In these German studies, "*forest regrowth on the Lange Bramke [catchment] has reduced streamflow, whereas clearfelling on the Wintertal [catchment] has led to an increase in annual flows*" (McCulloch and Robinson 1993, p.205).

A greater maturity of studies, results and reviews in forest hydrology would be reached in publications in the 1980s. The publication of the first forest hydrology review by Bosch and Hewlett (1982) is a world-renowned and much-cited example, which reports on evidence from the accumulated forest hydrology knowledge on different vegetation covers – among them, *Eucalyptus* and *Pinus* plantations – and their relationships with rainfall, evapotranspiration and runoff, in 94 catchments around the world, and in some cases, with more than 50 years of observation.

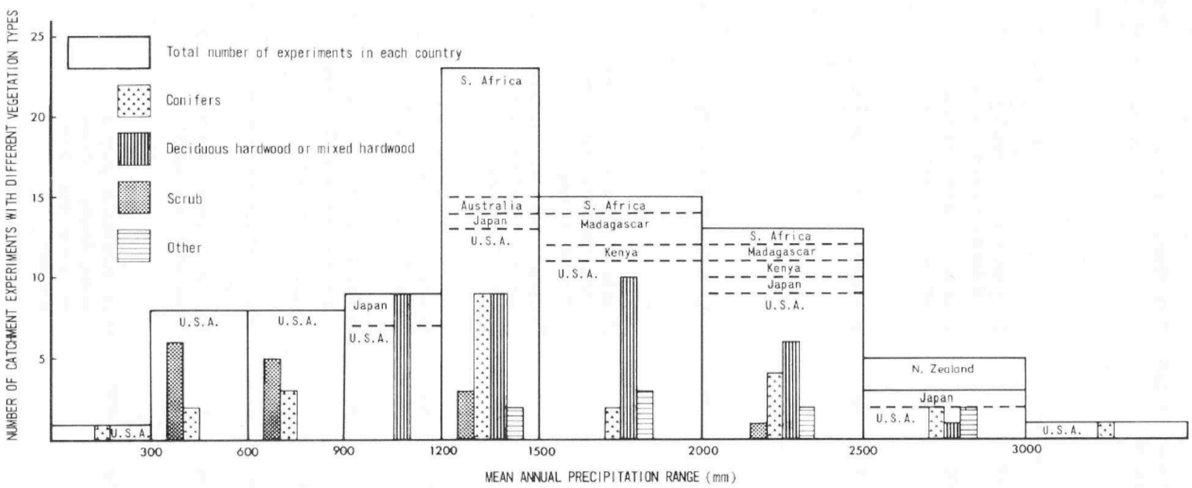
The Food and Agriculture Organization (FAO) of the United Nations, also published a report in the late 1980s, specifically dedicated to *Eucalyptus* tree species and its plantations. This report stated to address, among other things, the widespread concerns about *Eucalyptus* tree species as major water consumers. The report "*Efectos ecológicos de los eucaliptus*" (*Ecological effects of eucalyptus trees*), was commissioned by FAO-Rome in 1987, to professors and consultants from Spain, France and Brazil. This report aimed to understand the ecological effects – hydrological effects among them – of *Eucalyptus*, by carrying out a literature review from the library of the Commonwealth Forestry Institute, U.K. (FAO 1987); the research institute that carries out forestry research in the British Empire territories, including Australia, South Africa, Canada or India. Regarding the hydrological effects of *Eucalyptus*, this report concludes:

> "*The planting of extensive eucalyptus forests in any deforested watershed will substantially reduce water production in that watershed, and logging of these forests will increase it. The water reduction effect of eucalyptus is probably less than that of pines and greater than that of other hardwood species, but all tree species reduce water production more than stubble and grasses. Consequently, when the water yield of the watershed, or of the water table in adjacent lowlands, is important, the situation should be carefully considered before major reforestation or deforestation programs are undertaken*" (FAO 1987, p.25-26).

Knowing already some general aspects about the effects of eucalyptus on water in 1987, currently, FAO-Rome is working globally on how to improve understanding of forests and waters, how to better manage forests, and where to plant them, so that they do not have adverse effects on water (FAO-Rome, forest and water office, 8 October, 2018). To this end, FAO is promoting the use of remote sense technology (FAO-Rome, forest and water office, 8 October, 2018), as a more recent methodology in forest hydrology studies (Bren 2015).

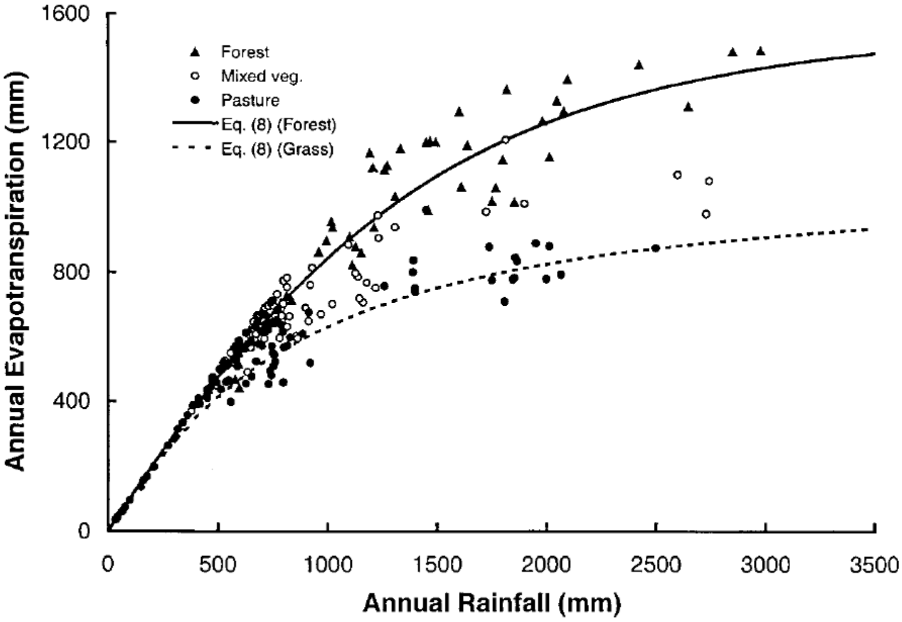
As member countries of the Commonwealth, the studies from South Africa and Australia, among others were the basis for the FAO-Rome report at that time. The case studies of South Africa and Australia are relevant to look at in this research, since they have been among the few countries starting forest hydrology studies on *Eucalyptus* trees, as well as, among the few who developed different policy measures in this respect (White et al. 2016). In this sense, they are among the first countries to develop knowledge on forest hydrology dynamics and systematise them in diagrams. Examples of this are the Nänni' curves in South Africa (Nänni 1970; L. Bren 2015), and the Kuczera' curves (Kuczera 1987) and Zhang' curves (Zhang et al., 2001) in Australia, widely known in forest hydrology studies. Also, the South African and North American contribution of Bosch and Hewlett (1982), "*A review of* *catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration*" was the first one in reviewing and summarizing 94 studies from watersheds around the world on the hydrological effects of *Eucalyptus* and *Pinus* on water resources. The Australian study of Zhang, Dawes, and Walker (2001), "*Response to mean annual evapotranspiration to vegetation changes at catchment scale*", extended the Bosch and Hewlett (1982) review to 250 experimental watersheds around the world, and revealed concluding patterns between water availability and monocultures, mixed forests and pastures water uses (see figure 8). The Zhang, Dawes, and Walker (2001) study, is the most extensive review on forest hydrology studies to date (see figure 9). Thus, the contributions of South Africa and Australia to global forest hydrology studies have been enormous and make them worth/crucial to review. Therefore, the historical backgrounds of South African and Australian forest hydrology contributions are reviewed in more detail in the following sections.

Figure 8. The number of catchment experiments carried out in different countries, various rainfall ranges, within various broad categories of vegetation types.



Source: Bosch and Hewlett (1982). The graph shows the total number of studies and their distribution by country and rainfall analysed in the review. In this study, Eucalyptus species are included in the category 'hardwood or mixed hardwood'.

Figure 9. Relationship between annual evapotranspiration and rainfall for different vegetation types.



Source: Zhang, Dawes, and Walker (2001). The graph shows the relationship between different types of vegetation and their different types of evapotranspiration according to the amount of precipitation. This study revealed that different vegetation types evapotranspirate/use more water if more water is available/precipitates. In this study, *Eucalyptus* and *Pinus* tree species are included in the 'forest' category.

4.1.2. Forest hydrology field and policy in South Africa

"*South Africa has carried out some of the most detailed and definitive studies of water use from forests and commercial eucalypt plantations of any country in the world*" (Calder 2002, p.37). Initiated in 1935, and still under monitoring (see figure 10), the Jonkershoek valley-catchment studies near Stellenbosch were the first forest hydrology studies in succeeding in the country. The Jonkershoek valley-catchment was followed by the development of a multi-project of 8 hydrographic catchments in the country (Gush et al. 2002). The design of this long-term study on the effects of afforestation was based on experimental studies of paired basins in the Emmental in Switzerland and in Wagon Wheel Gap in Colorado U.S.A. (Chapman 2007). These South African long-term study and programs overcame many difficulties, for which constant funding was key to overcoming them (Bennett and Kruger 2015; Van Wilgen and Wannenburgh 2016). The knowledge in forest hydrology produced through the South

African pioneering long-term monitoring project contributed to the formation of new forest hydrology catchment studies in Kenya, Uganda, Tanzania (McCulloch and Robinson 1993), Chile (Iroumé et al., 2005), Australia (Zhang et al., 2001), and worldwide (Calder 2002). Such knowledge was also used in the 1990s to produce one of the few – if not the only – water acts in the world that recognizes land uses such as forestry and sugar cane as higher water users and therefore subjected to a license fee in compensation (Calder 2002).

Figure 10. Monitored catchment in the Jonkershoek valley, South Africa (2019).

Source: author.

To contextualise the origins of these pioneering forest hydrology studies in South Africa and its subsequent policy application, it is useful to understand the economic, environmental and scientific contexts of South African history. As Bennett and Kruger (2015) report in their book "*Forestry and Water Conservation in South Africa*", the original forest hydrology studies are due to the early introduction of *Eucalyptus* and *Pinus* tree plantations in the country (Bennett and Kruger 2015) and the concerns that were raised about their high water use (Calder

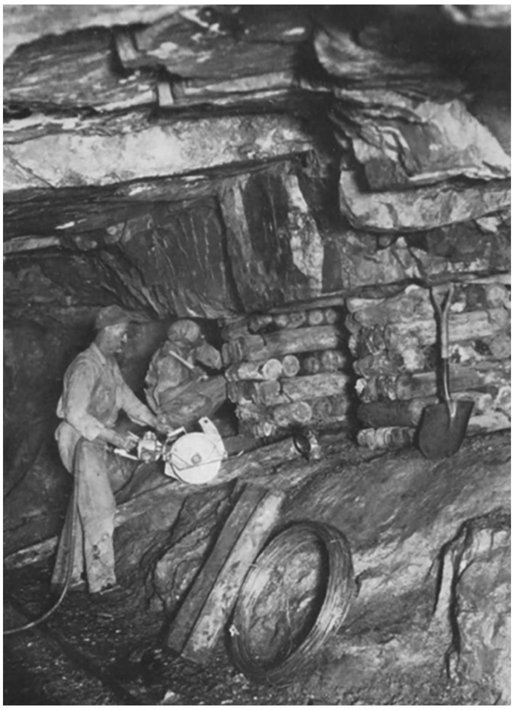
2002). *Eucalyptus globulus* were probably first introduced in 1828, through trade between the Australian and South African colonies. These exchanges increased between 1850 and 1890 with the development of multiple botanical gardens. And, by 1860, near Bloemfontein, an extensive plantation of various *Eucalyptus* species was developed (Bennett 2011; Bennett and Kruger 2015).

As in many other countries around the world, the promotion and expansion of fast-growing tree plantations began as a response to the growing demand of timber for mining purposes, such as the construction of support pillars in mining operations. It was through the mining revolution in the early 1870s, following the opening of diamond mines such as those in the Kimberley region, that the growing demand for timber in South Africa was triggered (Bennett and Kruger 2015). As the native forests and savannah trees started to be depleted, starting from 1894 the promotion of fast growing plantations for mining purposes became widespread in South Africa as a private initiative and as a solution to the high cost of importing timber (see figures 12 and 13) (Bennett and Kruger 2015). It was in this economic and environmental context, and after the intensive expansion of *Pinus* and *Eucalyptus* plantations in in the late 1890s, that the long-term forest hydrology studies in South Africa begun in 1930.

Figure 12. *Eucalyptus globulus* plantation in George, South Africa, 1910.

Source: the Department of Agriculture, Fisheries and Forestry of South Africa, as reproduced in Bennett and Kruger (2015).

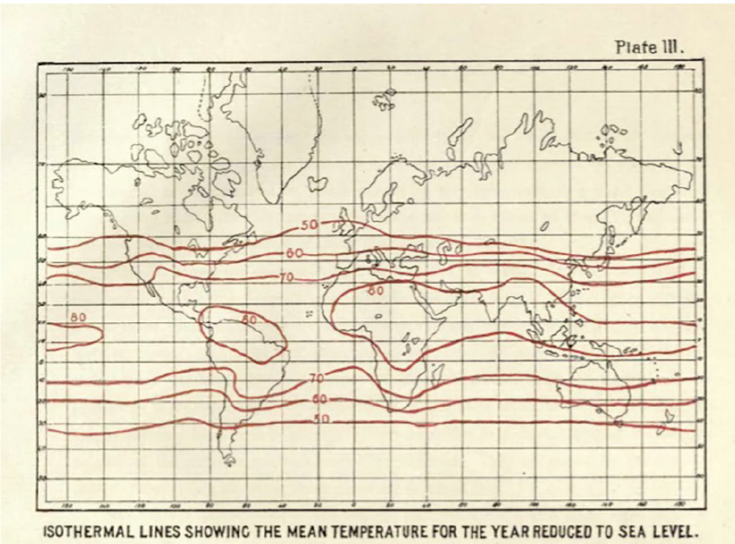
Figure 13. Timer supports in a mine on the Reef. South Africa, 1920s.



Source: the Department of Agriculture, Fisheries and Forestry of South Africa, as reproduced in Bennett and Kruger (2015).

The origin of forest hydrology studies in South Africa, in turn, was made possible by the prior existence of an educational base in the country that allowed the development of scientific forestry knowledge, and with it, the subsequent development of knowledge on forest hydrology. Forestry experimentation between British colonies was also based on meticulous climate analysis between continental regions (Bennett 2011; Bennett and Kruger 2015). In South Africa, analyses for importing *Eucalyptus* from Australia (Bennett 2011) were inspired by the mapping procedures developed by Humboldt (figure 11) (Bennett and Kruger 2015).

Figure 11. Climate map of the world with temperature isolines based on topographical analysis



Source: H.G. Fourcade report on the Natal Forests, as reproduced in Bennett and Kruger (2015). Prepared for the government of Natal, South Africa in1889. On this map, the south-central regions of Chile, South Africa and Australia share thermal characteristics.

Putting the South Africa's production of forestry science knowledge in context, in the 1900s, South Africa was a colony. England was one of the last European countries to develop a forestry school, which opened at Oxford University in 1905 (Commonwealth Forestry Association 1971). In 1906 the first forestry school in South Africa was opened in Cape Town (Bennett and Kruger (2015). But given the inter-colonial realities of funding and power circulation, it was closed in the early 1910s. This coincides with the founding of the Union of South Africa[1], and the Union-Wide Forestry Department in Pretoria in 1910, which between 1911 and 1932, promoted the circulation of upper-level officers from this agency for forestry training at British Universities, such as Oxford, Yale and Edinburgh (Bennett and Kruger 2015). The Union Irrigation Department started in 1910 the first forest hydrology studies at a State plantation in Jessievale. But, due to failures in gauging techniques, by 1924 the loss of data made it clear that the records were unreliable (Bennett and Kruger 2015). Moreover, in 1918[2] the University of Cape Town was founded as the first university in South Africa (UCT 2022), followed by the University of Stellenbosch also in 1918 (SUN 2022).

Whit the above mentioned educational and learning gauging backgrounds, the Department of Forestry and Agriculture in South Africa in 1935 created a major forest hydrology research programme in the Jonkershoek valley near Stellenbosch, to study the hydrological effects of exotic plantations. Specifically, it was in 1935, at the Fourth British Empire Forestry Conference[3] that discussions on the hydrological effects of fast-growing plantations of *Eucalyptus*, *Pinus*, and *Acacias* plantations in South Africa led to the creation of the long-term study in the Jonkershoek Valley, near Stellenbosch (Bennett and Kruger 2013). This research tried to offer a solution and consensus building to the existing disputes already present in 1910 on whether or not these introduced tree species consumed more water than native forests, shrublands or grasslands, their land management effects on hydrology, such as floods or dry water season supplies (Bennett and Kruger 2015). This research lasted from 1935 to

[1] "In May 1910, South Africa celebrated the unification of two former Boer republics and two former British colonies, and the creation of a South African nation state. (…) of English-speaking and Dutch-speaking South Africans. […] the Union of South Africa [was] a self-governing dominion within the British Empire (Merrington 1997, p.1).

[2] Later than their Australian peers, who opened the first two universities in Australia in the 1850's (USyd 2022; UMelb 2021), and later than the Chilean ones, who opened the 'Universidad de Chile' in 1842 as the continuation of the Spanish colonial 'Universidad Real de San Felipe' founded in 1738 in (UCH 2022b), or other Spanish colonial universities in the country, such as the 'Pontificia Universidad de Santo Tomas de Aquino' founded in 1619 (until 1747), or the 'Universidad de San Miguel' de la Compañia de Jesús' in 1624 (until 1738), both present in Santiago de Chile (UDJ 2022).

[3] The first British Empire Forestry Conference was held in 1920 in London, England. The delegates included representatives from the United Kingdom, Canada, Australia, South Africa, New Zealand, India, Newfoundland, the Sudan, and most of the Crown Colonies (The British Empire Forestry Conference 1920; FAO 2022). Then, it was held in 1923 in Canada, 1928 in Australia, 1935 South Africa (Bennett and Kruger 2015). The fifth British Empire Forestry Conference was held in 1947 in London, where representatives from FAO also attended (FAO 2022).

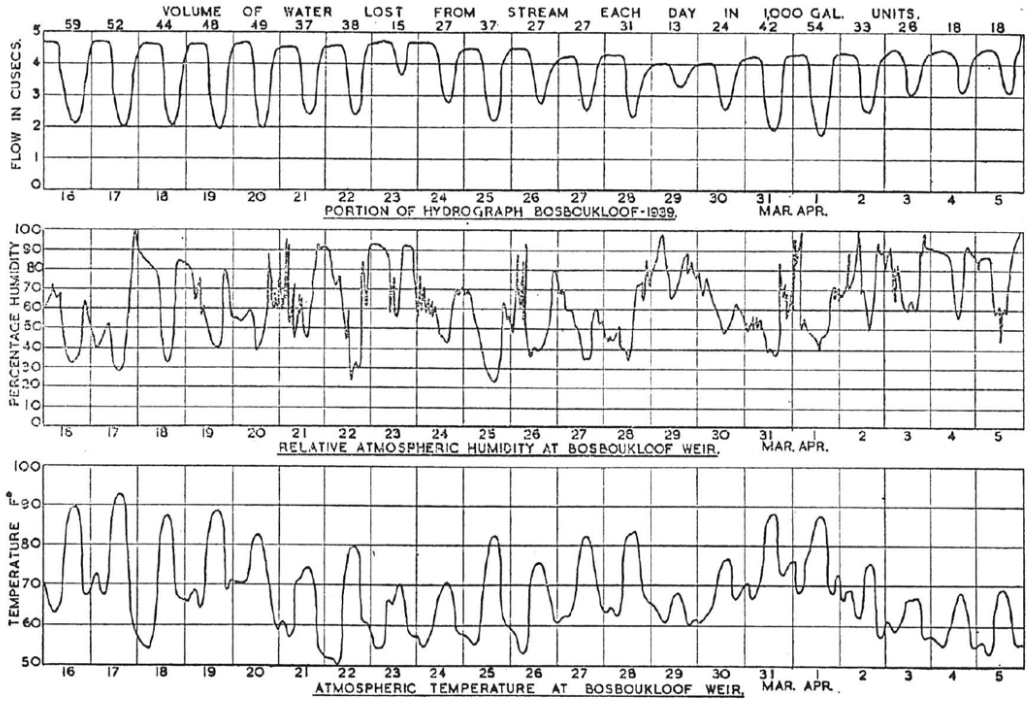
the mid-1990s (Bennett and Kruger 2013) and concerned 8 watersheds, 6 of which are still under monitoring (Chapman 2007), and it continues to this day.

From this solid study it was concluded that the introduced *Pinus* and *Eucalyptus* species reduce runoff compared to native fynbos and grasslands (Bennett and Kruger 2013). Gush's (2001) study would further extend this to other native South African forests, concluding that they do indeed transpire less and grow more slowly than introduced tree plantations of *Pinus* and *Eucalyptus* trees (Bennett and Kruger 2013). Furthermore, from this long-term study, diurnal-nocturnal flow fluctuations derived from vegetation transpiration were also observed and confirmed by groundwater level fluctuations measured in wells (figure 13) (Wicht 1945). Other major contributions derived from these monitored catchments (see Le Maitre and Versfeld 1997; Scott and Lesch 1997; Scott and Prinsloo 2008), are the Nänni' curves (Nänni 1970; Bren 2015), and many other relevant contributions (see Dye 1996). As general results, Chapman (2007) – researcher at the Council for Scientific and Industrial Research (CSIR)[4] – in his review of the history of the Jonkershoek Research Catchments, synthesizes:

> "*The onset of streamflow reductions was evident at ~5 years, and is strongly associated with plantation age, up to a peak reduction occurring at ~15 years, followed by a gentle decline in water use. A rule of thumb is 30-40 mm streamflow reduction per 10% of catchment planted, at peak water use*" (p.2).

[4] The South African's research and development organization.

Figure 13. Portion of hydrograph Bosboukloof, with associated temperatures and humidities, 1939.



Source: Wicht (1945). During the day the trees transpire water, and at night they reduce their water use.

South African studies and their discoveries were key in revolutionising scientific development in the field of forest hydrology because by 1930 the forest hydrology field in the world, was still a "*emergent field of science that lacked internationally agreed-upon concepts and methodologies*" (Bennett and Kruger 2015, p.166).

The results of South Africa's experimental watersheds also generated a series of institutional reforms, and forestry policy-regulations. Among them, in 1998 commercial afforestation in South Africa was regulated through the National Water Act, which adopted a preventive and remedial approach (Republic of South Africa 1998). This means, among other practical aspects, that forestry activity in South Africa is recognized as an activity that reduces water resources. Therefore, owners of forestry plantations must apply for permits to operate and pay a water license fee for their water use (Republic of South Africa 1998) and consider buffer protection zones recommendations between 6.3 and 50 meters to guarantee flows stability (Macfarlane et al., 2009). To assess the identification of sites suitable or unsuitable for afforestation, and to provide authorization to operate to the forestry agencies, the

Department of Water Affairs and Forestry adopted the ACRU model (see Gush et al. 2002). The ACRU model is a tool based on the data and scientific knowledge gained from the long-term forest hydrology studies in South Africa (Gush et al. 2002). This model represent diverse pluviometric and geographic forestry landscapes present in the country (Gush et al. 2002). Similarly, other programs were created, such as the South Africans Working for Water Programme (SAWW) (Van Wilgen and Wannenburgh 2016). The SAWW is an example of a large environmental intervention project, focusing on water security through the removal of invasive tree species such as some species of *Pinus, Eucalyptus*, and *Acacias*, that breed uncontrolled on South African lands. At the same time, the programme promotes the creation of local employment (Van Wilgen and Wannenburgh 2016).

The following section explores the Australian experience in the production and development of forest hydrology knowledge, and its practical applications in policy production in the country. With particular attention on *Eucalyptus* tree communities, from whose Australian and Oceania lands they originate.

4.1.3. Forest hydrology field and policy in Australia

The development of forest hydrology in Australia has common elements and distinctions with the South African or Chilean cases. In terms of the development of academic knowledge, in the 1850's the first universities were founded in Australia, i.e. earlier than its South African pairs. The University of Sydney in 1850 (USyd 2022), and the University of Melbourne in 1853 (UMelb 2021) were the first ones. Subsequently, in 1874, the University of Adelaide was the third to be founded (UAdel 2022). This university was the first Australian university to offer a degree in sciences (1882), to incorporate women in its classes (1881) (UAdel 2022), and to establish a forestry school course in 1911 (ACT Government 2021).

Similar to the South African case, the creation of an Australian's national forestry school was proposed in 1911, but it was only accepted in 1920 at the first British Empire Forestry Conference held in London (Commonwealth Forestry Association 1966). However, until recently, and unlike the South African and Chilean reality of forestry scientific schools that have a great diversity of institutions – the Australian Forestry School and its scientific training in Australia has been mostly centralised in a single institution for the whole country/continent –. This means that for decades the forestry training model was only possible in Australia through the Australian Forestry School (AFS).

The management of the Australian Forestry School has passed through the management of several institutions, which are reviewed below. In 1926, the Australian Forestry School (AFS) was founded and installed at the University of Adelaide (ACT Government 2021), as part of the Commonwealth Forestry Bureau and as the unique national scheme to train foresters at university level (Commonwealth Forestry Association 1966; Dargavel 2022). In 1927 the AFS was moved to Canberra under the control of the Commonwealth Forestry Bureau. It closed in 1964 (Commonwealth Forestry Association 1966; ACT Government 2021; Dargavel 2022). In 1960 the Commonwealth Government founded the Australian National University (ANU) in Canberra and the Australian Forestry School was re-established there in 1965 (Commonwealth Forestry Association 1966; ACT Government 2021; Dargavel 2022). The transfer of the AFS to the ANU was proposed as a solution to the dissatisfaction expressed by the academic circle of Australian universities, which had been seeking a link with the AFS for awarding degrees in forestry at university level for many years without success (Commonwealth Forestry Association 1966). In parallel with this change, the students of the Australian Forestry School "*also became eligible for a degree in Forestry from their home university in the case of the older State Universities*[5]" (Commonwealth Forestry Association 1966, p.28). Finally, in 1975, the CSIRO Yarralumla campus in Canberra was founded, and the Australian Forestry School was placed under its management and it was used as a forestry and bushfire research national facility (ACT Government 2021; YRA 2022). This is relevant, given that the current foresters and some of the main forest hydrologists of Australia have been formed and trained at CSIRO at some point in their career. Internally, the CSIRO structure has changed over time. But the current Division of Land and Water still holds some of the forest hydrology experts of Australia. Currently CSIRO also has three international Centres of Excellence, in the USA (Silicon Valley), France, and Chile (in Santiago and Antofagasta) (CSIRO 2022), where they provide scientific advice in multiple industrial areas, such as mining, fish farming, and forestry, among others.

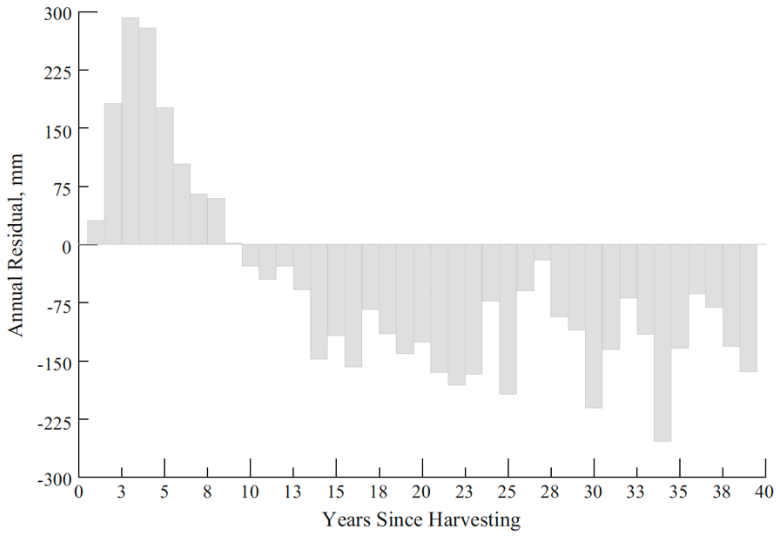
[5] At that time, at the Universities of Sydney, Melbourne, Adelaide, Tasmania, Western Australia, Queensland and New England (Commontwealth Forestry Association 1966).

It is in this context of scientific production and forestry development that Australia's forest hydrologists have been trained, making CSIRO today one of the most extensive centres of applied industrial research in the world. But how and why did forest hydrology studies begin in Australia? One of the most celebrated works that presents much of Australian history on the forest hydrology field is the book 'Forest Hydrology and Catchment Management. An Australian Perspective' written by Leon Bren (2015). He also was the researcher responsible for developing one of the most comprehensive – if not the most comprehensive – long-term study regarding forest hydrology dynamics of *Eucalyptus* and *Pinus* species in Australia.

According to Bren (2015), the first forest hydrology study of paired catchments was developed in Australia in the mid-1950's. There have been around 37 parried catchments studies since, analysing *Eucalyptus* native forests (the majority), plantations (mostly *Eucalyptus* and *Pinus*) and deforestation, as well as single catchments and plots studies. Most forest hydrology studies in Australia have been conducted in native *Eucalyptus* forests. From these studies, it has been concluded that tree age is important, as reported, for example, by studies in Australian mountain ash (*Eucalyptus regnans*) forests (figure 14):

> "*Australian mountain ash has a water yield which also depends on forest age. If the forest is logged then water yield increases, then declines, and then probably slowly increases to the pre-logging level. If the forest is burnt then water yield declines. Thinning may give modest increases in water yield for a few years*" (Bren 2015, p.117).

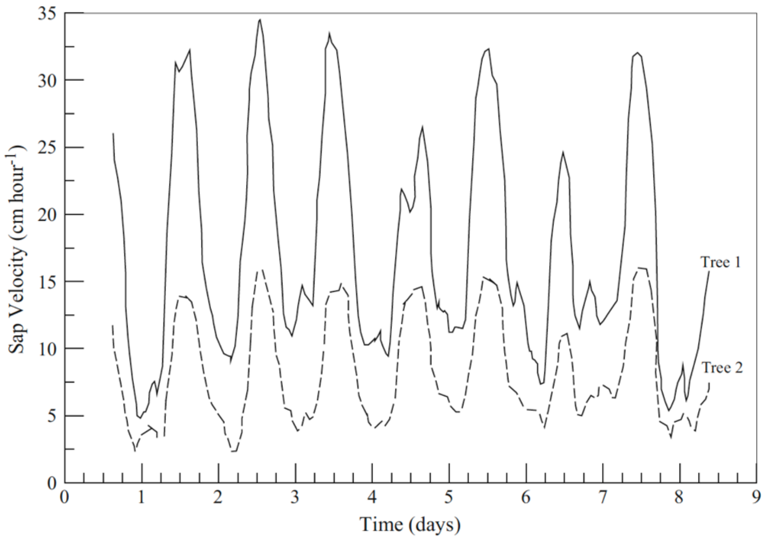
Figure 14. The annual change in flow by replacing an old-growth mountain ash forest with regrowth mountain ash.



Source: Bren (2015).

One of the best-known studies of forest hydrology in *Eucalyptus* forests has been developed by Kuczera (1987). It analysed streamflow data (1915-1981) in 7 watersheds with different land covers of over-mature, mature and re-growth Ash and Mixed *Eucalyptus* forests, and developed the well-known Kuczera curves. Carried out in the forests near the city of Melbourne where the main water sources that supply the city are located, it was the first study to show the relation between streamflow changes according to tree age changes. The study was initiated because, following recurrent forest fires, the Melbourne Water Agency noticed variations in flow rates, which put the city's water supply at risk (Kuczera 1987). After the recurrent fires, and observing this water reduction phenomenon over the years, the water agency wondered whether or not there was a relationship with the regrowth of forest cover (Kuczera 1987). After Kuczera's studies, several others followed, managed by the Melbourne Water, the Parks Victoria, and the Department Environment, Land, Water and Planning (DELWP) of Victorian State agencies (Melbourne Water 2021), and also in collaboration with the University of Melbourne. The knowledge produced by these studies showed that after fires affecting *Eucalyptus* forests, water quality is affected for months by sediment entrainment, and water reservoirs diminish as the trees recover and grow with time, which can take more than a century in these forests where trees can live for more than 300 years (Melbourne Water 2021). But, water reductions vary over time, and as trees get older they consume less water than younger trees (Melbourne Water 2021). With this knowledge, the city of Melbourne became one of the few cities in the world to protect its watersheds and forests, to safeguard the urban water service provision (Melbourne Water 2021), thus integrating scientific production in policy-making.

Figure 15. Variations in sap velocity as a function of time in two mountain ash (*Eucalyptus regnans*) trees 50 years old



Source: Bren (2015). Retrieved from Dunn GM, Connor DJ (1991) Management of transpiration loss and water yield in mountain ash. Faculty of Agriculture and Forestry, The University of Melbourne, Melbourne, 61 pp. The sap-flow technique allows to monitor how trees lift up water from the ground through their trunk (Bren 2015). By comparing figures 13 and 15 from different physical and temporal scales, it is possible to observe part of the internal physics of trees in their diurnal and nocturnal water use, and how these patterns are also expressed in the environment in which trees live and interact. Figure 15 also shows that between two trees of the same species and the same age, there may be variability in the intensity of their water use, but both show comparable behaviour at the same time.

But forest hydrology studies in Australia were also inspired and conducted by other environmental concerns. The Paired Catchment Project of Croppers Creek in Victoria is another famous Australian example. Consisting of three catchments: Ella Creek (113 ha), Clem Creek (46 ha) and Betsy Creek (44 ha), it was commissioned by the State agency of the Forest Commission-Victoria (Bren 2015). As Bren (2015, p.92) reports, the origins of the project were linked to discussions held by many downstream land owners in Australia, who argued that after the conversion of native *Eucalyptus* forests to *Pinus* plantations in the 1960's, they were affected by problems of "*excess flows causing flooding and erosion on downstream properties*". The Croppers Creek project has two monitoring periods: 1975-1987 and 1997 to the present. In 1980 the native *Eucalyptus* forests were cleared and planted with a *Pinus* plantation.

Then in 2006 the *Pinus* plantation was burnt as a forestry treatment. From this exceptional forest hydrology experience on the conversion from *Eucalyptus* forests to *Pinus* plantations in Australia, Bren summarizes the challenges and outcomes of this research experience as follow:

> "*Data has been used internationally in comparisons, and has contributed to studies on theoretical aspects of paired catchment research. Interestingly, the project has survived despite large changes in forestry administration over the years. The privatisation of plantation forestry has led to the separation of ownership and management of the "treated" and "control" catchment – something that could not have been envisaged at the time of project planning. Similarly, because of reorganisation of forestry agencies the project and the data have had about five different owners. Results from the project are given in many papers cited through this text. Briefly the results showed that there were real hydrologic effects of the conversion. Clearing led to a substantial increase in "runoff" (see Chap. 7) and had some short-term impacts on water quality. The water yield of the [Pinus] plantation always exceeded that of the native [Eucalyptus] forest it replaced, but as the plantation aged, the difference diminished*.". (Bren 2015, p.95).

The Murray Darlin Basin, in south-eastern Australia, is another famous and well-studied case. The Murray Darlin studies show a 'flip side' of forest hydrology phenomena, and notably of *Eucalyptus* or other native trees after their removal/harvesting, and subsequent replacement by other land uses that consume less water, such as grassland or agricultural land uses (usually with shorter roots). The Murray Darlin (MD) catchment demonstrated that the rising groundwater levels and the consequent salinisation problems – seawater intrusions –in the Murray Darlin Basin, were caused by land use change of native *Eucalyptus* and other tree species (deeper rooted) and their replacement by agricultural or grazing land (shorter rooted) (Pierce et al. 1993). Investigations in western (around Perth) and south-eastern Australia, also found the same results. With this knowledge, a series of projects were initiated in Australia to promote the planting of various *Eucalyptus* species to reduce the rising groundwater levels that were causing salinity problems in the country (Bari and Schofield 1991; Cocks 2003). By producing a series of agro-forestry management trials, these forest hydrology projects aimed to find forestry-agricultural management solutions to salinity problems (Bari and Schofield 1991; Cocks 2003). From these multiple studies, it was discovered that although different *Eucalyptus* tree species may be better adapted than others to saline water levels, the trees prefer to consume fresh groundwater (non-saline) if it is available (Holland et al. 2006; Benyon et al. 2006; Feikema et al. 2010). Thus, they enter in competition with agricultural productivity for water consumption (Eastham et al. 1994; Sanford et al. 2003). The Murray-Darlin basin is also an example of the Australian government's integrated catchment management plan, where the different States co-ordinate water allocation between different land and water users in the basin and through time, to prevent further salinity problems (Murray-Darling Basin Autority 2020a; 2020b).

The following section explores the Chilean case of forestry hydrology.

4.1.4. Forest hydrology in Chile

Although university education in the Republic of Chile began in 1842 with the founding of the Universidad de Chile (UCH 2022b), it was not until the mid-1950s that formal training in forestry sciences started at the university level with the foundation of the two main forestry schools of the country: the Universidad de Chile in the capital Santiago, and the Universidad Austral de Chile (UACH) in Valdivia city (Salas et al. 2016a).

At the Universidad de Chile, the forestry engineering school was founded in 1952 with FAO support, being the first forestry engineering career in Chile (Interview 19, November 2018). Later, in the 1960s, its Faculty of Forestry and Nature Conservation was founded (UCH 2022a). At its origin, the forestry school had a strong French influence, in the person of its first director Mr. Andre Cossigny, a water and forestry engineer from France, who previously worked in the north of Africa (Interview 19, November 2018).

The Universidad Austral de Chile (UACH), for its part, was founded in 1954 (UACH 2022c). It is located in the southern part of the country, in the heart of the Valdivian rainforest (temperate rainforest). The Faculty of Forestry Sciences and Natural Resources is one of the founding faculties of the UACH and is where in 1954, the forestry engineering degree was created (UACH 2022b). It was a pioneer in university training in forestry sciences in Chile and Latin America (UACH 2022b).

In the 1960s, other important forestry research institutions were created in the country. In 1961, INFOR was created as a FAO project. In 1965, it became an official institution of the Chilean government (Cabaña-Chavez et al. 2013). Subsequently, also in 1965 at the

Universidad de Concepcion, a technical degree in Forestry Technology was created in the city of Los Angeles[6], but the university only founded a Faculty of Forestry in 1992 in Concepcion (UdeC 2022a). The city of Concepcion is currently the administrative and operational heart of the forestry sector in Chile.

Regarding the educational backgrounds of the forestry academy in Chile, initially Chilean professors or experts with doctoral degrees in forestry had been trained at German universities, such as the University of Gottingen, the University of Freiburg, and the University of Munich (Salas et al. 2016a). Since the 1990s forestry scholars have been also trained at United States universities – mainly Colorado State University, Oregon State University, and North Carolina State University – and Spanish universities, such as Universidad Politécnica de Madrid, Universidad de Cordoba, and Universidad de Oviedo, among others (Salas et al. 2016a).

Regarding the forest hydrology studies as such, like in the previous countries and many others, forest hydrology studies have started in response to water and forest risk concerns. Thus, in Chile as well, since the 1850's and in the early years of the formation of the Chilean republic, there were already public concerns about the desertification of the country as a result of deforestation (Cabaña-Chavez et al. 2013). However, studies in forest hydrology at the university level started much later in Chile; in the 1960's, and initially as a response to the increasing risks caused by severe flooding in the country. In the early 1970s, the National Forest Corporation (CONAF) was created (1972) as a replacement for the previous forestry institution, the Corporation for Reforestation (COREF) (Cabaña-Chavez et al. 2013). Between 1968 and 1978, the Universidad de Chile, in collaboration with FAO and CONAF, started a forestry hydrology program which, with a remediation approach, sought to restore hydrologically altered areas in the country (Interview 19, November 2018). Cerro Las Minas in Punta Arenas, River San Jose in Arica, and Cerro Divisadero in Coyhaique, are examples of the National Forestry Development Strengthening (NFDS) Plan, that focused on flows (flooding) control in eroded watersheds (Interview 19, November 2018).
As for forest hydrology studies studying the effects between forests and water reductions, they started in Chile in the mid-1970's (Iroume and Soto 2013). Specifically, the first forest hydrology project identified as such in Chile dates back to 1970. This forest hydrology

[6] The University of Concepcion was founded in 1919 (UdeC 2022c).

project was created and implemented between 1970-72 by the Ministry of Agriculture of the Chilean state (Jones et al., 1975). The project had two objectives. The first was to establish a baseline of runoff and rainfall for water management (Jones et al., 1975). According to the authors, the data collected could have been used to develop predictive equations for runoff volumes and peak flows for small dams and reservoirs design. Likewise, the inspection of flow-runoff and land-use relationships may help to identify land-use patterns that are associated with the problems of water reductions, erosion and decreasing soil productivity among others in the country (Jones et al., 1975). The second objective was to assess the effects of land use on runoff (Jones et al., 1975). This second objective dealt with the practice of planting forestry species and the practice of clear-cutting, widely used in Chile and already identified as causing serious problems on runoff in certain areas. To this end, three watersheds with similar land use histories, located in Junquillar, coastal mountain range in the Maule region and whose waters flow into the sea, were instrumented (Jones et al., 1975). The Piragua basin (control), and the La Puente Nos 1 and La Puente Nos 2 basins, which last two were burned to evaluate their native-shrub land use/burn effects on runoff. All three catchments had land uses of native shrubs and small trees, and very few grasses but were characterised by a high presence for livestock grazing (Jones et al., 1975). Sediment concentration in the catchments was high in terms of water quality (Jones et al., 1975). The La Piragua control basin had a fire that burned half of its area in the summer (dry season) of 1971-72 (Jones et al., 1975). Data analysis of the three catchments resulted in an annual runoff relatively unaffected by the application of fire. However, they identified that "*peak runoff and sediment loads, however, are more sensitive to both climatic* [rainfall storm events] *and treatment changes, and may be more important in a region of high rainfall*" (Jones et al., 1975, p.16). Subsequently, in 1973 the country underwent a dramatic political change following a military coup d'état (see more details in the following section 4.2 Chilean forestry history) and this first forestry hydrology project in Chile was not reviewed or continued.

Subsequently, and after the extensive introduction of new private forestry plantations of *Pinus* and *Eucalyptus* tree species in the country promoted by D.L. 704 implemented in 1974, the forest hydrology studies in forestry plantations began under Professor Dr. Anton Huber and his then student Carlos Oyarzun – now Professor – at the Universidad Austral de Chile. Professor Huber, was the first to carry out forest hydrology studies in forestry plantations, from the fields of the CMPC company in southern Chile (Interview 2, November 2018). Many of these studies are published in international journals (e.g. Huber et al. 1998; Oyarzún and Huber 1999; Huber and Iroumé 2001; Huber et al. 2010). They show general dynamics of evapotranspiration, interception, etc. of *Pinus* and *Eucalyptus* plantations, consistent with previous findings from South Africa and Australia, among others. Subsequently, Prof. Huber started a close collaboration with Dr. Andrés Iroume at the same Universidad Austral de Chile, who – after Prof. Huber's retirement – continues until today to carry out research on CMPC's forestry plantation lands (Interview 2, November 2018). Additionally, at the same Universidad Austral de Chile and in the city of Valdivia, other relevant researchers and academics, such as Luis Otero and the professor Antonio Lara, developed pioneering contributions to the Chilean forest hydrology field related to the cadastre and measurement of native forests (Interview 20, December 2018; Interview 29, November 2018). In this respect, some of the major contributions to the origin and evolution of forest hydrology in Chile have come from the Universidad Austral de Chile, in the city of Valdivia.

During the 1980's, at the Universidad de Chile, there was for some years a watershed management course directed by Professor Dr. Manuel Contreras Salas, who had studied forest hydrology at CATIE in Costa Rica and in Seattle, USA. But later, this watershed management course was transformed because the American approach to the study of large 'unpopulated' catchments was too complex to adapt to the Chilean reality, and this course began to include human management in its approach (Interview 19, November 2018).

In 1981, the Universidad de Talca was also founded (UTalca 2022b). The Universidad de Talca (UTalca), is the newest of the four traditional universities involved in forest hydrology studies in Chile. The forestry engineering career at Universidad de Talca was taught between 1981 and 2020, but this career was closed in 2020 due to low scientific productivity (UTalca 2020). In the early days, an academic from this faculty also worked on hydrological monitoring projects for the forestry company Masisa, CORMA forest hydrology reports, among others.

From the 1980s to the mid-1990s, several other private and public forestry schools were opened in the country, leading to an oversupply of forestry engineers (Salas et al. 2016a). This oversupply was especially visible at the beginning of 2010, when many universities closed their forestry degrees, due to the lack of a job market in forestry and, consequently, a decrease in the number of new undergraduate student enrolments. Universidad de Talca, is a late example of this. However, traditional forestry schools still remain in the country. Although, not all universities have forestry faculties or have developed forest hydrology studies as such, there are two main universities that have a long tradition in forest hydrology studies and contributions (publications, conferences, doctoral degrees, undergraduate degrees, courses, networks, among others) in Chile. These are the Universidad Austral de Chile (Valdivia), and the Universidad de Concepcion (Concepcion, and recently in Chillan too).

On the part of the Chilean state forestry agencies, in the mid-1980s the State institution of CONAF contacted – at least – one international forest hydrology expert, who posteriorly contributed to designing a new forest hydrology project in diverse watersheds of the country to monitor and model streamflow in forest plantations and natural forests of the country. The project SHETRAN implemented between 1994 and 1999, was a technology transfer project, focused on setting up, instrumenting watersheds and training CONAF professionals for the monitoring and modelling of forest hydrology watersheds with the SHETRAN software (Personal communication 26, January 2021). The project started due to the water reduction concerns that forest plantations were facing in the country (Interview 33, November 2018). SHETRAN sought to be relevant to CONAF's forestry management decisions (Personal communication 26, January 2021). This was an ambitious project that was thought as a pilot and model project in long-term forest hydrology watershed research for the South American continent, as it is expressed in the conclusions of one of the articles of the project:

> "*Above all, the application of SHETRAN in Chile provides an exciting opportunity to demonstrate the relevance of advanced technological models to minimize the environmental impacts of forestry industry and soil and water resource management activities. Its transfer will provide CONAF with the following benefits: 1) Ability to predict the impacts of soil management activities on flooding, water production on flooding, water yield, water table levels, soil erosion and sediment production; 2) Improved efficiency and reliability of decision making in watershed development by incorporating environmental protection. The transfer of SHETRAN to Chile can also be seen as a pilot study for further implementation in other Latin American countries*" (Bathurst et al. 1998, p.11).

The SHETRAN project (see figure 16) was developed between CONAF and the University of Newcastle (UK), to study land use changes and water interactions of floods, reductions, and transport sediments, in 4 watersheds with *Pinus radiata* plantations – La Reina y Minas del Prado watersheds – and native forest – Los Almendros watershed – as a plan for water security for the cities (Bathurst et al. 1998). It was funded – at that time – by the United Kingdom government's Department for International Development (Personal communication 26, January 2021). As the SHETRAN project approached completion (1999), in 1998, experts from the University of Newcastle and CONAF reported the lessons learned in its summary:

> "*The simulations indicated potential flood damage during the early years of the plantation cycle, while later years are characterized by a decline in water availability. These results are comparable to field observations recorded in other studies*" (Bathurst et al. 1998, p.1).

The relevance of the SHETRAN project is enormous for the country's forest hydrology. By the time when professor Iroume[7] closed La Reina catchment – located on the southern side of the lower section of the Bueno River basin, X Region of Los Lagos – about a year or so ago, it had become Chile's longest-running forest research catchment (Personal communication 26, January 2021). However, with successive administrations of CONAF, the other SHETRAN catchments fell into disuse and, CONAF subsequently made no further use of the SHETRAN model in its forestry management decisions as the project originally intended (Personal communication 26, January 2021).

[7] Professor Dr. Iroume was not part of the SHETRAN project, but he collaborated closely on a voluntary basis, and when the project ended in 1999, he took over maintenance and monitoring of the watershed (email communication, January 2021).

Figure 16. Map showing the location of the SHETRAN project's experimental catchments

Source: Bathurst et al. (1998).

Parallel to SHETRAN, between 1993 and 1999 CONAF together with the Japan International Cooperation Agency (JICA), developed a project for erosion control and watershed afforestation in the semi-arid zone of the country (CONAF-JICA 1999). The project consisted of 8 soil loss plots located in Alto Loica, San Pedro de Melipilla, RM (Vargas 1998). In the plots, different soil conservation techniques were evaluated, among which: infiltration ditches, walls, dissipaters and biological conservation techniques with the aim of favouring the germination and growth of vegetation cover, such as pastures and exotic forest plantations (Vargas 1998). The project also produced an erosion control treatment manual in 1996 (Tokugawa 1996).

At the university level for its part, during the 1990's the Forestry Science faculty of the University of Chile reports that the constant funding for research projects was a repetitive challenge, which added to the bad working experiences with the project manager of CONAF – JICA. As a result, research in forest hydrology did not to continue actively between these two institutions (Interview 19, November 2018). To overcome the challenges of sustaining long-term studies in Chile, several academics in the country have called for "*establishing a national network of sites for long-term ecosystem studies*" (...) "*efforts must also be made to secure funding for the development of a solid national network from the outset, which can link up with networks in other countries*".

Arguing that "*research at long-term sites will provide crucial information for public and private decision-makers, supporting the development of laws and regulations*" (Lara et al. 2010, p.617).

Despite this funding challenge, during the 1990s and 2000s further studies in forest hydrology emerged in the country. Several studies from academia analyse the reduction of water flows and exotic *Eucalyptus*, *Pinu*s plantations, native forests, agriculture or grasslands (see for instance Gayoso and Iroume 1995; Iroume 1997; Huber et al. 1998; Oyarzún and Huber 1999; Huber and Iroume 2001; Pizarro et al. 2006; Little et al. 2009; Lara et al. 2009; Huber et al. 2010; Stehr et al. 2010; Iroumé and Palacios 2013; Oyarzun et al. 2015; Aguayo et al. 2016; Soto-Schönherr and Iroumé 2016; Hervé-Fernández et al. 2016; Alvarez-Garreton et al. 2019).

Since the late 1990s, forestry companies started to undertake research in Chile as well. Primarily oriented to the technological development for the forestry production increase (Arze & Svensson 1997), Arauco S.A. created in the 1990s a subsidiary company called Bioforest S.A. (Arze & Svensson, 1997). They carry out a wide range of research, including the increase of forest productivity through selection and breeding of superior genetic varieties of eucalyptus (Rubilar and Valenzuela 2011). And, since 2008, the two main forestry companies in the country – Arauco S.A. and CMPC S.A. – started to undertake their own long-term forest hydrology research studies (Balocchi et al. 2021; Iroumé et al. 2021).

Despite the wide existence and diverse background of forest hydrology in the country (Interview 23, December 2018), in Chile there has been a constant and controversial debate about the effects between forests and waters (CR2 2021). Given that the Chilean case is the main case study of this research, the scientific production, its circulation and the application of forest hydrology knowledge in forestry policy-making, is analysed in greater detail in chapters 6 and 7. The following sections provide the historical, geographical and legal-institutional context of the forestry and water sectors in Chile, which contributes to the analysis of the Chilean case.

4.2. Chilean forestry history

This section focuses specifically on Chile. Section 4.2.1 introduces the Chilean actors present in the results chapters 6 and 7 of this research. Section 4.2.2 addresses the historical context of the development of the forestry sector in the country. It deals with the end of the colonial period of the Spanish Empire (end of 1700s), the independence and foundation of the State of Chile (1810), and the various milestones in the evolution of the forestry industry and sector up to the 1990's. Section 4.2.3 presents an overview of the location, geography and environmental conditions of the forest and forestry region in Chile. Section 4.2.4 focus on presenting current characteristics of the forestry sector economy in Chile (2000-2022). Finally, section 4.2.5 presents current policy related to forest hydrology in the country.

4.2.1. Overview of the Chilean forest hydrology actors and institutions

This section provides a broad overview of the Chilean actors present in the result chapters 6 and 7 of this research. This clarification is made because some producers of forest hydrology science in Chile (chapter 6), were also part of the reduced group of forest hydrology experts that participated in the creation of soil and water protection measures in the production policy of the Forest Plantation Protocol in Chile (chapter 7). In addition, some of these actors have a long history and presence in the country. More in-depth information on these actors is provided in the following sections of chapter 4.2, and in chapters 6 (social structure of actors in the field of forest hydrology) and 7 (policy actors in forest hydrology discussions).

4.2.1.1. Forest hydrologists: scientific knowledge producers

Currently in Chile, there are three main groups of experts that have worked or are working on the production of forest hydrology in the country: (i) academics based at universities, (ii) forestry State institutions, (iii) forestry private companies.

First, academic actors – until 2020, when the University of Talca closed its forestry faculty and career – are mainly represented by 4 universities: Universidad Austral de Chile, Universidad de Concepcion, Universidad de Talca, and Universidad de Chile. Second, forestry governmental institutions composed by the National Forest Corporation (CONAF), and the National Forestry Institute (INFOR), both of which depend on the Ministry of Agriculture of the Government of Chile. And third, private forestry companies. Although, historically, several forestry companies have conducted hydrological monitoring, such as Forestal Los Lagos (Fresia, Chile) (Interview 28, January 2019), Forestal Masisa SA., among others, currently, Forestal Arauco SA. (Bioforest) and Forestal CMPC SA (Mininco) are the two main forestry companies and its subsidiaries conducting research on forest hydrology in Chile.

More in-depth information on these actors is given in chapter 6, where the social structure, production and circulation of knowledge in the Chilean forest hydrology field is analysed.

4.2.1.2. Forest Plantation Protocol: scientists and institutions involved

Four main stakeholder groups were involved in the governance process of the Forest Plantation Protocol (FPP), especially in the soil and water experts commission (SWEC) and the discussions hold about this SWEC. First, governmental actors, represented by CONAF and INFOR. Second, forestry companies, represented by the Chilean Timber Corporation (CORMA), and Forestal CMPC SA (Mininco). Third, some university-based academics from Universidad de Talca, Universidad de Chile, and Universidad Austral de Chile. Fourth, the Peasant Farmers' Movement (MUCECH) as a civil society representative.

Later, during the FPP process, other actors from government, business, academia and civil society organisations will also participate in the FPP plenary discussions. Further details on these actors and their role in the protocol process are presented in chapter 7, where the circulation and application of forest hydrology knowledge in policy-making is analysed.

4.2.2. Historical background of the Chilean forestry sector

Presenting a historical review of the Chilean forestry history is relevant as part of this thesis, given that "*the Chilean forest industry has been a century in the making*" (Clapp 1995, p.274; Otero 2006; Cabaña-Chavez et al. 2013). According to Otero (2006) in his book "The footprint of fire. History of native forests. Settlement and changes in the landscape of southern Chile", during the Spanish colonial period the forestry sector in Chile was characterized by the development of an artisanal timber industry for the construction of furniture, shipyards, shipbuilding and defence of the Spanish crown. Also, the use of wood for mining, foundries, tanneries and wood for domestic charcoal was developed (Otero 2006). A special role was played by the *Fitzroya cupressoides*, millenary trees that can live more than 3.500 years (Frene and Nuñez 2010a; Otero 2006), which came to be used in Chile as a 'real de alerce' or 'real de madera' coin (Otero 2006). Other original forests, such as temperate forests that have life cycles between 300 and 500 years, and *Araucaria araucana* trees that can live up to 1000 years were also used (Otero 2006). Despite this, the colonial period was not a period of deforestation (Otero 2006), and wider deforestation of the Chilean forests only began shortly after Chile's Independence (Otero 2006; Cabaña-Chavez et al. 2013).

Upon the independence from the Spanish Crown in 1818, the newly founded Chilean State began a process of occupation of the southern lands – mainly inhabited by autochthonous communities – with the aim of clearing the forested areas and transforming them into productive agricultural lands, as well as to consolidate its national sovereignty (Otero 2006). To this end, the Chilean State developed a colonisation programme in five phases between 1850 and 1950 (Otero 2006), by inviting German, Swiss, Belgian, French and Spanish citizens, to work the southern lands through a system of concessions (Otero 2006; Dufey 2017). With this selective immigration, the Chilean State sought also to "*incorporate with them the new technologies that were emerging in Europe*" (Otero 2006, p.77).

According to Cabaña-Chavez et al. (2013) in their book "CONAF, its history and role in the forestry and environmental development of Chile", at the beginning of the 19th century, forest harvesting was carried out both for mining uses, and agriculture and livestock (Cabaña-Chavez et al. 2013). It was in this period that deforestation rates intensified. This further increased in the second half of the 19th century, with the opening of new wheat markets (Cabaña-Chavez et al. 2013) when Chile became 'the wheat granary of America' (Otero 2006). Also, the demand from other domestic industries such as smelting, leather and cider were supplied with wood from native forests (Otero 2006). In the process of agricultural expansion, the tool of fire was widely used to clear more than 300 thousand hectares of native forest (Otero 2006). The excessive use of fire, combined with intensive and inadequate agricultural practices led to a rapid depletion of the soil (Cabaña-Chavez et al. 2013).

Already in 1830, 1840 and 1855, there were public concerns about the deforestation, erosion and desertification problems touching much of the landscape of the Chilean republic, and there were opposite views on the responsibility of mining and agriculture in this (Cabaña-Chavez et al. 2013). As Cabaña-Chavez et al. (2013) point out, in 1855 the Chilean citizen Benjamin Vicuña Mackenna called for the creation of a Forestry Code to regulate deforestation in the country. It was in this context that the idea of reforestation gained ground in the country's public opinion circles, which called for more energetic action on the part of the Chilean State (Cabaña-Chavez et al. 2013). In this way, the Chilean State developed a series of measures. In 1879 the first legislative decree on the 'Fiscal Forest Reserve' was promulgated with the aim of conserving native forests, while the first protected area in Chile was created in 1907, the Malleco Forest Reserve (Otero 2006; Cabaña-Chavez et al. 2013). Further on, in this context, in 1889 the Chilean State hired the German scientist Federico Albert as professor in the Department of Natural Sciences of the Museum of Natural History. His work promoted a series of botanical and zoological trials at the Chilean Ministry of Industry (Cabaña-Chavez et al. 2013), as he actively worked to develop a policy for conservation and protection of forests and the recovery of forest soils (Cabaña-Chavez et al. 2013; González-Hidalgo and Zografos 2017) (see figures 17).

Figure 17. Lota Alto, Biobio VIII Region, 1860.

Source: Collection of the National Historical Museum of Chile. Imprenta y Librería del Mercurio, 1864 p.150. BN code: MC0012629. (Martin Palma, Museo Histórico Nacional 1860).

Moreover, the Chilean Republic was in the process of expanding its markets, industrialising and internationalising its economy, which had been developing rapidly since the 1850's (Otero 2006). Its strategic position in the Pacific[8], coupled with other international events,

[8] Chile controlled the Strait of the Magallanes, which was the only sea route existing at the time to connect the Atlantic and Pacific Oceans. The Panama Canal was not built until 1914 (CEPAL 2014).

such as the California Gold Rush, integrated Chilean ports into the global commodity route between the Pacific and Atlantic oceans through the Magallanes channel (Otero 2006). It was in this context – of increasing national development, global circulation, wood demand for mining, agricultural expansion, and colonization of southern Chile – that the first seeds of North American *Pinus* and Australian *Eucalyptus* trees arrived in Chile, and its first plantations were established between Concepcion and Lota, in the VIII region. These facts were a conjunction of multiple independent and interconnected events. The Chilean citizens, new European immigrants and their descendants were at the forefront of these events, circulating – sometimes by accident – the first seeds of the trees from Europe and elsewhere.

According to Otero (2006), the introduction of the first *Pinus radiata* in Chile happened by mistake. It would have been a farmer from the Concepcion area, who ordered seeds from France, and who by mistake, received *Pinus radiata* seeds from Monterey, California. The mistake was discovered in 1886, when the shape of the trees was not as expected, their growth rates were double, and with a great capacity for adaptation (Otero 2006). Afterwards, in 1890 Arturo Junge, a Chilean of German origin, was the first to establish a nursery and trials of *Pinus radiata* – also known as Monterrey pine – near to the city of Concepcion, after received the seeds from Germany by ship (Krebs 1973, in Clapp 1995). In this way, simple Chilean citizens, European immigrants and their descendants, played a key role in the first introductions and growth of *Pinus radiata* plantations in the country.

Later, in Santiago, the German scientist, Federico Albert, hired by the Chilean State in 1889 started the botanical and zoological trials of the Ministry of Industry (Cabaña-Chavez et al. 2013), which among other things, culminated in the first plantations at the Compañia Carbonifera Lota, in Lota (Arze & Svensson, 1997), in 1907 (Otero 2006).

> "*Among initiatives that made this decision possible was the pioneer work within botanical and zoological determination of species done by the German born researcher Federico Albert, which resulted in, among other things, the first plantations of Pinus radiata at Compañia Carbonifera Lota. The rapid growth of Pinus radiata attracted much attention, and at the end of the thirties yearly plantations of the species amounted to approximately 7000 hectares*" (Arze & Svensson, 1997, p.189).

As the trials of *Pinus* species developed by farmers during the mid-1880's in the Concepcion area – near Lota – proved to be successful and fast growing, this prompted the Cousiño family – owners of the Lota mines – to establish plantations on their land (Clapp 1995). Compañia Carbonifera Lota prefered *Eucalyptus* over *Pinus tree* species, as they proved to be more resistant for the construction of the Lota mine shafts (Clapp 1995; Otero 2006) (see figures 18 and 19).

> "*Trials of the new species proved successful in the Concepcion area, and Matias Cousiño, owner of the Lota coal mines south of Concepcion, established the first plantations. Mine shafts required large volumes of timber, which originally came from the native forests on the hills overlooking the mines. Worried about future timber supplies as the coastal forest neared exhaustion, Cousiño planted pine and eucalyptus on the company's cleared land*" (Clapp 1995, p.278).

The growing demand for timber from coal mining started the deforestation of the Coastal Mountains (Otero 2006). As the native forests surrounding the mine began to be depleted and given their slow growth rates, the Cousiño family looked for alternatives to supply the mine without having to increase the cost of transport to more distant places (Clapp 1995; Otero 2006). By 1915, the company already had 34.339 hectares of *Eucalyptus globulus*, *Pinus radiata*, Maritime pine and various cypresses, constituting the largest plantations in South America (Otero 2006). Similar to the processes of the North American *Pinus* and the Australian *Eucalyptus* species introduced in South Africa (Bennett and Kruger 2015), in Chile the growing arrivals of the first exotic trees plantations were also seen by some, as a solution to the depletion of local forests and the need for a constant and rapid supply of timber for mining activities.

Figure 18. Foresters working in *Pinus* tree plantation in Lota, BioBio VII Region.

Source: Lota, su cultura e historia (2019). Photographer and year unknown.

Figure 19. *Eucalyptus* tree plantations in Lota, BioBio VII Region.

Source: Lota, su cultura e historia (2019). Photographer and year unknown.

With the collective knowledge developed and accumulated through this multiple conjunction of independent and interconnected forestry events, the Chilean State embarked on the new enterprise of building a forestry industry in the country. In 1911 the first General Inspectorate for Forestry, Fisheries and Hunting institution was created (Otero 2006), and in 1931, the Chilean State formally encouraged forestry development and plantations in the country, through the creation of the Ministry of Lands and Colonization and the first Forestry Law of 1931 (Supreme Decree n 4.363) (Cabaña-Chavez et al. 2013). "W*hen direct State promotion began in 1931, pine already grew on 25.000 hectares*" (Clapp 1995, p.278).

The promotion of industrial forestry development by the Chilean State was linked to the economic crisis of 1929, when the value of copper fell, strongly affecting the national economy (Clapp 1995), and as an attempt to strengthen the country's economy through asset diversification. The crisis of the export model broke out in Chile in the 1930's, preceded by the impossibility of continuing the production of wheat in degraded soils and by the saltpetre (salitre) crisis (Otero 2006). This led Chile in the early 1940's to develop a new economic model, known by CEPAL as 'import substitution', which promoted the industrialisation of the country (Otero 2006). To this end, in 1938 the State created the Development Corporation (CORFO) within the Ministry of Economy, with the role of promoting the development of forest-based industries, providing financing to private industrialists, guaranteeing markets and acting as a broker (Clapp 1995). By the end of 1943, Chile already had an area of 143.540 hectares of plantations, as reported by the Haig Mission (Otero 2006), and had a first notable peak in its production in 1945 (Clapp 1995). At that time, "*Chile's concentration on domestic production was due in part to the limited world market. Transportation costs were high, and many countries had not yet exhausted their native forests, instead relying on lumber available locally*" (Clapp 1995, p.279).

In 1944 the Chilean State, through CORFO, sought advice on forestry knowledge from the Forest Service of the United States Department of Agriculture, to carry out the first forestry cadastre of the country and to promote the industrial forestry and timber expansion with the creation of forestry production plants (Otero 2006). In this process of promoting the forestry development and expansion of plantations in Chile, other international organizations were also involved. For instance, in 1949, the Economic Commission for Latin America and the Caribbean (CEPAL in Spanish) of the United Nations, strongly urged governments to include forestry plantations in their economic and soil conservation plans (Cabaña-Chavez et al. 2013). Subsequently, in 1951 Chile approached the United Nations Food and Agriculture Organization (FAO), to modernize the Chilean forestry industry (Cabaña-Chavez et al. 2013). The late 1950's also saw the development of the Chillan Plan, in collaboration with the United States Alliance for Progress, to promote the forestry industry and plantations (Otero 2006). "*The Chillan Seed Centre was created, as well as forest management trials in the Malleco Forest Reserve*" (Otero 2006, p.138). As another important milestone, it was as part of this forestry industrial development strategy that in 1952 and 1954 the Chilean State created two forestry schools at the Universidad de Chile and Universidad Austral de Chile (Otero 2006), as described earlier in section 4.1.4.

In addition, in 1952 the Chilean Timber Corporation (CORMA) was founded as the entity that brings together the private entrepreneurs of the forestry sector, and which since its creation had an active participation in the promotion of economic policies to the forestry sector (Otero 2006) (see figure 20).

> "*Initially,* [CORMA] *was led by representatives of companies that exploited the native forest, such as Ralco, Bima and Neltume, but later plantation companies, such as Maderas Cholguan, Carbonifera Lota, Compania Manufacturera de Papeles y Cartones (CMPC) and others, joined in force*" (Otero 2006, p.139).

In 1956, in a joint venture, the Chilean State and 44.000 private entrepreneurs founded Industrias Forestales, S. A. (INFORSA) (Clapp 1995). Between 1958 and 1964 CORFO and FAO worked together, to develop the national forestry and industrial strategy (Cabaña-Chavez et al. 2013), which culminated in the creation of the National Forestry Institute (INFOR) in 1965 (Otero 2006). In 1959, the private company CMPC started to operate the first pulp mill plant, located in Laja, southern Chile, through credits from the World Bank (Arze & Svensson, 1997). Subsequently, "*in 1960*[9] *a tsunami flooded much of the southern coast, and a particle board factory, Maderas y Sinteticos, S. A. (MASISA), opened in Valdivia to supply the increased demand for building materials*" (Clapp 1995, p.280).

[9] The mega-earthquake and tsunami of 22 May 1960, with its epicentre in the city of Valdivia, was the largest earthquake ever recorded with seismic sensors in the world. It measured 9.5 of magnitude and lasted for more than 15 minutes (Cisternas et al. 2005).

Figure 20. Logging of native forests in Curacautín, Araucania IX Region, 1960.

Source: Collection of the National Historical Museum of Chile. Photographic Archives; PF-000124. BN Code: MC0027310. (Rey B., B., Museo Histórico Nacional 1960).

According to CORFO, in 1965 there were already 350.000 hectares of plantations, mainly of *Pinus radiata* (Otero 2006). In 1965, Chile also started the first national afforestation programme financed by the Inter-American Development Bank to further boost afforestation with the goal of 5 million hectares over 35 years (Cabaña-Chavez et al. 2013). The Chilean State considered that plantations, especially of *Pinus* trees, were one of the best solutions to promote soil conservation and the development of Chile (Cabaña-Chavez et al. 2013). This decision was not a Chilean exception, since the worldwide promotion of forest plantations in developing countries has also been linked with international institutions, and mainly with the FAO (Doughty 2000).

In 1967 and 1969 respectively, CORFO built two further pulp mills. First, the Celulosa Arauco SA., in Arauco, as a joint venture with the British firm Parsons and Whittemore (Clapp 1995; Arze & Svensson, 1997; Cabaña-Chavez et al. 2013). Second, the Celulosa Constitucion SA, in Constitution, with funding from the Agency for International Development (AID) (Cabaña-Chavez et al. 2013) and the French firm Creusot-Loire (Arze & Svensson, 1997). In 1970, the State was the main forestry producer, with 90% of the total planted area (Cabaña-Chavez et al. 2013). Subsequently, in 1972 CORFO acquired the shares of its partners in the pulp mills of Arauco S.A. and Constitucion S.A. (Arze & Svensson, 1997).

In 1973, Chile experienced a coup d'état by the army (Frene and Nuñez 2010). The Chilean economy and its sectors took a drastic turn into neo-liberalism, and inspired by the 'Chicago Boys' model (Budds 2013) the country's economy was transformed. Shifting from a model based on industrialisation, to a model based on 'import substitution', with a wide range of natural resource-based industries oriented towards international exports (Clapp 1995). During this transformation, by 1994, 437 of 507 State enterprises were privatized (Clapp 1995). The forestry sector was one of the first to transform quickly. In 1974 and 1976, the Celulosa Arauco SA., and Celulosa Constitucion SA. pulp mills were sold, and in 1979 the private company COPEC (CMPC group), and the private company Celulosa Arauco y Constitucion (Arauco group) were founded as a result of these sales (Arze & Svensson, 1997). According to Clapp (1995), the Italian group Compañía Manufacturera de Papeles y Cartones (CMPC) had acquired minority shares in the Cholguan forestry complex in 1950, and during the period of State auctions, their share went from 19.2% in 1970 to 65% in 1978. CONAF also sold land and plantations, nurseries, equipment, among others (Clapp

1995). The dissociation of CONAF's productive work in the forestry sector was crystallised with the sale of all the seed production nurseries to privates investors in 1978 (Cabaña-Chavez et al. 2013). Between 1985 and 1989, the military junta further deepened the privatisation process in the country, and 30 large State industries were sold to private investors, with losses in the millions due to the low sales prices negotiated (Frene and Nuñez 2010a). By 1987 three of the four pulp plants in operation which owed their existence to the State-owned CORFO had been sold off (Clapp 1995).

The military government strongly promoted plantations of *Pinus* and *Eucalyptus* by creating the Forestry Development Law of 1974 (DL701) (Frene and Nuñez 2010a). CORMA played an active role in its promotion (Otero 2006), as did Julio Ponce Lerou, son-in-law of General Pinochet (Interview 19, November 2018), who between 1974 and 1978 was the appointed director of CONAF (Cabaña-Chavez et al. 2013). The Decree 701, subsidized 75% of planting costs for more than 20 years, ensures the land tax exemption, and the impossibility to expropriate land categorised as suitable for forestry[10] (Cabaña-Chavez et al. 2013). "*Eighty per cent of subsidy payments went to Chile's three largest forest companies, which shifted to private capital markets*" (González-Hidalgo and Zografos 2017, p.65). Additionally, with D.L.701, various complementary administrative actions were reducing the role of the State and transferring the execution of productive forest activities to the private sector (Rossi 2005).

By the 1990s, Arauco and CMPC (Mininco) became the two main companies managing Chile's forestry sector, pulp mills and sawnwood production, and were among the 50 largest forest companies in the world (Arze and Svensson 1997b; Epstein et al. 1999). These companies control the total forest production chain, which ranges from the planting of forest plantations, to industrial factories for the production of pulp for paper and tissue, wood sawmills for the production of furniture and various wood articles (Meneses and Guzman 2000). In this way the Chilean forestry sector gained an international reputation and was often mentioned as an example of a 'miracle' or a 'success story' (Arze and Svensson 1997b; Clapp 1998), as "*in a generation Chile has created one of the world's most competitive forest resources*" (Clapp 1995, p.273).

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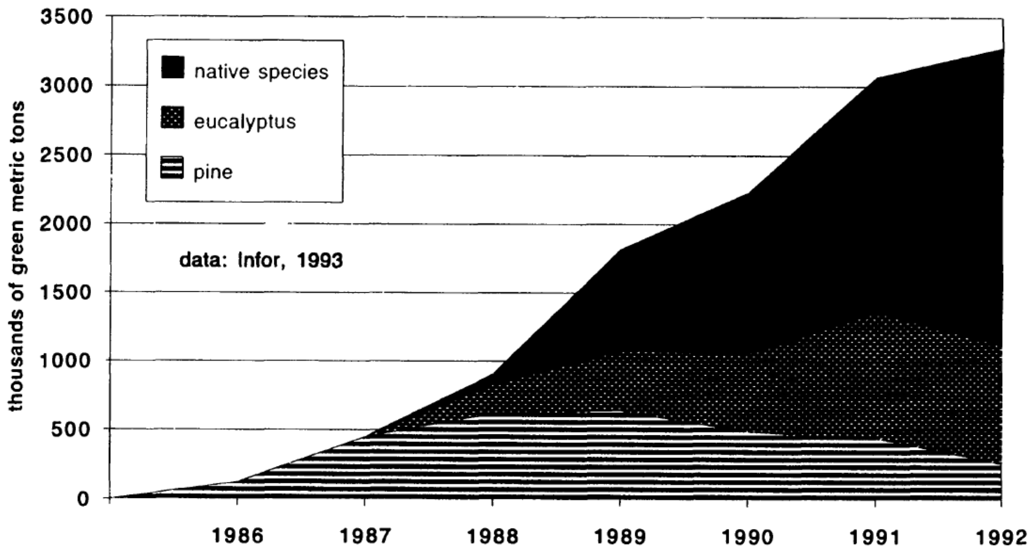
[10] This was done because of the fear of private shareholders of being expropriated by the State, given that in the Second Agrarian Reform implemented in 1970, no expropriation of native forest lands or forest plantations took place in Chile (Cabaña-Chavez et al. 2013).

The political and economic transformations that the country underwent since 1974, not only transformed its economy and forestry institutions, but also intensely transformed the country's environmental landscape. With Decree 701, forest plantation expansion in the country almost tripled from about 33.000 hectares planted between 1970-1974 to about 82.000 hectares planted in 1975 (Otero 2006). Although the main initial justification for Decree 701 was the recovery of eroded or degraded soils, this objective was overtaken by the economic expansion and export of the sector (Otero 2006). In concrete terms, around 400.000 and 500.000 acres – some 200.000 hectares – of native forests were replaced by *Pinus* and *Eucalyptus* plantations during the 1970s and 1980s (Salas et al. 2016b). In parallel, the logging of native forest intensified even more since 1988 (see figure 21) (Clapp 1998). As *Pinus* and *Eucalyptus* plantations expanded, the market for raw timber has increasingly developed (Clapp 1995). By the 90's "*the most rapidly growing export category, however, is wood chips, more than half of which come from the native forest and not from Chile's vaunted plantations*" (Clapp 1995, p.291). In 1992, this national scenario, prompted a discussion for the creation of a law on native forests to promote the conservation and productive utilisation of native forest, which was finally approved in 2008 (Frene and Nuñez 2010a; Salas et al. 2016b). "*But its application has been negligible because of the small amount of the subsidies*" (Salas et al. 2016b, p.5).

Figure 21. Chip exports by species, Chile (1985 – 1992)



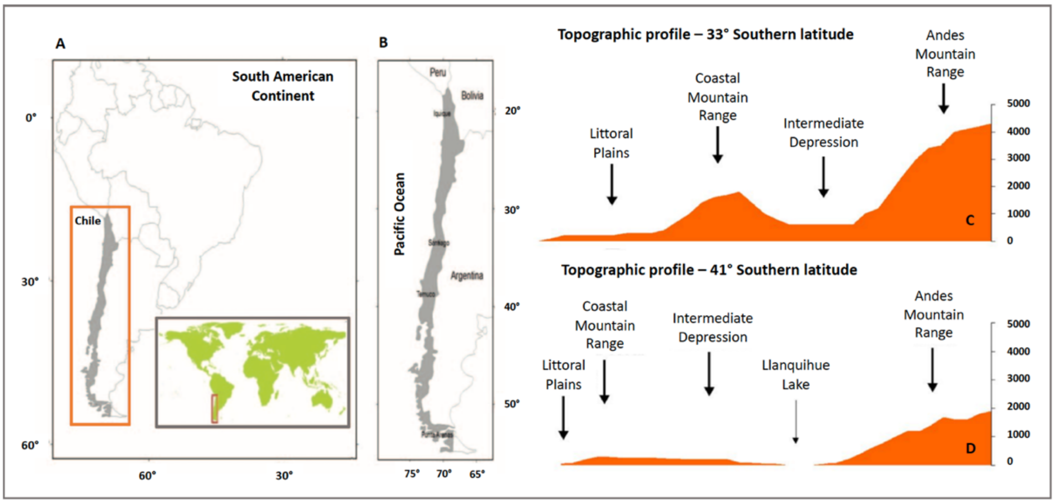
Source: Clapp (1998, p.10)

4.2.3. Geography and environment: forests, plantations, and water

Chile has an area of 185.3 million acres – 75,6 million hectares , it has 4500 kilometres in length and warm temperatures in the north decreasing towards the south (Salas et al. (2016b). Putting the length of Chile into perspective, this distance corresponds roughly to the distance between Lisbon and Moscow, between South Africa and Kenya, between California and New York, and more than between Brisbane and Perth, in Australia.

Its geomorphology is characterised by the presence of two mountain ranges from north to south: the Cordillera de la Costa (Coastal Mountain Range) – geologically older – and the Cordillera de Los Andes (Andes Mountain Range) – geologically younger – which are separated by a predominantly flat longitudinal strip called the Depression Intermedia (Salas et al. 2016b). The Andes Mountain Range decreases in elevation from north to south, with its peaks reaching about 6.700 metres in northern and central Chile, 3.000 metres in south-central Chile, and between 1.000 and 2000 meters in the southern part in Patagonia (Salas et al. 2016b) (see figure 22).

Figure 22. Continental Chile and geomorphology of the central-southern part of the country.

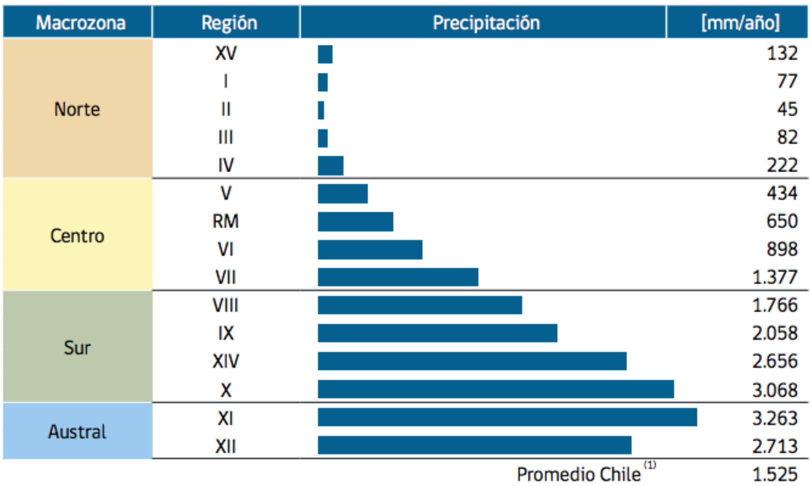


Source: Salas et al. (2016b) and Mitodio (2020). Figures A and B. Continental Chile. Source: Salas et al. (2016b). Figure C. Longitudinal relief (average) of Chile, between V-RM-VI-VII-VIII regions. Source: Mitodio (2020). Figure D. Longitudinal relief (average) of Chile, between IX-XIV-X regions. Source: Mitodio (2020).

In geographic terms, Chile is bordered by the Pacific Ocean to the west, the Andes Mountains to the east, the Atacama Desert to the north, and the Arctic Ocean to the south

(Salas et al. 2016b). These geomorphological features are relevant, because they provide Chile with different climatic characteristics (Salas et al. 2016b). For instance, precipitation regimes are influenced by both mountain ranges. In general terms, oceanic winds provide the west side of the coastal mountain range with more humidity and rainfall than the west side of the coastal mountain range, where a 'rain shadow' is produced. The intermediate depression and the Andean foothills, on the other hand, are influenced by higher humid winds and tend to receive more rainfall. The resulting environmental conditions makes that the forestry region in Chile is situated between the Coquimbo Region (IV) and the Aysén Region (XI). But, the forestry region is mainly concentrated along 800-kilometer between O'Higgins region (VI) and Los Ríos region (XIV) (INFOR 2021a), and between the 33° and 40° southern latitudes. The biogeographical zone between 35° and 43° south latitude is known as the Valdivian Rainforest Ecoregion (see figure 26), where natural forests are characterised, among others, by Coihue (*Nothofagus dombeyi*), Arayan (*Luma apiculata*), Luma (*Amomyrtus luma*), and Avellano (*Gevuina avellana*) tree species.

Figure 23. National average annual precipitation distributed by region from north to south (mm/year).

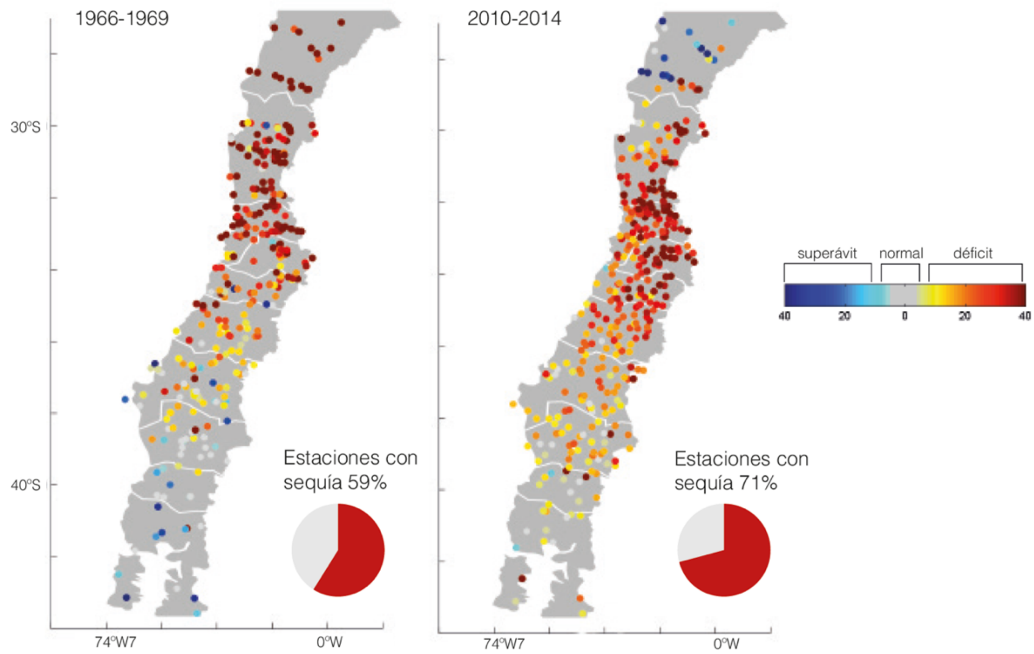


Source: DGA (2015, p.48). Atlas of Water in Chile 2016. Elaborated on the basis of the National Water Balance D.G.A.

The Andes Mountain Range is crowned with a vast network of glacial water reservoirs. According to the library of the National Congress of Chile, the central part of the country – where the capital Santiago is located – has about 1300 registered glaciers, covering 900 km². The central-southern part of the country between the regions of Maule (VI) and Los Rios

(XIV) – where the forestry region is mainly located – has about 300 glaciers, covering 400 km² (Biblioteca del Congreso Nacional de Chile 2016). This decrease in the volume of glaciers is due to the decrease in altitude of the Andes mountain range observed from north to south in the country (Biblioteca del Congreso Nacional de Chile 2016) (see figure 23). However, like the rest of the world, Chile is facing the consequences of climate change, and is suffering from decreasing rainfall and increasing temperature variations. Chile has a mega drought declared since 2010; observing that between the regions of Coquimbo (IV) and Maule (VII) – 32° and 36° latitude south approx. – there is the presence of the highest number of monitoring stations with an average annual deficit of up to almost 40%, in relation to the period 2010-2014 and the long-term average (1970-2000) (see figure 24) (CR2 2015).

Figure 24. monitoring stations with drought in south-central Chile



Source: CR2 (2015).

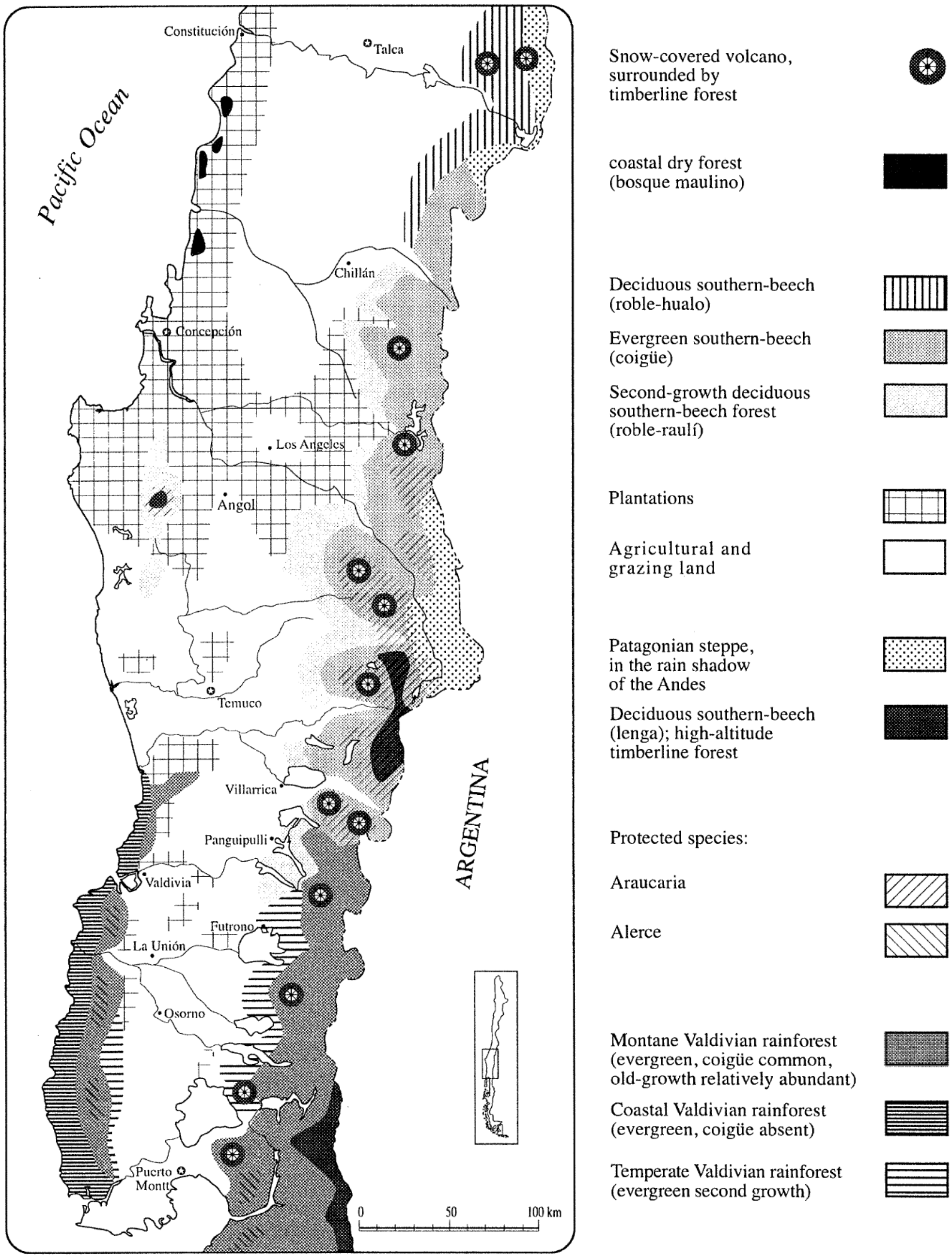
Chile has many volcanoes and active seismic activity (Cisternas et al. 2005; Dura et al. 2015). For this reason, Chile's soils are strongly influenced by volcanic ashes. This provides excellent physical properties for forest growth (Otero 2006; Salas et al. 2016b), since the ashes act as a natural fertilizer (see figure 25). In general terms, the soils of the south-central region of the country (33° and 43° south latitude) are of diverse granulometry, ranging from deep to moderate deep soils, and are especially located in the coastal plains and intermediate depression (Universidad de Chile 2008). According to Clapp (1995) these climatic and soil conditions of south-central Chile give this region a natural advantage for forestry development. This is evidenced by the faster growth rates and shorter forest rotations observed in Chile compared to other major forestry countries such as the United States, Canada or Scandinavian countries (table 7) (Clapp 1995).

Table 7. timber yields compared among major forestry countries (1980-1990), including Chile.

Site	Yield (m^3/ha/yr)	Rotation (years)
Temperate and boreal softwood forests		
Canada average	1	—
British Columbia	1.5–5.3	—
U.S. average	2.6	—
Sweden average	3.3	—
Finland	2.5	60–100
Russia	1–2.9	—
Siberia	1–1.4	70–200
Softwood plantations		
Britain (Sitka spruce)	14	40
South Africa (pine spp.)	10–25	20–35
New Zealand (Monterey pine)	18–30	20–40
Chile (Monterey pine)	20–30	15–35
East Africa (pine spp.)	25–45	20–30
Brazil (pine spp.)	15–35	15–35
Tropical hardwoods		
Malayan dipterocarp forest	up to 17	—
Mixed tropical high forest	0.5–7	—
Teak plantations	14	40–60
Eucalyptus plantations		
Portugal and Spain	10–15	8–12
South Africa	15–20	10
Chile	20–30	8–20
Congo	30–40	7–20
Brazil	30–70	5–20

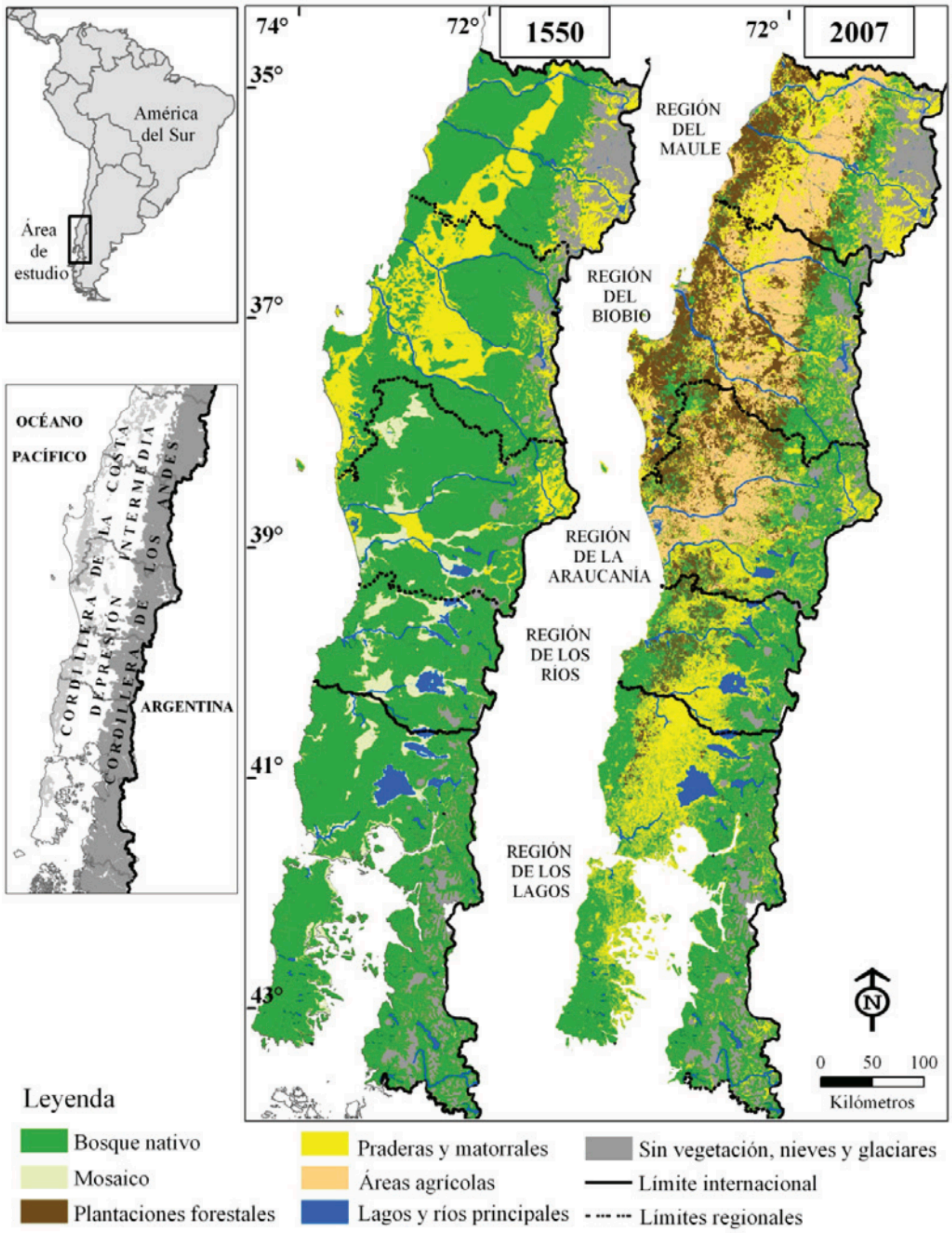
Source: Clapp (1995, p.276). Based on Evans (1982); Gessel (1984); Zobel, van Wyk, and Stahl (1987); Stier (1990).

Figure 25. Forestry region and dominant forest types in Chile (1994)



Source: Clapp (1995, p.277).

Figure 26. Reconstruction of vegetation cover and land use in 1550 and their change towards 2007 in the Rainforest Ecoregion of Chile (35º – 43º 30´ S)



Source : Lara et al. (2012, p.15). In brown, forest plantations; in yellow, grassland and scrubland; in green, native forests; in salmon, agricultural land; in blue water bodies; and in grey, without vegetation/ with glaciers and snow.

4.2.4. Chilean forestry sector economy nowadays

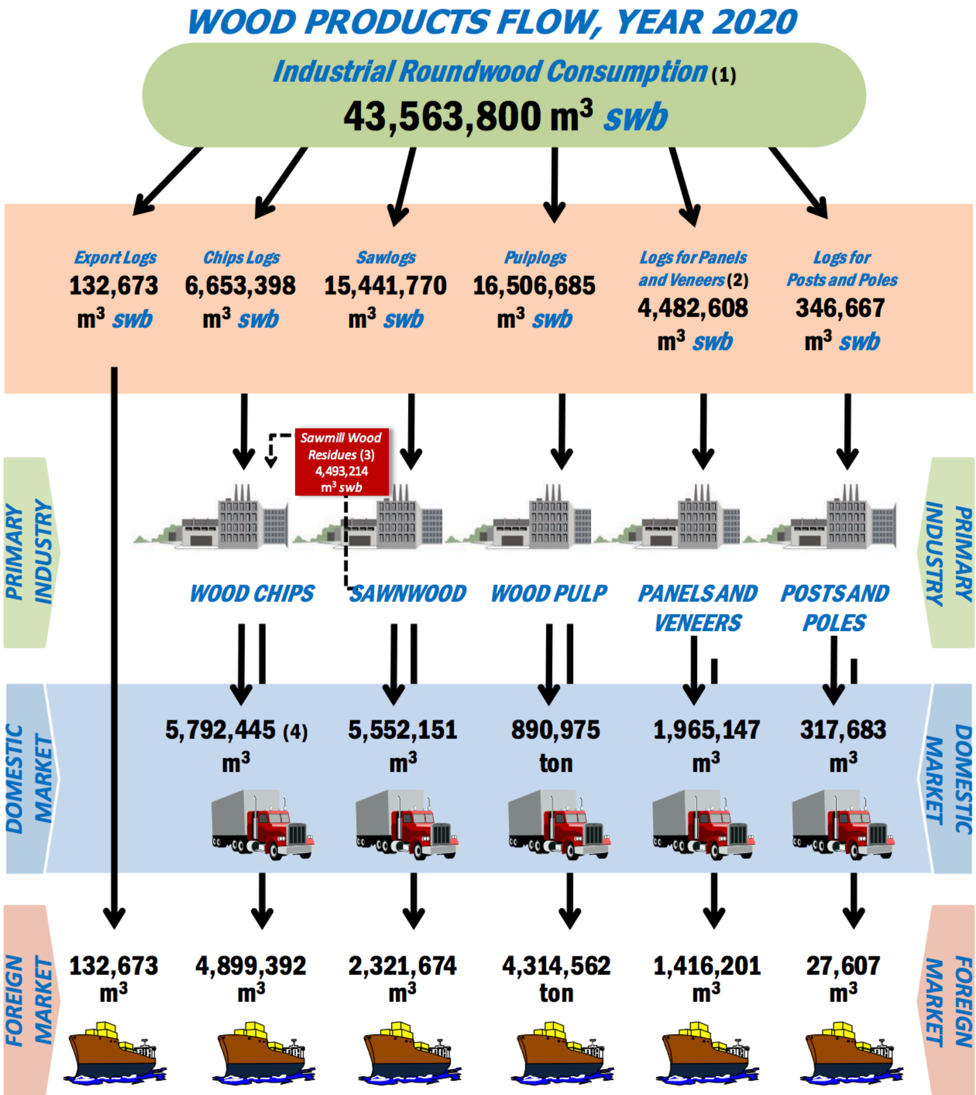
According to the World's Top Exports (2020), since 2020 Chile is the first country in South America, and number 10 in the world ranking of sawn wood export value, with 2% of the world exports' value and revenues of more than 730 million dollars. This positions Chile at the forefront of the forestry industry in South America and the world. This is also reflected in the relevance of the forestry sector within Chile; as the forestry sector is the country's second largest export income after minerals (Cubbage et al., 2007), and contributes 2.7% of the national GDP (INFOR 2012, in Salas et al. 2016b). Chile is also one of the top 10 countries in the world in terms of land dedicated to forestry plantations (Cubbage et al., 2007), and its forestry area continues to grow (INFOR 2021a). This constant growth in the forestry sector is crucial, since as an economy based on low value-added products, it is dependent on the scale of production for profitability. So, the future of the Chilean forestry sector will depend on its capacity to increase the range of its exports (Clapp 1995).

Regarding forest land management in Chile, as noted earlier, since the wave of privatizations in the mid-1970s and 1980s, productive forests are privately owned and managed (Rossi 2005). This represents a particular feature in the global scenario of the forestry sector, given that in the vast majority of countries, all or a large part of the forests are owned by the State, and companies must request licences for their use for productive purposes (Rossi 2005). From 2000 to 2012, Chile was the second country in the Latin American region, after Uruguay, in terms of total area increase in forestry plantations (Jones et al. 2016). By 2012 in Chile, 62% of trees grown in forest plantations were *Pinus radiata* and 31% were *Eucalyptus* species (mainly *Eucalyptus globulus* and *Eucalyptus nitens*) (Salas et al., 2016). But currently, the forestry market has changed, and *Eucalyptus* has been strongly promoted by forestry industries around the world and in Chile (Balocchi et al. 2021). Especially for the production of pulp focused on the production of biodegradable products, such as paper and cardboard (King 1978), or more recently, for the production of vegetable fibre for textiles (Väisänen et al. 2016). This implies that in years to come the *Eucalyptus* will be the principal species used in Chile (Interview 15, December 2018; Interview 16, December 2018).

In 2021, the update of CONAF's Inventory of Native Vegetation Resources of Chile, reported that Chile has 18 million hectares covered by forests – 23.8% of the national surface – of which 14.7 million hectares correspond to native forests, 3.1 million hectares to forest plantations, and 180 hectares to mixed forests (CONAF 2021a). By 2021, forest plantations in Chile corresponded for 36.8% to *Eucalyptus* species, 57.6% to pine species, and 5.6% to other tree species (INFOR 2021a). This confirms that in Chile, the presence of *Eucalyptus* species is gaining predominance, and about 5% of other land uses were converted to *Eucalyptus* species during the last 10 years.

Eucalyptus species are mainly used for producing wood pulp, and are harvested in cycles stretching from 5 years (Clapp 1995; Morales et al. 2015) up to 14-15 years (Salas et al. 2016b). Therefore, their rotational cycle is more intense than *Pinus* species, which have forestry rotations between 15-40 years (Clapp 1995). The main products from the forestry industry in Chile are pulp for paper and tissue, and much less wood for sawmills (Meneses and Guzman 2000). In 2020, Chile exported more than 4.300.000 tons of wood pulp, and 8.700.000 m3 of chips, sawn wood (figure 27) (INFOR 2021a). All this makes *Eucalyptus* a highly relevant tree species for the Chilean forestry market.

Figure 27. Production chain of the forestry sector in Chile and timber production volumes (2020)



Source: INFOR.
(1) *It includes sawlogs and pulplogs.*
(2) *Includes logs for boxes, bins, and matches and similar products.*
(3) *It refers to wood slabs and wood offcuts.*
(4) *Wood chips for domestic market is divided into: 4,845,735 m³ are used for wood pulp industry; 436,433 m³ for panel manufacturing; 373,177 m³ for fuel and 137,100 m³ are used to other destination.*

Source: INFOR (2021a).

4.2.5. Forests and water policy

The following sections review the main bodies of Chilean law related to aspects of forestry and water resources in Chile.

4.2.5.1. Forestry laws and management in Chile

The legal and administrative institutional framework for natural resources in Chile tends to be distributed among various institutions, which sometimes overlap in their powers. This is also the case for the legal instruments linked to the forestry sector in Chile, where many legislations are present and sometimes overlap. There are at least four legal instruments – with the force of law – related to forest management in Chile, and other indicative legal instruments – without the force of law – that are adopted on a voluntary basis by forestry companies. The Forestry Plantation Protocol – deeply analysed in this research in chapter 7 – is one of these.

Currently, the most widely used forestry instrument is Decree Law N°701 (1974) on forestry development, which is managed by the Ministry of Agriculture. The Decree Law N°701 is the "*instrument that, meeting the requirements established in said legal body, regulates the rational use and exploitation of the renewable natural resources of a given piece of land, with the aim of obtaining the maximum benefit from them, while ensuring the preservation, conservation, improvement and enhancement of said resources and their ecosystem (DL 701 of 1974, art. 2°)*" (CONAF 2016, p.50). The economic subsidies from the D.L. N° 701 finished in 2012 (Mardones and Hernández 2017), but were later extended at least until 2015 (CONAF 2016a). However, the legal attributes of the D.L. N° 701 remains in force today while the creation of a new forestry incentive instrument is being analysed (Interview 24, November 2018). In addition, D.L. 701 has four complementary regulations (Cabaña-Chavez et al. 2013).

Secondly, according to the Decree 40 of 2012 (Art. 3) (Ministerio del Medio Ambiente 2020), forestry development and forestry plantations projects in Chile must be submitted to the environmental impact assessment system of Law 19.300 (1994), under the Ministry of Environment (Art. 10) (División Jurídica de la Comisión Nacional del Medio Ambiente 2007), if they cover a single area of clear-cut harvesting per property of 20 ha/year (between the regions of Arica and Parinacota), 200 ha/year (between the regions of Valparaiso and

Metropolitana), 500 ha/year (between the regions of Libertador Bernardo O'Higgins and Aysen), or 1000 ha/year (in the Region of Magallanes). The purpose of Law 19.300 is to evaluate possible environmental impacts of different projects developed on the national territory, before granting authorisations to enter into construction/operation (División Jurídica de la Comisióo Naciona del Medio Ambiente 2007).

Moreover, the Law N°20.283 (2008) which 'regulates the recovery of the native forest and forestry development' is managed by the Ministry of Agriculture (Biblioteca Nacional del Congreso de Chile 2008). Finally, Decree 82 (2010) is the soil, water and humidity regulation – also under the Ministry of Agriculture – which seeks to comply with the obligations set out in Law N°20.283, and the plantations established under Decree Law N°701 (Ministerio de Agricultura 2010). Further details on Decree 82 are discussed in Chapter 7.

As for the indicative instruments that private forestry industries can adopt for the management of their properties and surroundings, three instruments stand out in Chile. First, the Forest Stewardship Council (FSC) is an international and national private market-based certification approach created in 1993 to improve forestry practices worldwide (FSC 2020). The FSC was created after the failure to produce an international agreement to stop illegal deforestation in 1992, at the United Nations Conference on Environment and Development (UNCED) in Rio – also known as the Earth Summit Rio (FSC 2020). The FSC seeks to develop outcomes around sustainability, while focusing on laws, community rights, indigenous peoples, and environmental values, which also require management plans, monitoring and evaluation mechanisms (FSC 2016). By 2003, 3.2% (124 million ha) of the world's forest plantations had been FSC certified (Rametsteiner and Simula 2003). Chile has approximately more than 3.000.000 hectares of forest plantations, of which, by January 2022, some 2.330.000 hectares have a Forest Management (FM) certification (FSC Chile 2022). The FSC has been involved in Chile since 2005 and has an office in the country since 2010 (FSC Chile 2022).

Additionally, 'the Forest Policy (2015-2035' was designed by the Forest Policy Council (Decree 8 of 2015), whose members, in addition to defining the strategic axes of the policy[11],

[11] The main lines of action of the Forestry Policy are: forestry institutions; productivity and economic growth; inclusion and social equity and protection and restoration of forest heritage (CONAF 2015).

are responsible for proposing, elaborating or evaluating plans, programmes or instruments to achieve the objectives of the policy (CONAF 2015). The Forestry Policy Council - composed of representatives of the government, forestry companies, social organisations and universities - is responsible for designing and structuring the development of a forestry policy for sustainable forestry development, contributing to economic, ecological and socio-cultural development of Chile in the future (CONAF 2015).

> "*The aim of a long-term sectoral policy is to outline the strategic axes, define general and specific objectives, elaborate plans and programmes, identify instruments and specify mechanisms to achieve Sustainable Forestry Development, understood in terms of challenges and vision, as the contribution of the Chilean forestry sector to the economic-productive, ecological and social-cultural development of the country, ecological and social-cultural development of the country, by means of conservation, integrated management and the rational use and exploitation of resources, of watersheds and forest ecosystems*" (CONAF 2015, p.9).

The Forest Plantations Protocol (FPP) – analysed in detail in chapter 7 – was created in 2017, under the umbrella of the Forestry Policy (CONAF 2017a). The Forest Plantation Protocol established and produced a series of criteria and standards for the establishment and management of future forestry plantations in Chile, which, among other aspects, addressed – for the first time at national level – the contested nexus between forestry plantations and water reductions in rural areas (CONAF 2017a). Given that the FPP is the first national instrument produced through a governance system, and the most recent to address the development of standards around the issue of forest plantations and water reductions, the FPP is the major case and policy instrument of analysis in this research. Further details about the PPF production are analysed in chapter 7.

4.2.5.2. Water laws and management in Chile

Water management in Chile is regulated through various normative instruments, especially the Water Code of 1981 (DGA et al. 2015). The Chilean Water Code operates through a system of allocation of 'Water Use Rights' (WU.RR.) (Donoso 2018). Whereas in its origins, the Water Code (1981) offered free and perpetual WU.RR. to the first applicants (Donoso

2018), subsequently and at present, the allocation of surface and groundwater WU.RR. is done through a water market (Budds 2013; Prieto 2015). This means that the WU.RR. are materials that can be sold and traded on the public market. In this sense, the role of the State has consisted of governmental oversight over water, and seeks to favour the allocation of WU.RR. to the most profitable activity through the market mechanism (Bauer 2015). Management based on the Chilean Water Code, has been extensively investigated (Bauer 2004; 2012; 2015; Prieto 2015; Palomino-Schalscha et al. 2016; Budds 2020), wich came to demonstrate that the system of evaluation and modelling of aquifers under the supervision of the General Directorate of Water (or DGA in Spanish) for the allocation of WU.RR., has been highly inaccurate and has favoured access to water for large sectors of Chilean agro-industry located upstream and disadvantaged rural communities located downstream of these watersheds (Budds 2009; 2012; 2013).

The Chilean Water Authority (Dirección General de Aguas de Chile - DGA) is the State entity responsible for overseeing the implementation of the Chilean Water Code:

> "*In Chile, water is a national asset of public use and is granted to individuals by means of 'Water Use Rights' (WU.RR.) in accordance with the provisions of the current regulations. This right is expressed in units of volume per unit of time allowing the holder to use and enjoy them in accordance with the law. In turn, the holders can dispose of this right.*
>
> *Continental waters are classified as surface water and groundwater. Consequently, WU.RR. can also be surface or groundwater. Surface water is water that flows through natural or artificial watercourses or is accumulated in reservoirs such as lakes, ponds, swamps, marshes, ponds, water holes, swamps, ponds or reservoirs. Groundwater, on the other hand, is water that is hidden in the earth and has not been illuminated.*
>
> *The WU.RR. are also classified as consumptive and non-consumptive. Consumptive rights entitle the holder to fully consume the water in any activity. Non-consumptive rights, on the other hand, allow the use of the water without consuming it and oblige the holder to return it in the manner determined by the act of acquisition or constitution of the right. In addition to the aforementioned characteristics, the nature of the WU.RR. may also be exercised permanently or occasionally, continuously or discontinuously, or alternately with other persons*." (DGA et al. 2015, p.106).

As drought problems are increasing in different regions of the country (CR2 2015), rural society, indigenous people and small farmers have organised to demand solutions to reform the Water Code (1981) (Modatima 2022). Recently, on April 6th 2022; and after years of negotiation (2014-2022), the Chilean Congress has approved a new reform to the Water Code: the Law 21.435, which among other aspects establishes the prioritisation of water for human consumption and self-subsistence, sanitation, and the preservation of ecosystems (Art 5) (Biblioteca del Congreso Nacional de Chile 2022). In addition, with this new reform of the Water Code from 1981, the State will be able to reorganise proportionally the WU.RR. in those places strongly affected, and even to suspend WU.RR. in case a user causes serious and persistent affectations to the availability of surface or groundwater, affecting third parties and mainly the human consumption of water (Biblioteca del Congreso Nacional de Chile 2022). Furthermore, like other innovative aspects of the reform, it attributes greater supervisory capacities to the General Water Directorate to avoid inappropriate use of WU.RR. (Biblioteca del Congreso Nacional de Chile 2022). On the other hand, the reform of the water code provides free right of use of groundwater found during mining operations, and guarantees the perpetuity of the previously owned WU.RR. while the future WU.RR. requested will be granted for a maximum term of 30 years, among other new aspects of this reform (Biblioteca del Congreso Nacional de Chile 2022).

During the elaboration of this new Water Code in the Congress, the forestry industry was mentioned as an important water consumer in the country in discussions hold in the Chamber of Deputies (Camara de Dipitados 2016), yet it was not discussed at all in the committee on agriculture, forestry and rural development in the process of formulating the current Water Code Reform Law 21.435 (see Comision de Agricultura camara de Diputados 2016).

Other innovative features of the reform that might become closely linked to the forestry sector in today's Chile, consist in the development of strategic plans for water resources in watersheds. This will be based on the hydrogeological modelling of watersheds (Articles 293 bis and ter) which, among other aspects, require:

> First, "*a cost analysis of the different alternatives, the identification of the potential environmental and social impacts for a subsequent evaluation, and the projections of demand for human consumption for ten years*" (Art.293 bis) in charge of the General Directorate of Water. (Biblioteca del Congreso Nacional de Chile 2022, p.29).

> Second, it also determines the creation of a "*fund for Research, Innovation and Education in Water Resources, under the Ministry of Public Works, through the General Directorate of Water*" and that "*a public competition will be held annually to select the research and studies to be financed by the fund*" (Art. 293 ter) (Biblioteca del Congreso Nacional de Chile 2022, p.29).

Additionally, the current Water Code Reform guarantees the free use of water from small river or body water banks to the owners of the land containing those waters and riverbanks (Art. 20), as well as the free use of rainwater falling on land and considering it as natural ground water recharge (Art. 66) (Biblioteca del Congreso Nacional de Chile 2022).

Chapter 5

Water and Eucalyptus forests: a review

This chapter focuses on reviewing the state of the art and knowledge gaps in the scientific field of forest hydrology. The following four questions are investigated: (A1) What are the effects of eucalypts on water quantity at different stages in the hydrological cycle: during evapotranspiration, in soils, in streamflow, and in groundwater? (A2) What are the effects of eucalypts on water quantity for different types of forests and species, type of land cover and changes, treatment comparisons and bio-environmental conditions? (A3) How can the context and study design explain nuances? (A4) What are the knowledge gaps regarding eucalyptus-water interactions?

The chapter is based on a review of the peer-reviewed literature of three relevant countries with active forest hydrology research programmes: South Africa, Australia and Chile. The chapter is organised as follows. Section 5.1 recapitulates the practical and theoretical relevance of this analysis. Section 5.2 provides the general context of the sampled studies. Section 5.3 presents a broad overview of the main effects of eucalypts on hydrology, found through this review. Section 5.4 analyses the bio-environmental conditions at play when understanding the effects of eucalypts on hydrology. Section 5.5 examines the effects of eucalypts on the evapotranspiration part of the hydrological cycle. Section 5.6, analyses the effects of eucalypts on soil water resources. Section 5.7 focuses on analysing the effects of eucalyptus plantations on surface hydrology. Section 5.8, examines the effects of eucalypts on groundwater. Section 5.9 provides a general observation on the differences found in a minority of outlying studies. Section 5.10 presents identified knowledge gaps. Section 5.11, finally, presents the conclusions of this chapter.

5.1. Introduction

This chapter deals with the scientific knowledge on *Eucalyptus* trees published in forest hydrology journals, and reviews its state of the art, in particular with regard to their effects on hydrology. Eucalypts have long been criticised for their negative impacts on water availability, due to their high water use (Barros Ferraz et al. 2019). Impacts on hydrology are a key concern where eucalypts become dominant as invasive species in semi-arid regions (e.g. Hirsch et al. 2020). Furthermore, climate change has made water scarcity a key global concern (UN-Water 2021) and availability and access to water is a primary issue among different water users (Oppliger et al. 2019). In a world facing global and local water constraints that present multiple complexities and uncertainties, the nexus between water resources and eucalypts has been a subject of worldwide debate, including among public and private actors, forest hydrologists and other scientists (Calder 1999; 2004; Dye and Versfeld 2007; Doody et al. 2011; Albaugh et al. 2013; White et al. 2016).

Despite the extensive body of forest hydrology research (see section 2.1), in several countries where eucalypts are widely planted or are invasive, the nexus between eucalypts and its water use effects remains contested in ways that can have important influences on forestry and water resources policy-making (Doody et al. 2011; Albaugh et al. 2013; White et al. 2016). Disagreements over eucalypt-water interactions can have their roots in how results are produced and communicated. Or, there can be gaps in the knowledge on forest hydrology that may lead to different understandings (Scarascia-Mugnozza et al. 2000). Therefore, it is important to systematically analyse the scientific evidence to establish the current state of knowledge on the effects of eucalypt trees on water. Drawing upon forest hydrology scientific knowledge and based on more than 200 peer-reviewed journal articles (1980 – 2019) from Chile, South Africa and Australia, this chapter contributes to the literature by reviewing the science on the effects of eucalypts on major components of the hydrological cycle (evapotranspiration, soil water content, streamflow and groundwater), and exploring its study design and identifying knowledge gaps regarding eucalyptus-water quantity interactions.

5.2. General characteristics of sampled studies

As mentioned in the methodological section 3.5.1, the final number of articles reviewed in-depth was 206. These articles reported on research in a wide diversity of geographical contexts. These are reported below for the three countries investigated.

Chilean case studies were in temperate rainy climates and Mediterranean climates; South African studies highlight sub-tropical climates; while Australian studies cover a diversity of climates but with an emphasis on Mediterranean-type climate zones with cool, wet winters and hot, dry summers (figure 28). Mean annual rainfalls in the locations of the studies ranged from 230 mm to 2800 mm, with good representation of studies of all parts of the hydrological cycle across this range. Rainfall gradients in Chile ranges from 816 mm to 2357 mm, in South Africa from 545 mm to 2600 mm; and in Australia from 230 mm to 2800 mm.

Research ranged across a wide range of soil types. In the three countries, dominant soil types in the studies included loam, sandy, clay texture soils and their combinations. Groundwater depths also varied, for example, Australian studies reported aquifer depths of between 1 and 40 metres below the surface.

More than 60 *Eucalyptus* species were analysed; the most common were *Eucalyptus camaldulensis E. globulus*, *E. grandis. Pinus radiata* was common as a comparison plantation species. Tree or stand ages were not always indicated in the studies but there was a good representation of age diversity in all parts of the hydrological cycle. Studied stand age classes in Chile for eucalypts ranged between 2 and 16 years old, and for pines between 4 and 27 years old. In South Africa ages studied for eucalypts were between 1 and 20 years old, for pines between 1 and 45 years old, and for acacias between 5 and 20 years old. In Chile and South Africa, forest or stand age was often not reported for native trees but the studies generally indicated comparison with mature forests, probably multi-aged. In Australia, ages studied in eucalypt forests and plantations range between 1 month old and 230 years old and non-native pines between 1 and 45 years old. The time period of forest hydrology studies ranged from a minimum of 20 days to 69 years.

Figure 28. Eucalypts in three Southern Hemisphere countries.

Source: author. Photo A: natural eucalypt forest in Tasmania, Australia. Photo B: a mono-culture of planted eucalypts in BioBio, Chile. Photo C: a mono-culture of planted eucalypts in KwaZulu-Natal, South Africa. Photo D: a mono-culture of planted eucalypts in Victoria, Australia.

5.3. Effects of Eucalyptus on hydrology

Most of the examined studies found that planted or native eucalypts reduce water quantity (measured as increased evapotranspiration losses, reduced soil water content, streamflow, or groundwater reserves), when compared with other land covers, under certain forestry treatments and under certain bio-environmental conditions. Eucalypts generally exploit a greater volume of soil water, streamflow and groundwater reserves than other land use covers, such as agriculture, grassland, other kind of native forests, shrubs, wetland vegetation, or other tree species. Reviewed studies also indicate that eucalypts may have a greater impact on water reserves under certain types of management such as first versus later forestry rotations, high plantation densities, irrigation and fertilization, among others. Various bio-environmental conditions may also result in high water usage; these factors include tree age, season, proximity to water resources (rainwater, groundwater, etc) and whether trees are under attack by insect pests. Replacing other land covers with eucalypts was generally found to reduce streamflow. Land cover changes in the opposite direction (removal of eucalypts) resulted in water resource increases, this occurred with conversion from eucalypts to pines, eucalypts to acacias, or from eucalypt forests and shrubs to agriculture and grassland. These results hold irrespective of whether the eucalypts were present as native or non-native trees. The few studies that did not support these findings often add nuance to the dominant trend, as we describe in the following sub-sections.

The section below analyses in more detail the hydrological effects of eucalypts based on the reviewed studies. It begins with a general discussion of the understanding of the hydrological behaviour of eucalypts under various bio-environmental conditions (5.4). Next, it analyses the hydrological effects found by investigating land cover changes or by comparing land covers and forestry treatment for different components of the hydrological cycle (sections 5.5 evapotranspiration, 5.6 soil water, 5.7 streamflow, and 5.8 groundwater).

5.4. Bio-environmental conditions

All plants consume water in the processes of photosynthesis and evapotranspiration. In general terms for survival of plants, sun, water and soil nutrients are basic elements. Therefore, the bio-environmental conditions are key aspects to consider, as these conditions contribute to determine the major or minor tree hydrological effects on evapotranspiration, runoff, water in the soil, or groundwater stages. Under certain bio-environmental conditions, plants can increase or decrease their water use rates. In this respect, forest hydrologists have studied how the water use of eucalypts varies with (i) age, (ii) seasons, access to (iii) rainfall and (iv) groundwater, (v) flood or (vi) drought conditions, (vii) saline content of water, (viii) time of day or night, and under (ix) insect attack. Key findings from our review are briefly summarized below.

In terms of age, stands of young trees generally have higher evapotranspiration than mature trees (Dunn and Connor 1993; Jayasuriya et al. 1993; Cornish and Vertessy 2001; C. Macfarlane et al. 2010). Water use varies between eucalypt species, but compared to many other types of tree, eucalypts have the ability to keep their water consumption relatively constant during wet or dry seasons when they have constant access to water reserves, such as water stored in the soil (Eamus et al. 2000; O'Grady et al. 2009). Their water use behaviour is adaptable and they have the ability to access different water sources (Farrington et al. 1996). They transpire more with higher water availabilities, such as greater rainwater volumes in soil reserves (Farrington et al. 1994; Dye 1996b; Eberbach and Burrows 2006; Morgan and Barton 2008), greater access to stream water (Mensforth et al. 1994), or groundwater reserves (Crosbie et al. 2008; Macfarlane et al. 2018). After floods (Akeroyd et al. 1998) or episodic rainfall events (Eberbach and Burrows 2006) eucalypts have the ability to rapidly increase rates of water consumption. Accordingly, eucalypt forests have higher water uses in areas of high rainfall or during wet seasons (Zhang et al. 2001; Farley et al. 2005), but the most visible effects on water resources are observed in dry regions and dry seasons (Soto-Schönherr and Iroumé 2016).

Like many deep-rooted trees, eucalypts can vary their water access strategy in different seasons, using water from soil water reserves, or directly from streams or aquifers when these soil water reserves are depleted (Mensforth et al. 1994; Dawson and Pate 1996); and they can access deep groundwater to survive periods of drought (Silberstein et al. 2001; Leuning et al. 2005). The access to groundwater may depend on the age and root development of the trees, as well as on the depth of groundwater (Benyon et al. 2001).

Some studies reported that eucalypt water consumption rates drop at night to 5-8% of total transpiration during some seasons (Benyon 1999; Mitchell et al. 2009; Pfautsch et al. 2011). Exceptionally, the study of White et al. (2000) was the only study to suggest that *Eucalyptus camaldulensis* and *E. saligna Smith, E. leucoxylon F. Muell and E. platypus Hook* do not transpire at night. Although some eucalypt species can tolerate saline water (Benyon et al. 1999), most preferentially consume fresh water when it is available (Holland et al. 2006; Sudmeyer and Simons 2008). Healthy eucalyptus trees consume more water than those affected by pest or insect attacks (Cornish and Vertessy 2001; Cunningham et al. 2009).

5.5. Evapotranspiration

Evapotranspiration includes transpiration of water through leaf stomata, evaporation of intercepted water from tree leaves, and evapotranspiration from the soil. Most studies on evapotranspiration confirm that eucalypts have higher evapotranspiration rates than other forms of land cover or forest tree species. This finding is confirmed in studies that compare eucalypts with grassland (e.g. Hutley et al. 2000; Dye 2013; Dresel et al. 2018); with shrubs (e.g. Scott-Shaw and Everson 2019; Kongo et al. 2011); as well as when eucalypts are compared with some acacias (Meijninger and Jarmain 2014) or pines (Dye 1996a; Huber et al. 2010). Regarding interception losses, although eucalypts intercept less water than pines (Pook et al. 1991), the total evapotranspiration loss is higher in eucalypts than in pines (Huber et al. 2010).

Studies which investigated the effects of land cover change on evapotranspiration confirm that changes from grassland to non-native eucalypt plantations increase evapotranspiration rates and decrease streamflow or groundwater (Eastham et al 1993; 1994; Dean et al. 2016). The impact of changing from eucalypts to other species depends on their comparative water use. For example, changing from eucalypts to acacia may decrease evapotranspiration and increase streamflow (Hawthorne et al. 2018), while converting from willow to eucalypt did not change evapotranspiration rates since these taxa have similarly high water use (Doody et al. 2011).

Evapotranspiration at a catchment scale increases with the plantation area (Kongo et al. 2011). When investigating different forest stand conditions or treatments, evapotranspiration rates are higher in re-growth of trees after fire compared to older growth stages (Buckley et al. 2012); with coppice regrowth compared to planted trees (Drake et al. 2012); with the increase in stand density (Huber et al. 1998; Huber and Iroumé 2001), and with irrigation (White et al. 2016) or fertilization (Huang et al. 2008). Also, trees recovering from defoliation have higher transpiration rates (Quentin et al. 2011). Harvesting (Dzikiti et al. 2016; C. Macfarlane et al. 2018) or thinning (Forrester et al. 2012; Roberts et al. 2015) decrease rates of evapotranspiration in the short term, but are followed by an increase in evapotranspiration and reduction of flows as trees regrow after harvest or crown density recovers following thinning.

Some evapotranspiration studies reported results that diverged from the dominant trend. In contrast to the general consensus that eucalypts transpire more than grasses, Wright et al. (2012) reports greater transpirations rates for grasses than for eucalypts located on the edges of a plantation. They attribute this to the greater water availability in pasture than eucalypts on the edges of the plantation (Wright et al. 2012). Another study found similar evapotranspiration rates between eucalypts and pine species after conversion from agriculture (Benyon and Doody 2015), while Soto-Schönherr and Iroumé (2016) found no significant difference in interception between eucalypts and pines. Moreover, Gush (2017) reported similar water use efficiency rates among clonal eucalypt, pine, *Casuarina* species and the indigenous tree *Vachellia kosiensis* in South Africa. In addition, the study of Carbon et al. (1981) reported only small differences in transpiration rates per unit leaf area between original eucalypt forests and eucalypt plantations.

5.6. Soil water resources

Soil water studies included studies of soil water content or moisture content and water infiltration rates. Among studies comparing soil water between eucalyptus plantations or forests and other types of land cover, most studies confirmed that soil moisture was lower under eucalypts. Studies that compare eucalypts with agriculture (Robinson et al. 2006; Sudmeyer and Hall 2015), grassland (White et al. 2003; Le Maitre et al. 1999; Eastham et al. 1993), other kind of native forests (non-eucalypts trees) (Barrientos and Iroumé 2018; C. E. Oyarzún et al. 2011; Soto et al. 2019), or native shrubs (non-eucalypts trees) (Scott and Everson 2019; Soto et al. 2019), agreed that soil water content and infiltration rates are lower under eucalypts. Single studies comparing eucalypts with peatland vegetation (Cartwright and Morgenstern 2017) and with pines (Scott 2000) also found lower soil water infiltration under eucalypts.

Soil water content was also found to be lower under certain forest conditions or treatments such as increasing stand density (Huber et al. 1998; Barrientos and Iroumé 2018); fertilization which was found to deplete soil water stores earlier and faster (White et al. 2014); after harvesting or thinning treatments (Rab 1996; Ruwanza et al. 2013) which can lead to poorer soil structure, compacted soils and decrease porous continuity (Oyarzún et al. 2011); or between forest rotations, where the second rotation will have lower soil water than the first (Morales et al. 2015; Mendham et al. 2011), and which may have a cumulative impact on losses of soil water reserves (Oyarzún and Huber 1999).

Soil water repellency was also found to increase in areas invaded by eucalypts compared to natural sites (Scott 1993), or in dry soils under eucalypts (Thwaites et al. 2006). This can increase run-off, but reduce infiltration and decrease soil water. Fire in eucalypt forests may have diverse effects on soil repellency depending on the soil temperature reached (Shakesby et al. 2003) and on heating duration (Doerr et al. 2004). Under moderate fire temperatures (between 100-150 °C) soil water repellency of eucalypts does not change significantly, but it can decrease considerably at high temperatures (above 250 °C) (Doerr et al. 2004; Granged et al. 2011; Smith et al. 2011; Zavala et al. 2010).

Only three studies varied from the general patterns described above. Ruwanza et al. (2013) observed that eucalypts invasions in grassland and shrub soils did not induce resistance to infiltration. Likewise, when extending the comparison to shrub soils, Kerr and Ruwanza (2016), reported no significant differences of soil moisture between natural shrubs, invasive *E. camaldulensis* and sites cleared of invasive eucalypts. Oyarzún et al. (2011) found no difference in water repellency between native forests and eucalypt plantations soils.

5.7. Streamflow

Most studies comparing catchments of different land covers confirm that those afforested with eucalypts or pines have lower streamflow. These studies compared eucalypts with agriculture (e.g. Bell 1999; Cocks 2003), with grassland (Bosch and von Gadow 1990; Adelana et al. 2015), with other kind of native forests (non-eucalypts) (Correa-Araneda et al. 2016; Lara et al. 2009; Oyarzún and Nahuelhual 2005) or with other native shrubs (non-eucalypts) (Scott 1998; Hawthorne et al. 2013). Streamflow was found to be lower under eucalypts compared to other tree species such as pines (Huber et al. 2010; Albaugh et al. 2013; Sahin and Hall 1996).

Studies of land cover change through time have reported similar findings. When land is converted from agriculture to eucalypts or pines, streamflow is reduced (Versace et al. 2008; Stehr et al. 2010). Similarly, this is the case when grassland is converted to eucalypts or pines (Van Lill et al. 1980; Scott and Lesch 1997; Smethurst 2019); from native forest to eucalypts or pines (Alvarez-Garreton et al. 2019; Little et al. 2009; Aguayo et al. 2016); and from shrubs to eucalypts or pines (Scott and Prinsloo 2008; Scott and Smith 1997; Smith and Scott 1992; Bosch and Smith 1989). Streamflow increases are observed when converting from eucalypt forests to pine plantations (Bren and Papworth 1991; Bren and Hopmans 2007); or from eucalypt forests to non-eucalypt species (Hawthorne et al. 2013). Nevertheless, in terms of streamflow and land conversions, the studies of Brown et al. (2015) and Liu et al. (2004) have results that, while not disagreeing with the consensus, indicate a spatial threshold for hydrological effects, as we outline below in part 5.

Some interpretation is necessary when considering streamflow effects between different types of eucalypt forest age classes or when considering stand treatment effects such as fire or timber harvesting. Changes from old-growth native eucalypt forests to younger age classes through fire or timber harvesting and regeneration resulted in lower streamflow (Kuczera 1987; Cornish 1993; Cornish and Vertessy 2001; Webb et al. 2012; Brookhouse et al. 2013). This reduction in streamflow was reported to be less when mature mixed eucalypt forest species were converted to younger post-harvest mixed eucalypt forest species than for forest dominated by Mountain Ash (*E. regnans*) forests in the same region (Webb and Jarrett 2013).

A short-term increase in streamflow and subsequent reduction due to tree regrowth is also observed with stand dynamics following fire (Scott 1993; Lane et al. 2010; Smith et al. 2011) but flow trajectories depend on the severity of the fire: a high severity fire reduces evapotranspiration, but a moderate severity fire leads to higher evapotranspiration and higher flow reductions (Nolan et al. 2015).

Studies reported that streamflow increases in the first few years after harvesting (Bren et al. 2010; Iroume et al. 2005; Post et al. 1996), or thinning (Stoneman 1993; Lesch and Scott 1997; Ryan 2013) due to the removal of trees after which there is a reduction in flows due to the growth/evapotranspiration of trees.

Several studies addressed mitigating factors such as buffers adjoining eucalypt plantations. Native tree buffers along streams in eucalypt plantations increased streamflow and decreased sediments and nutrients in rivers (Little et al. 2015). Grass buffers along streams in eucalypts plantations may increase streamflow levels (Dresel et al. 2018). Streamflow may be lower with higher stand density (Cornish 1993; Le Maitre et al. 2002) when trees are planted closer to streams (Mensforth et al. 1994); or if a large proportion of the catchment is under plantations (Little et al. 2009; Iroumé and Palacios 2013; Alvarez-Garreton et al. 2019).

5.8. Groundwater

Groundwater levels under eucalypts or pines were generally found to be lower compared to areas under agriculture (Bari and Schofield 1992; Pierce et al. 1993), grasslands (Eastham et al. 1993; Adelana et al. 2015), native shrubs (Le Maitre and Versfeld 1997; Le Maitre et al. 1999), or acacias (Nolan et al. 2018). The same effects were observed in land cover change studies. Groundwater reserves are lowered where land cover changes from agriculture to eucalypt plantations (Stolte et al. 1997; Versace et al. 2008); and from grassland to eucalypt plantations (Bari and Schofield 1991; Sanford et al. 2003; Dean et al. 2016). Moreover, an increase in water tables was reported where land cover changes from native eucalypt forests and shrubs to agriculture or pastures happened (Eberbach 2003), which have caused salinity troubles in Australian groundwaters by seawater intrusions (L. L. Pierce et al. 1993), and confirmed that eucalypt trees use more water than agriculture or grassland.

Studies also showed that some stand treatments may affect the impact of eucalypts on groundwater levels. For instance, groundwater levels were lower with higher stand density than lower stocking (Heuperman 1999); grass buffers along streams can enhance groundwater recharge and streamflow (Dresel et al. 2018); and groundwater levels increased after thinning and removal of trees (Stoneman 1993).

5.9. Analysis of factors behind outlying results

The structured review of studies on eucalypts and water interactions demonstrates a strong scientific consensus that eucalypts affect water quantity in all parts of the hydrological cycle (evapotranspiration, streamflow, soil water content and groundwater). A minority of studies did not support this finding, reporting either no effects, no clear trends, or no differences between compared categories. These studies did not cluster at any particular scale of analysis, nor do they show any patterns related to the native or non-native status of the eucalypts (Australia versus the other two cases), nor were they associated with any particular methodological differences (with the exception of Silberstein et al. (2001), who used four measurement techniques for evapotranspiration and reported differences in one of these that used the eddy covariance technique).

A primary difference identified in some of these outlying studies was the study design. For instance, Benyon and Doody (2015) compared evapotranspiration of *Eucalyptus globulus* and *Pinus radiata* plantations, but of quite different ages and densities (the pine stands were twice as old and less dense), and their results was the only study to suggest that both trees have similar evapotranspiration in a conversion from agriculture to plantations. Benyon and Doody (2015, p.1185) state that "*On the basis of our results, conversion from agriculture to conifers will have no greater or lesser effect on water resources than conversion to a broad-leaved, evergreen eucalypt species, once the canopy of the plantation has closed. Differences between species in time to canopy closure or rotation length may have an impact, but we have not examined these effects here*". Soto-Schönherr and Iroumé (2016), also comparing pines and eucalypts, reported that their results were actually influenced by the use of mixed stands (e.g. eucalypts with native broadleaves, pines with the native *Fitzroya cupressoides*), given that the characteristics of native broadleaved in high rainfall sites strongly influenced the analysis of the data (Soto-Schönherr and Iroumé 2016). The above studies have in common that they refer to the evapotranspiration phase. Finally, in studies making conclusions based on land cover change, a key issue in study design was the proportion of study area subjected to the change. This might explain the divergent results of Liu et al. (2004) and Brown et al. (2015), who found no changes in streamflow. In both studies the land use change affected less than 4% of the catchments being measured, whereas the other studies we reviewed reported higher change catchment areas (10%-100%). The two studies cited appear to be below a threshold to identify a hydrological response.

5.10. Knowledge gaps

A final component of this review was to identify knowledge gaps and proposals for future research. These are summarized here. First, regarding streamflow, Dresel et al. (2018) highlighted the need to explore in more detail the transit times between surface and groundwater, since they found large reductions in groundwater by trees, but no clear trend of reductions in streamflow. This shows a gap in our understanding of surface-groundwater interconnection and time response for measurable hydrological effects of trees (Dean et al. 2016). Little et al. (2009) call for more detailed studies on the long-term hydrological impacts of forest plantations through their rotation periods.

Second, on evapotranspiration, according to Albaugh et al. (2013) improving our understanding of water use efficiency of clonal trees is important for understanding the implications of genetic improvement on water use, as well as to improve understanding of the structure and physiological functions of trees. Additionally, more measurements of the impacts on evapotranspiration by insect and pest attack are suggested by Cunningham et al. (2009).

Third, regarding soil water, Hervé-Fernandez et al. (2016) suggest that further work is required to elucidate the soil compartments from which trees extract water and the interactions between water, carbon and nutrients. In addition, Barrientos and Iroumé (2018) recommend further investigation of soil water storage processes and their interrelations with rainfall, streamflow, groundwater, evapotranspiration and forest management to allow better analysis of the implications of climate change scenarios for different types of forest.

Finally, about groundwater impacts, there are important knowledge gaps regarding root architecture and maximum root depths reached in different growth phases for different tree species (Benyon et al. 2006) and how this influences their capacity to access water from soil and aquifers (Benyon et al. 2001) because root depth is an important component in hydrological models to estimate tree water consumption (Milly 1994; Zhang et al. 2001; O'Grady et al. 2005). In this regard, in Chile and South Africa, the effects of *Eucalyptus* tree species on aquifers are an important gap in forest hydrology knowledge. Finally, few studies have explored the impacts of climate change on tree water use and catchment hydrology and the implications of different forest fire scenarios (Albaugh et al. 2013). Of the three countries, most work on fire and climate change scenarios has been in Australia (Lane et al. 2010; Li et al. 2012).

5.11. Conclusion

The review of published studies across three countries, comparing components of forest hydrology between eucalypt tree cover and other types of land use or vegetation cover, reveals that both native and non-native eucalypts generally reduce catchment water availability through higher rates of evapotranspiration that reduce streamflow, soil water content and groundwater. The effects of eucalypts on hydrology varies with bio-environmental conditions such as stand age, precipitations, soil, or groundwater availability, pest attacks, etc.; land use history; and forestry treatments. A small minority of studies do not support these findings. They add nuances to the overall understanding of the relationship between eucalypts trees and water use, with these deviations related to variations in study design: such as divergent tree ages and densities used in comparisons, mixed land cover categories, diverse water availabilities, and the scale/percentage of catchment-based studies. This highlights the relevance of understanding the study design in forest hydrology studies in order to contextualise and understand its results.

The results of this review are relevant for the general investigation, as it reveals that from the point of view of published peer-review articles on these revised forest hydrology topics there is mostly scientific consistency, despite the existence of some knowledge gaps in the field. The findings of this chapter are also consistent with other international reviews on forest hydrology (section 2.1). This makes it worthwhile to investigate the social dimensions of the production, circulation and application of the forest hydrology field and its knowledge contestations in Chile.

Chapter 6

Production and circulation of scientific knowledge: the forest hydrology field in Chile

This chapter focuses on analysing the social production and circulation of environmental knowledge in the field of forest hydrology in Chile. Four main questions are investigated: (B1) How have the forest hydrology field and its agents evolved over time? (B2) What are the schemes of perception, the choice of objects, approaches and the evaluation of possible solutions? (B3) How are the scientific capitals of the field composed by different claims of legitimacy, power and authority? And (B4), how do external political-economic relations shape production-circulation within the forest hydrology field?

The chapter guides its analysis on the concepts of the 'field theory' (Bourdieu 1975; Lave 2012) (see section 2.4.1), and is organised as follows. Section 6.1 introduces the empirical and theoretical context of this research. Section 6.2 provides an overview of neoliberal reforms in the forestry and scientific-university base sector in Chile. Section 6.3 provides an overview of the types of discussions currently present in the Chilean forestry hydrology field. Section 6.4 presents the participants and the social structure of the field. Section 6.5 analyses the habitus with its choice of objects and trends. Section 6.6 examines the capital of the field, with its struggles of legitimacy and authority. Section 6.7 analyses the relative autonomy of knowledge production and circulation in the field of forest hydrology in Chile. Section 6.8 presents the main conclusions of the chapter.

6.1. Introduction

The nexus between forest plantations and water resources has been a subject of debate among scholars in forest hydrology – the scientific field that studies how water flows through forests (Jones et al. 2009). In Chile, since the late 1980's, there have been many scientific and public debates about the nexus between forest plantations and water depletion. Although the scientific literature and global reviews of the forest hydrology field from the last forty years mostly conclude that converting other land covers to forest plantations generate lower water yields (see eg. Bonnesoeur et al. 2019; Jones et al. 2016; van Dijk and Keenan 2007; Zhang et al. 2001; Bosch and Hewlett 1982), in Chile - at least until 2019 - there is no unified official view on the matter.

Chile is the country with the second-largest expanse of forest plantations in South America (Jones et al. 2016), and since the 1990's, it has been one of the ten largest exporters of forestry products in the world (Jelvez et al. 1990). Additionally, Chile is facing a 'mega drought' with predominantly dry years since 2010 (Garreaud et al. 2020), and water scarcity has become one of the country's most important environmental problems (Bachelet 2015). Some members of civil society associate the increase of water depletion with the introduction of exotic forest plantations (Palma et al. 2013; INFOR 2013; Torres-Salinas et al. 2016; CONAF 2017a), but others attribute these water reductions mainly to environmental causes of climate change, or to an increasing use of water by population growth in rural areas (Interview 8, November 2018; Interview 24, November 2018).

In this kind of environmental debate, different environmental or scientific explanations are produced and circulated at the initiative of diverse actors. Sometimes by individual researchers, as well as, sometimes, in collaboration with the State services, academics, or forest industry, each of them with different or similar interests. These interests may challenge the production and circulation of scientific knowledge that are subsequently mobilized in policy-making processes (Forsyth 2003; Paulson et al., 2003). When this type of challenges occur, environmental studies become a political-economic issue (Blaikie 1985), which is a topic of interest for science studies and political ecology, both of which address the production of environmental science.

To further understand the multiple social influences in the generation of environmental knowledge, several scholars have called for the importance of understanding the interconnection between the production, circulation and application of knowledge (Goldman et al. 2011); where often less attention has been paid to the production of that science (Robertson 2016; Duvall 2011). To account for this social-production view of a field, this research relies on the field concept developed by Pierre Bourdieu and subsequently operationalised by Rebecca Lave (see section 2.4). In the common sense of the word, a field is "a particular branch of study or area of expertise or competence" (Oxford Dictionary 2021), a discipline or subject. But more than that, a field is constituted by people, institutions and their social relations. In this sense, a field is a socially constructed space with dynamic borders, without components but formed by agents and institutions that occasionally face struggles (Bourdieu 1988; Bourdieu 2004).

Based on interviews with key forest hydrologists doing research in Chile and drawing upon the *field* concepts operationalised by Lave (2012), this chapter analyses the external neoliberal political-economic context and the internal scientific struggles in the production of knowledge about forest and water in Chile, looking at the role of university, State, and private-sector institutions over the past 40 years. In more general terms, this chapter furthermore argues that science studies and political ecology studies working on the production and circulation of environmental knowledge could benefit from the field's theory and its concepts to deepen the comprehension of the social aspects of habitus, legitimacy and autonomy that underpin scientific production. Empirically, this chapter contributes to the literature by investigating how the production and circulation of knowledge in the Chilean forest hydrology field has evolved since mid-1970s.

6.2. Neoliberal reforms in Chile: plantation forestry and science

Any kind of field – scientific, social, economic, artistic, etc. – is organised at any given historical moment (Bourdieu 1975; Lave 2012), which as such has to be considered. As already mentioned in section 4.2, Chile's forestry sector has a long history that has contributed to building the current forestry and scientific sector in Chile. As a reminder of certain milestones of this macro-historical context of current neoliberalism in Chile; until the mid-1950s, the Chilean forestry industry was oriented mainly to the domestic market for native sawn timber (Arze and Svensson 1997b). In 1965 the first National Forestry Program was created with the goal of afforesting[12] eroded lands, using *Pinus radiata* (70%) and native species (30%) (Cabaña-Chavez et al. 2013). In 1967 and 1969 the Chilean Economic Development Agency (CORFO) created the forestry companies Celulosa Arauco and

[12] 5 million hectares in 35 years (Cabaña-Chavez et al. 2013).

Celulosa Constitucion to strengthen development of the forestry industry in Chile (Frene and Nuñez 2010; Cabaña-Chavez et al. 2013) (see section 4.2.3 for more details).

In the early 1970's there were cultural, economic and political forces driven by a coup d'état (11th of September 1973) in the country to promote further private industrialization and expansion of the Chilean forestry sector that led to an increase in conversion of agricultural land, native forests and shrubs to exotic forest plantations (Heilmayr et al. 2016). Specifically, this forestry transition (Kull 2017) was facilitated by Decree Law N°701 in 1974, which introduced extensive exotic forest plantations in south-central Chile (Biblioteca Nacional del Congreso de Chile 2008). During the first three decades the dominant tree species in these plantations was *Pinus radiata*. But since the mid-2010 eucalypt species have been gaining predominance in the national forestry context (Interview 15, December 2018; Interview 16, December 2018).

In addition to economic production, the promotion of large-scale monoculture forestry in Chile environmentally aimed at reversing soil degradation-erosion processes (Aliste et al. 2018). At the same time, it sought to increase the development of the national forestry with a series of economic incentives aimed at transferring the execution of productive forestry activities to private actors (Niklitschek 2007; Cabaña-Chavez et al. 2013). In particular, Decree Law N°701 provided a legal incentive for forestry activities by subsidising 75% of the net forestation costs for 20 years and exempting forestry companies from land taxes (Cabaña-Chavez et al. 2013). Additionally, in 1976 and 1979 the companies Celulosa Arauco and Celulosa Constitucion were sold to COPEC companies and the current company Arauco was founded (Arze and Svensson 1997b). Since the 1990s, CMPC and Arauco have become the two main companies in the Chilean forestry sector (Epstein et al. 1999).

The set of political reforms to forestry that Chile has undergone over the last decades have been very successful in generating economic benefits (Reyes and Nelson 2014). These reforms meant that in one generation Chile created one of the most competitive forestry industries in the world (Clapp 1995). Already in 1990, Chile was one of the 10 largest exporters of forestry products in the world and had the largest *Pinus radiata* plantations in the world (Jelvez et al. 1990). For this reason, the forestry sector has been labelled by some as 'the Chilean miracle' (Arze and Svensson 1997b).

This growth and export boom has been associated with a broader set of free market policy reforms in Chile (Kurtz 2001), and in particular, with a shift to neoliberalism, on the basis of which the whole country was restructured after the coup d'état in 1973 (Kay 2002). The Chilean case has been labelled as 'the first laboratory, experiment, or revolution for neoliberal reforms' in the world (Escobar 2003; Castro-Hidalgo and Gomez-Alvarez 2016; Stromquist and Sanyal 2013; Clark 2017; Alemparte 2021), and currently, as the most mature neoliberal regime in the South American region (Alexander 2009; Pérez-Ahumada 2014). The term of neoliberalism is characterised by multiple and contradictory meanings (Venugopal 2015) but maintains certain common features in its process of neo-liberalisation (Bakker 2015). In general terms, Chilean neo-liberalisation has consisted in a trade of liberalisation to increase industrial efficiency (Clark 2017). Chilean neoliberalism reside in the prioritisation of economic activities over other social relations, the reduction of the State's role (Gutiérrez 2019), and privatization mechanisms (Bakker 2015), among others. Thereby transforming the Chilean State into an 'umpire State' (Barandiaran 2018), which in certain cases has influenced the State's knowledge production, circulation and decision-making, as evidenced in the case of Petorca in Chile (Budds 2009).

In Chile's neoliberal transition, deep regulatory reforms were implemented in all domains (Ffrench-Davis 2002; Holmes 2015). These concern neoliberal reforms on water (Bakker 2003; Bauer 2012; Baer 2014; Molinos-Senante and Sala-Garrido 2015; Correa-Parra, Vergara-Perucich, and Aguirre-Nuñez 2020), fisheries (Altieri and Rojas 1999; Javiera Barandiaran 2018a), mining (Singh 2014), health (Unger et al. 2008; Rotarou and Sakellariou 2017), or highways (Trumper and Tomic 2016), among others. Neoliberal changes in environmental and regulatory institutions (Javiera Barandiaran 2015; Ibarra et al., 2018), were paralleled by changes in forestry.

As presented in section 4.2.2, neoliberal transformations in the forestry sector were one of the first to be applied in the country. Where the State forestry sector, including its industries, pulp mills, sawmills, plant nurseries, technical training and research centres and land, among others, were privatised. All this, has led to important restrictions for the production and circulation of forestry knowledge by the Chilean State. All those aspects are relevant, as the privatisation is one of the main characteristics that Lave (2012) recognises in the neoliberal science regimes.

In this sense, a major change also took place in the university and research sector. In the 1980s, State funding for universities was reduced (Barandiaran 2012). The traditional universities adapted to the neoliberal economy and gave rise to the creation of private and for-profit universities in the country (Barandiaran 2012). Currently, the Chilean State invests around 0.5% of GDP in research and development, and uses a competitive resource allocation model (Diaz 2013). This means that doing science in Chile is very challenging and competitive for academia, and that a great amount of scientific capital (i.e., reputation, publications, CV, networks) is required in order to obtain the competitive scientific funding from the National Commission of Research, Science and Technology (CONICYT) (Interview 21, November 2018). In the same way, the various State agencies, such as the environmental institutions, often do not have the funding to conduct their own investigations (Ibarra et al., 2018). The aforementioned is also a reality in the State forestry institutions in Chile.

6.3. The Chilean forest hydrology discussions

As mentioned before, a field is a social open space formed by institutions and agents which occasionally may face struggles (Bourdieu 1988; Lave 2012). In this perspective, it is relevant to know when and how the forest hydrology field started in Chile and when discussions about it appeared. As presented in section 4.1.4, forest hydrology studies in Chile, started in 1970 (Iroume and Soto 2013; Jones et al., 1975) and subsequently in early 1980s, with work carried out by Professor Anton Huber and at the time student, Professor Carlos Oyarzun of the Universidad Austral de Valdivia (Interview 2, November 2018; Interview 7, January 2019; Interview 23, December 2018). Huber started his research at the experimental sites of the university (at that time in the Los Lagos region). Afterwards, he worked in the area of Concepcion, especially with the forestry company Mininco (Interview 23, December 2018; Interview 2, November 2018). The studies were conducted because there were many discussions surrounding water consumption of *Pinus* and *Eucalyptus* plantations, introduced extensively in south-central Chile in the mid-1970s with the introduction of Decree Law N°701 (Biblioteca Nacional del Congreso de Chile 2008). At that time, there was a lack of national forest hydrology data and the discussions relied primarily on international studies developed in Australia, New Zealand and South Africa (Interview 2, November 2018; also Iroume et al. 2005).

Since then, debates over the influences of plantations on water resources have continued. For instance, in the 2010s, some actors stated water depletions in forestry territories is due to the decrease in rainfall (climate change), forestry plantations, or water pollution, among others (Oppliger 2011; Palma et al. 2013; INFOR 2013; CONAF 2017a). For some agents, the reasons were complimentary, whereas for others they were mutually exclusive; making the understanding of the issue highly complex and uncertain. At the same time, there were also several actors who totally denied the existence of water depletion problems in these rural areas of the country (Interview 2, November 2018), which further distanced the diverse understandings about this phenomenon.

But what is generally said by the experts producing scientific knowledge in Chile about forestry plantations and water reductions? Most forest hydrology researchers from academia, and some regional State representatives maintain that forestry plantations influence water depletions in forestry lands, stating that this is nationally and internationally known (Interview 3, November 2018; Interview 4, December 2018; Interview 6, December 2018). At the same time, there seems to be a gradient in the academic world about the uncertainty or knowledge gaps on the subject. Some researchers also declare (or declare that other academics state) that there are still certain processes to be understood because it is not known how they work, especially around knowledge gaps such as ground-soil water dynamics or climate change (Interview 2, November 2018; Interview 20, December 2018). Other academics, while also acknowledging the effects of forestry plantations on water reductions, also stress the complexity of nature, the magnitude/significance of reductions, and the existence of many uncertainties (knowledge gaps) that would make it somewhat difficult to mention that there is an effect on water reductions from forestry plantations. In this sense, some academics seem to stress the complexity and uncertainty of forest hydrology phenomena as an impediment to be able to say effectively that forestry plantations have an effect on water reductions downstream. As two academics put it when talking about uncertainty on the effects of forestry plantations on water reductions (researched in Chile since the 1980s):

> "*In general, and I would say that forests* [*forestry plantations or native forests*] *in general, what are the downstream effects of the presence of a forest is undoubtedly that a forest will consume more water than a shorter vegetation* [*grassland, agriculture, etc.*], *I think there is a strong, a strong agreement in the research. And the big discussion is what is the difference* [*in magnitude*], *where*

there begins to be [uncertainty]… what are the uncertainties to be able to say effectively what there is the effect [of water reductions] that a forest has downstream and probably a plantation since it is a being, a younger being is going to have a greater effect than a more adult forest and that is logical because the same thing happens to us, a young growing being is going to eat much more than a much older gentleman let's say and that no longer requires so much energy to move" (Academic 1).

"[there are] *5 minutes of certainty and the rest of the time of uncertainty (...) Of course, if we are honest, any hydrologist who is honest or any person who is honest who works on water resources issues, we know that we have a lot of uncertainty because we work with nature, we work with the work of god, god took this to laughter looking at joseph, what we do and because the system is not linear and it is multidimensional, so what we are going to do is approximate it little by little.*" (Academic 2).

Some industrial and academic researchers for their part, while also acknowledging that forestry plantations influence water reductions, do not openly affirm it either, and some doubt the significance of the effect as it is seemingly small for them or state that it has non-significant effect on water reductions (Interview 9, December 2018; Interview 1, December 2018). Currently, there is a diversity of scientific views among the country's forest hydrologists (comprising academics, government agents and forestry companies). Three main issues appear to stand out in (oral) discussions about the forest hydrology studies: (1) contradictory statements about existence, availability or denial of forest hydrology research in the country (2) aspects of material and symbolic power about the legitimacy of this research; and (3) other communicational-language aspects in circulating knowledge about forest hydrology that can lead to misunderstandings (or confusion) on the effects of forestry plantations over water resource.

First, there are contradictory perceptions about the existence or availability of forest hydrology research in the country, and this concerns in particular state forestry institutions. These differences among forestry state institutions are also observable across administrative scales within the state. For example, on the one hand, at the national level, senior state forestry representatives declare that they are unaware – ignorant or deny – of the existence or relevance of research about forest hydrology in the country. These senior governmental stakeholders state that to their knowledge there is no information on forest hydrology that demonstrates adverse effects of plantations on water resources in the country, or that studies are insufficient or irrelevant research because research does not provide solutions for the forestry market (Interview 24, November 2018; Interview 8, November 2018; see also INFOR 2013). As national leaders linked to the Chilean State's forestry institutions stated in 2018.On the other hand, regional levels of the State forestry institutions, recognise the existence of multiple forest hydrology studies in the country and develop and monitor some micro-watersheds themselves (Interview 17, December 2018). Academics and the forestry industry for their part, also acknowledge that there are many forest hydrology studies scattered across the country (Interview 7, January 2019; Interview 23, December 2018). But the industry representatives state, for instance, that there are few long-term studies in the country (Interview 23, December 2018). International organisations linked to forestry, for their part, have other statements on forest hydrology research in Chile. For instance, according to an officer from FAO (forest and water section in Rome), Chile is one of the world's leading countries in terms of forest hydrology research:

> *"Chile is in a better position than most countries globally. Because you have a research institution like INFOR within the government for example. And because perhaps the issues have been politic contentious, going from agriculture to exotic plantations versus native … so yes, I would say from a forest-water perspective, Chile is maybe more advanced than other countries. Even the fact that water is part of the forest strategy until 2023. Most countries do not have this".* (Interview 34, October, 2018).

This FAO-Rome statement may also be consistent with an academic study conducted in early 2010 – written but unpublished (being an internal forest hydrology report) by one of the Chilean State forestry institutions at the national level – this study reports that in Chile there have been monitored at least more than 80 watersheds between Valparaiso region (V) and Los Lagos Region (X). Ten of those correspond to large basins, mainly monitored by the Universidad Austral de Chile, followed by the Universidad de Concepcion and Universidad de Talca. And more than 50 experimental catchments were still under active monitoring by early 2010. Such contrasting claims and facts make the debates complex, and are used to establish or deny existence of forest hydrology studies and knowledge in the country.

Second, with regard to the legitimacy and authority over forest hydrology studies – as shown in the previous point – these have been frequently put into question, notably by different groups producing forestry hydrology studies in the country. Aspects such as the nature of the data (generated by whom, how, during what period of time, etc); the cross revision of the information; and the communication of the information produced (where, how to publish, etc), have been important elements in discussions on the legitimacy of the country's forest hydrology studies. For instance, the use of monitoring stations of the General Directorate of Water of Chile (DGA) for developing forest hydrology research, is considered by some academic actors as a sign of transparency and legitimacy of the forest hydrology information, given that this database consists of public information that all actors can access and review (Interview 1, December 2018; Interview 7, January 2019). However, other, industrial, actors don't seem to agree with this and prefer to develop their own databases (monitoring) without sharing them. Therefore, the legitimacy of forestry industry studies has been put into question for not sharing their forest hydrology databases on which there are based with other forest hydrologists who during years have requested this (Interview 2, November 2018; Interview 3, November 2018; Interview 7, January 2019; Interview 20, December 2018). The communication of the forest hydrology research results at scientific conferences (Interview 7, January 2019), or by the publication of peer-reviewed forest hydrology works has been considered by some actors as another crucial manner of validating and legitimising forest hydrology studies in Chile (Interview 2, November 2018; Interview 21, November 2018). Considered by some as less legitimate, are forest hydrology works that are published and circulated in reports by certain forest hydrology actors without blind external review (Interview 2, November 2018). Additionally, legitimacy of some research has been challenged by some industrial actors because they would have short time frames (Interview 23, December 2018), or because of the antiquity of the methodologies used by the first studies, versus new technologies that would be more accurate and valid today (Interview 23, December 2018). Or, some methodologies would simply be imperfect and provide less valid studies than others (Interview 7, January 2019). All these aspects are discussed in more detail in section 6.6 about legitimacy and authority in the Chilean forest hydrology field.

Third, when communicating knowledge about forest hydrology studies, there are different issues and certain objects at stake. For some forest hydrology actors, despite the influence of climate change and diverse environmental conditions that play part, forestry plantations – of *Eucalyptus* or *Pinus* – clearly contribute to water reductions. This would be due for instance, to the fact that forestry plantations have a lower water regulation capacity compared to other permanent vegetation cover, such as grasses, native forests, etc., and to the age of the trees growing, because younger trees consume more water than older forests (Interview 7, January 2019; Interview 13, December 2018; Interview 17, December 2018; Interview 18, December 2018; Interview 20, December 2018; Interview 30, November 2018). On the other hand, there are field agents who – while recognising or at least not denying that forestry plantations contribute to reduction of water resources – state that the hydrological differences between native forests and forest plantations may perhaps not be that much to become significant/relevant (Interview 1, December 2018; Interview 4, December 2018; Interview 9, December 2018; Interview 14, November 2018). This is, so they argue, because there are still many uncertainties[13], and because climatic, geological and soil factors are more relevant than the type of vegetation cover (Interview 3, November 2018; Interview 6, December 2018; Interview 14, November 2018). In this respect, a sub-group of academic actors has come to put forward a new hypothesis base on which they intend to propose a new theory or trend in the forest hydrology field. According to this hypothesis, some state that Chile would be an exception to the international scientific forest hydrology findings – which acknowledges the large water uses that these productive forestry plantations have – due to its unique[14] Mediterranean climate (Interview 1, December 2018; Interview 12, November 2018). For this reason, it would not be possible in Chile to use international literature to refer to the effects of forestry plantations on water resources (Interview 12, November 2018). All this generates doubt on, and challenges about what is already known nationally and internationally about the effects of fast-growing forest plantations on the hydrology of a site.

Additionally, there are different stances on whether local experiences or knowledges of rural inhabitants, should be taken into consideration to find possible solutions to this issue. For instance, regarding the issue of water and rural communities living in forestry regions, there are views that argue that the generation of local knowledge[15] about people's water-

[13] Understood by them as some issues where the processes involved are not fully understood or where there are knowledge gaps, e.g. climate change, groundwater and soil water storage dynamics, the complexity of scaling up processes, etc.
[14] This declaration of Chile as having unique Mediterranean climatic characteristics is very inaccurate. Many countries around the world growing *Pine* and *Eucalyptus* tree plantations have Mediterranean climates. Some regions in Australia and South Africa are among them.
[15] Lave (2015, p.246) understands local knowledge as an extramural production of knowledge "typically used to describe the agro-ecological knowledge of marginalized peoples in the developing world".

experiences (experiences of water increasing or decreasing in forestry lands) should be considered in forest hydrology discussions (Interview 2, November 2018; Interview 7, January 2019); while other views hold that peoples' perceptions could sometimes be too inaccurate to be considered in forest hydrology discussions (Interview 3, November 2018; Interview 13, December 2018). Additionally, for some of the actors, population growth and people's or agriculture water consumption would be factors that, together with climate change, would be responsible for water scarcity in rural areas of the country (Interview 1, December 2018; Interview 12, November 2018).

The different aspects mentioned above become more relevant when, subsequently, it is time to evaluate what scientific information to use or not for the formulation of public policies, and what measures should be applied or not, in the forestry territories.

The resulting uncertainty about the legitimacy and authority discussions on water-forest interactions in Chile among stakeholders, has helped to keep the forest hydrology debates going. This observation is in line with what Barandiaran (2015) says about the analysis of the role of science in the system of environmental assessments in Chile, where uncertainty helps to maintain tensions that make environmental assessment difficult.

6.4. The social structure of the Chilean forest hydrology field

As explained before (section 2.4.1), a field is socially constructed by agents and institutions (Bourdieu, 1994; Bourdieu 2004; Lave 2012). In Chile, since the 1980s forest hydrology research has been undertaken mainly by the traditional public universities, namely the Universidad Austral de Chile (Valdivia), the Universidad de Concepción (Concepción), the Universidad de Chile (Santiago), and the Universidad de Talca (Talca), this last one until 2020 when the forestry career (and its forest hydrology teaching) was closed due to its low scientific productivity (UTalca 2020). Forest hydrology research has also been undertaken pioneeringly (since 1970 but inconstantly) by Chilean State agricultural and forestry institutions, and most recently (since 2008) by the largest Chilean forestry industries, as detailed in the historical review of the science of forest hydrology in Chile, in section 4.1.4.

Currently, these institutions are collaborating as well as competing for legitimacy and authority on the subject of water and forest interactions. In academia, forest hydrology is taught in some bachelor's and master's degree courses. There are three doctoral programmes doing research in forestry in Chile (Salas et al. 2016), at the Universidad Austral de Chile, Universidad de Concepción and Universidad de Chile. In particular, the Universidad Austral de Chile historically had the scientific authority in the field. It was this university that started the forest hydrology studies in the country, with the work of Professor Anton Huber and his assistant – currently professor – Carlos Oyarzún in the early 80's. The first studies began at the Faculty of Science, and then spread to the Faculty of Forestry and Natural Resources, where the largest amount of research in this area has been carried out. Nevertheless, it is important to highlight that from the early beginnings of Chilean forestry hydrology research, there were incipient and diverse collaborations between academics, governmental institutions and forestry companies. Cooperation strategies have changed over time, but some still remain.

Nowadays, the Universidad Austral de Chile, is the only forestry faculty in Chile to offer a doctorate in forest ecosystems and natural resources, with the option to obtain a degree in water resources and global change (UACH 2022a). The Universidad Austral de Chile has also been the only national university who has held two national and international congresses specifically on the theme of forests and water. This in 2013 and 2018, in collaboration with the International Union of Forest Research Organizations (IUFRO), and State forestry institutions. Some academics from this university also collaborate with forestry industry projects.

For its part, the Universidad de Concepcion has been the only university in Chile that has developed two research projects focused solely on *Eucalyptus* species and their water use efficiency to understand the relationship between water uses and growth (Rubilar and Valenzuela 2011). This happened in cooperation with the companies Bioforest and CMPC (Interview 23, December 2018). At the Universidad de Concepción, the environmental sciences center (EULA) also stands out for its studies in forestry hydrology and watersheds (UdeC 2022b).

The Universidad de Chile for its part, is only recently taking up again a curriculum more oriented to forest hydrology by developing – together with other faculties – a bachelor degree focused on the study of water resources that includes social and forest assessments with an interdisciplinary approach (Interview 21, November 2018; UCH 2022c). But this bachelor degree is not yet in operation and plan to open in 2023 (UCH 2022c).

In 2020 the board of the Universidad de Talca took the unanimous decision to close the faculty and the forestry engineering course, given the low number of students enrolled and the fact that "*the productivity of the faculty was also below the institutional average, while the number of projects in execution represents only 0.01%*" (UTalca 2020). However, previous to the closure of the faculty and career; the University of Talca hosted the CTHA (Technological Centre for Environmental Hydrology), which has been an institution that has developed multiple national – and occasionally international – reports on forest hydrology in Chile (UTalca 2022a). Recently, and after the closing of the career, one of these professors has changed his institutional affiliation from University of Talca to the Faculty of Forestry Sciences of the Universidad de Chile, and subsequently to the UC Wood Innovation Centre of the Universidad Catolica de Chile

Second, there are two main State forestry institutions that have done or are doing forest hydrology research: CONAF (National Forest Corporation) and INFOR (National Forestry Institute). Under the mandate of the Ministry of Agriculture, they are in charge of overseeing the forestry activities in Chile. CONAF was created in 1972 as a replacement for the previous forestry institution, the Corporation for Reforestation (COREF) (Cabaña-Chavez et al. 2013). CONAF is a private and non-profit organization through which the Chilean State contributes to the forestry development (Salas et al. 2016). An example of its forest hydrology activities is the development of the technology transfer SHETRAN project, from 1994 to 1999, in collaboration with the University of Newcastle (Bathurst et al. 1998). The project measured flow and sediment transport in forests and forest plantations in the three micro-watersheds of La Reina (pine and later eucalypt), Rio Clarillo (native forest), Minas del Prado (pine), and two carcavas in Chosme (pine) (Bathurst et al. 1998). Subsequently, a professor from the Universidad Austral de Chile – without being an official part of the project – collaborated closely with the SHETRAN project, and after the closure of the project, this professor continued voluntarily with the monitoring of the La Reina catchment for more than 20 years (Personal communication, January 2021). This confirms that in the mid-1990s there was scientific cooperation on this issue between governmental institutions, international partners and academics from the Universidad Austral de Chile. Nevertheless, there are some criticisms of CONAF for not always being constant in its hydrological monitoring watersheds projects (Interview 23, December 2018). Currently, CONAF has a National Programme for Watershed Management and Soil and Water Conservation focused on hydrological forest-soil-watershed restoration (CONAF 2021). However, its participation in forest hydrology research has decreased in the national context, as they have not continued with active projects in the field.

INFOR for its part was created in 1961 as a FAO project and in 1965 became an official institution of the Chilean government (Cabaña-Chavez et al. 2013). INFOR is the governmental institution which “generates scientific and technological knowledge for the sustainable use of forest resources, including the statistical information for different aspects of the forestry sector” (Salas et al. 2016, p.6). However, the institution's research has mainly prioritized forestry development (Frene and Nuñez 2010b), and the institution over time has gone through active and less active periods of work on forest hydrology issues. As an example, in 2014, the first Forest Ecosystems and Water Programme was created by INFOR in the regions of Valdivia, Concepcion and Chiloe (Interview 17, December 2018; Interview 18, December 2018). One of the objectives of the Forest Ecosystems and Water Program is to create an online platform/dataset, inviting forest hydrology actors to register on the website all hydrological monitoring stations in the country (Interview 17, December 2018; INFOR 2021c). In this respect, in 2021, Llancahue, San Pablo de Tregua, Reserva Costera Valdiviana (Universidad Austral de Chile), and Rio Futa (instituto Forestal, sede Los Rios) were the unique long-term flow monitoring stations in forest areas officially reported in the online catalogue of the Forest Ecosystem and Water Program (INFOR 2021c). This programme was originally funded until 2020 (Interview 18, December 2018) after which funding had to be extended. The above reflects the situation that INFOR does not have constant funding and usually it must compete with universities or other institutions for research funding, which has led them to focus mainly on short-term projects (Salas et al. 2016). For this reason, according to Donoso and Otero (2005), until the 2000’s, INFOR did not have experimental forests for carrying out long term research.

Third, the private sector actors include forestry companies which have done forest hydrology research in Chile, such as Celulosa Arauco y Constitución S.A. (Arauco), Mininco S.A. (CMPC), as well as Masisa S.A. The main forestry companies in Chile are Arauco S.A. and CMPC S.A. (Chilean based investments). Currently, Arauco is among the top 5 pulp and mill suppliers globally; and it has become the largest owner of forest plantations in South America (1.67 million hectares) (MundoMaritimo 2012). During the late 1990s, Arauco created a company for forestry research called Bioforest S.A., focussing on forest product development and market solution-oriented forestry research (Arze & Svensson, 1997). Bioforest developed a wide range of research, including amongst others on the selection and breeding of genetic varieties of eucalypts, aiming at the increase of forest productivity (Rubilar and Valenzuela 2011). In the 1990's, the forestry company Mininco – without carrying out research themselves – collaborated with Professor Huber from the Universidad Austral de Chile by giving him access to their forestry lands for carrying out forest hydrology monitoring-projects. In 2005, forestry Masisa started watershed monitoring (Interview 28, January 2019).

In 2008, motivated by growing national debates about the water effects of forest plantations, Bioforest – the research filial of Arauco forestry company – started its own multi-long-term forest hydrology monitoring project[16]. This project includes the development of partnerships with academia, and the diffusion of the information that is generated to different actors and decision-makers (Interview 9, December 2018; Interview 10, December 2018; Interview 11, December 2018). In this project, Bioforest is carrying out various collaborations on specific topics with some Chilean academics and two Australian expert consultants who have specialised in forestry hydrology issues (Interview 9, December 2018; Interview 5, November 2018). The project was born as a response to the growing demands and concerns of small rural communities living in the vicinity of forestry industry plantations, who blame the arrival of the industry for causing problems of 'reliability of water resources' (water reductions) (White et al. 2018). This is due to the fact that in Chile there are many small communities that are supplied with water from small streams or wells fed by catchments planted by the industry (White et al. 2018). Bioforest is seeking to develop a forestry hydrogeological model that will allow themselves to model water availability and diverse water uses (consumptions) in catchments (Interview 9, December 2018). The project has three specific objectives (White et al. 2018). The first goal (phase 1) is to generate models that allow in their visions a more accurate quantification of the effects of forest type, management, climate, soils and geology and how each of these factors may have relative influences in different locations. Second

[16] This project is measuring rainfall, sap flow, interception, runoff, soil moisture and aquifers (wells), among others, measurement instruments that were reviewed during the guided on-site visit at this experimental forestry plantation long-term monitoring project.

(phase 2), the project aims to develop a company forest management plan based on its modelling. This model seeks to include not only forestry plantations in its modelling, but also to consider factors such as agricultural water uses and human consumption of water that may contribute to water reduction in watersheds (Interview 9, December 2018). In this sense, the project's strategy in its modelling and management plan in the face of water scarcity states: "*water scarcity is not simply a matter of supply* [climate, soils, geology, or diverse land uses] *but must also factor in current and future demand due to changes in population and demographics. This must also be part of the modeling in the Bioforest strategy"* (White et al. 2018, p.4). In this sense, its research approach takes the affected rural communities and their increasing water consumption as a key external factor to be considered when addressing – the causes of and solutions – to water scarcity. Third, the project seeks to generate engagement with diverse external and internal industry stakeholders to guide future plantation and water scenarios in the country. This third objective (phase 3) also includes notions of adaptation, securing water infrastructure as a solution for communities, while also meeting the economic objectives of the industry in the affected rural areas/communities. In this regard *"the results of the project will be used to raise awareness of the complicated issues surrounding water supply and forest"* (White et al. 2018, p.1). In 2018, they were already in phase 3 of the project (White et al. 2018). Additionally, Arauco company seeks to establish close relations with the State (especially the MOP and DGA related to management of water resources in Chile) for the establishment and financing of infrastructural solutions for forest plantations' neighbours affected by the country's water shortage (Interview 25, December 2018). In this context, this industrial research project is born as part of a solution to social and environmental problems that the forestry company faces in neighbours' rural communities, and which constitute a challenge to its industrial economic sustainability. What is also at stake in this project is the company's intent to establish links with State politicians, academics and other experts, in order to produce, propose, influence and guide the construction of new forest hydrology science and future policy - solutions to the problems of plantations and water in Chile.

In a similar way, CMPC company also started in 2008 to develop its independent long-term forest hydrology monitoring research project; always in collaboration with one academic from the Universidad Austral de Chile (Interview 23, December 2018). Both companies use their own revenues to invest in their forest hydrology research. They have their own experimental plantations where they are performing long-term research in collaboration with some Chilean university-based forest hydrologists, as well as – as in the case of one company – since 2016 with two international consultants (former CSIRO Australian forestry researchers). (Interview 9, December 2018; Interview 5, November 2018). One forestry company claimed to have invested close to a million dollars in ecohydrology research development over 3 years (Interview 9, December 2018), and one academic noted that "Nacimiento is one of the largest (maybe is the largest) multi-catchment studies in the world and may be ranked with the H.J. Andrews Forest catchments in Oregon and the Caspar Creek catchments in California" (Personal communication 26, January 2021). Both companies, in turn, have created departments to deal with "water and communities" issues, through which they seek to support neighbours with water scarcity problems with infrastructural solutions (ARAUCO 2021; CMPC 2022). However, these two forestry companies have not collaborated much with CONAF or INFOR in forest hydrology research (Interview 23, December 2018; Interview 9, December 2018).

From the side of academia, there is a wide perception that forestry companies have not been open to collaborate and share forest hydrology information and state that this industrial practice has been in place for many years (Interview 21, November 2018; Interview 3, November 2018; Interview 22, December 2018). Among some accounts, there are academics who have tried to approach/collaborate and obtain information from the biggest forestry companies, and state that although they have been received and listened to, the conversations do not bear fruit, they are prolonged and do not arrive at anything concrete, so the researchers get tired and give up (Interview 20, December 2018; Interview 22, December 2018). Forestry industries have kept this 'selective' attitude in particular with those researchers who ask certain types of questions linked to the effects of water depletions and to whom one forestry company declared that it felt 'judged' and therefore avoided collaborating with these researchers (Interview 23, December 2018). One professor, however, states that one of the largest forestry industries has been 'very generous' in sharing information related to LIDAR imagery, among others. (Interview 14, November 2018). As to the industry side, on the other hand, acknowledging a selective criterion for collaboration with Chilean forest hydrology producers, they declare their intention to extend and continue to collaborate with multiple scientific actors in the future (Interview 9, December 2018; Interview 23, December 2018).

6.5. The habitus: research objects, concepts and possible solutions

Bourdieu (1975) understands habitus as social schemes of perception and action, which are acquired through an educational system (e.g. scientific training) and which enable the choice of research objects or the evaluation of possible solutions. It is argued here that there are two research trends in forest hydrology.

Although there is a great richness of research topics present in the forest hydrology field, as a broad generalisation, it is possible to identify the existence of two main research trends. These trends can be called 'ecosystem' and 'forestry hydrogeology' sciences approaches. They are visible in the comments of interviewed participants. These different trends present different research objects, concepts, as well as visions of different possible solutions to the water and forest discussions.

Both trends of scholars (across academia, industry and government members) are concerned with water care issues. Both recognise the existence of the mega-drought in the country, and both have done research in forest hydrology. However, they have focused their research and action in different ways (see Table 8). By using different research objects and concepts both trends are producing different "systems of generative schemes of perception, appreciation and action" which Bourdieu (1975, p.30) recognises as key habitus components.

On the one hand, the 'ecosystem' trend highlights not only the study of forestry plantations, climate, or soil, among other environmental components, but sets to study native forests and forest plantations alike to understand the forest hydrology of both. In this sense, this approach focuses on investigating the diverse internal factors present within forestry plantations that influence water depletions, and on comparing them with other land uses, such as native forests, shrublands, agriculture or grasslands in different geographical and climatic contexts. These factors are investigated in terms of runoff, evapotranspiration and soil studies. Researchers from this trend distinguish the terms 'forestry plantations' and 'native forests' as spaces with different environmental processes and water behaviour/phenomenology. For them, some key elements that distinguish a forestry plantation are the constant dynamics of harvesting, soil compaction, tree regrowth, and water consumption in young tree forestry plantations, among others. To study both native forests and plantations this trend uses concepts or disciplinary frameworks such as sustainability, ecosystem services, ecology, biological sciences, chemistry, climate, soil, watershed management, restauration, landscapes, and hydrology (Interview 2, November 2018; Interview 13, December 2018; Interview 17, December 2018; Interview 20, December 2018; Interview 22, December 2018). One example of this is the 'Forest Ecosystems and Water Programme' at the regional level, which applies theoretical concepts such as forest ecosystems, conservation, and watershed management, among others in its framework (INFOR 2021b). As a result, the programme participants have proposed solutions focused on the identification of areas or micro-catchments necessary for human consumption and aimed at managing, restoring and conserving areas, with a permanent land cover (i.e. without harvesting) of native forests or a mixture of native forests and forest plantations. At the same time, they promote water governance coordination mechanisms between rural inhabitants, forestry companies and the State at a micro-watershed level (Interview 17, December 2018; Interview 18, December 2018). These aspects also reflect an ecosystemic vision of possible solutions to the forest and water issues.

On the other hand, the 'forestry hydrogeology' trend studies forestry plantations too, but it pays attention to external socio-environmental factors of forestry plantations in influencing water reductions, such as soil water capacity and geology, and climate or biological aspects (e.g. tree clones) to understand how/to what extent these hydrogeological aspects may affect the hydrology of a site as well. These factors are investigated in terms of runoff, evapotranspiration and soils. For them, some elements that stand out are the gaps in knowledge or the relevance of the impact of planning on water resources over other external environmental factors such as rainfall, climate change, geology, soils, agriculture, people, etc., or the relevance of forestry plantations themselves in influencing water reductions. Some of them mention that some geological cracks/fault lines – in the Andes Mountain range – could be influencing the decrease of water. In addition, for some of them, there are also social factors to be considered, such as the growing demand for water from increasing rural populations as the increase of human water consumption might contribute as well to the water depletions in the forestry territories. To study these aspects, this trend usually uses concepts and disciplinary frameworks such as hydrogeology, water use efficiency, efficiency, climate, forestry management, ecohydrology, sustainability and productivity (Interview 1, December 2018; Interview 3, November 2018; Interview 6, December 2018; Interview 10, December 2018; Interview 23, December 2018). Furthermore, some of these scholars and field participants of this trend are also notable for using the concepts of 'forests', 'forest mass' or 'vegetation mass', to refer to productive 'forestry plantations' and 'native forests' alike, or to a mix[17] of both. Also, they use the term 'short vegetation' to refer for instance to 'grasslands'. An example of this trend is the Bioforest experimental research catchments, which focus on theoretical concepts such as drought (meaning decreasing rainfall), geomorphology, and human water consumption, among others (Bioforest 2014). As a result they have developed the 'Water Challenge Programme' (ARAUCO 2021) which proposes solutions focussed on infrastructure for drinking water, such as the construction of wells, mini-tanks, solar and electric generators, as well as the possible translocation of water between basins (Interview 9, December 2018; Interview 25, November 2018). These aspects also reflect an external and infrastructural vision of possible solutions to the forestry and water issues.

As one forest hydrology researcher states:

> "*From the human point of view with those costs versus making the change of use from plantation to something else, I don't know, which could even be native forest, even though the native forest at the beginning is still going to consume, therefore you are not going to notice the effect, but let's think about a use more like an adult forest in a year's time, or a meadow that also has its maintenance cost, But if you compare these costs of infrastructure versus forestry, they are orders of magnitude of difference in relation to increasing the flow that the communities have by one more litre, that is to say, look if it would be more expensive to make a forestry change than to make an infrastructure if you want to increase or normalise the additional litres to be delivered, then, the best is going towards...well* [infrastructural solutions]*"* (forest hydrology researcher in a forestry industry).

In this regard, for this forestry industry researcher, 'efficient' means a lower cost and faster solution. For that, the forestry industry focusses on water infrastructure-engineering solutions, such as the transport of water from one basin to another, and also divert attention from forestry plantation management or nature-based solutions.

[17] The above adds nuances on the water behaviour/phenomenology of forest hydrology, as shown in chapter 5 of this research.

Additionally, industrial researchers and representatives of the forestry company state that their social water program seeks to engage with the State institutions of the Ministry of Public Works (MOP) and the General Directorate of Water (DGA), so that these institutions are also engaging to finance these infrastructural solutions (Interview 25, November 2018). It is important to mention that under the current Chilean rural drinking water regulation the maintenance costs of the water infrastructures are borne by the rural inhabitants, as new water users of these infrastructures. This is something that all users of rural water infrastructures in Chile have to face, and these costs of water consumption generally depend on how much energy must be used to clean water (e.g. sediments) or to transport the water over distance and altitude changes from one point to another. Moreover, social and forest hydrology experts from a forestry company state that a) 'quotas' of water consumption per inhabitant-household could/should be established, as well as that b) rural settlement could/should be better planned and controlled through municipal regulation (policy), where in some cases the authorization of new houses construction should be prohibited when the watershed is not capable of supplying more water for a growing population, among others. (Interview 9, December 2018; Interview 25, December 2018).

All of the above suggests that in the particular case of one of the largest forestry companies in Chile, regarding possible infrastructural solutions, an economic aspect of externalisation or co-sharing of costs with Chilean society seems to be at stake. This co-sharing of costs involves especially the State and the rural population living in forestry territories. In addition, infrastructural solutions also divert attention from forestry plantation management or nature-based solutions (e.g. rewild, conservation, restoration, etc.) to water problems in rural communities.

These different research trends (e.g. focus on objects), its circulation (e.g. concepts, meanings and theoretical tools) and its application of knowledge (e.g. possible solutions) may also reflect cultural differences. Although the habitus does not dominate behaviour, it makes actions very likely (Lave 2012). Therefore, it is through the habitus that we can understand in a deeper way the conscious and unconscious practice of participants (Lave 2012) through which they construct science (Bourdieu 1988). By paying attention to 'research objects' or 'objects of knowledge' (e.g. the microbes Pasteur investigated, or trees investigated in the forest hydrology field) (Bourdieu 1975; Bensaude-Vincent et al. 2011; Knorr Cetina 2007), it is possible to understand some of the aspects that comprise the diverse "systems of generative schemes of perception" (Bourdieu 1975, p.30), or the "different machineries of knowing" (Knorr Cetina 2007, p.363). In this way, science and knowledge may or may not be unitary as has been thought, but fragmented, multiple and diverse in their construction (Knorr Cetina 2007; Brady 2013). This construction and its components can only be fully understood through historical analysis and by exploring them as psychological objects transformed by theoretical activity (Danziger 1993). In this sense, these different habitus trends of the forest hydrology field, may be consciously and unconsciously made and move the trend of scientific production towards different research directions. These trends directions focus on either the inside (ecosystem) or the outside (forestry hydrogeology) of forestry plantations.

Table 8. Forest hydrology trends: actors and objects of analysis

Institutions	Forest hydrology trends	*	Examples of forest hydrology activities	Specialities (main research objects)	Concepts and disciplinary frameworks used	Orientation and possible solutions mentioned
Government	*Forestry hydrogeology approach*	*No*	*(before e.g., Shetran project and Jica project)*	*Plantation, climate and soils*	*Productivity, efficiency, relevance*	*External and water infrastructure solutions related to people (e.g. human water demand should be evaluated); and forestry management solutions (e.g., design 'the magic hectare').*
	Ecosystem approach	*Yes*	*Watersheds and plots monitoring; e.g., forest ecosystem and water program*	*Plantations, native forests and sediments*	*Ecosystem services; watershed management; restauration; conservation, significant-relevant, etc.*	*Forest ecosystem solutions (e.g., a percentage of permanent land cover of native forest or a mix with plantations); and watershed governance solutions among different land users*
Academia	*Ecosystem approach*	*Yes*	*Watersheds and plots monitoring*	*Plantations, native forests, climate and soils*	*Sustainability; ecosystem services; ecology; conservation; restauration; biological sciences; soil sciences; hydrology, significant-relevant, some uncertainties (some gaps), etc.*	*Forest ecosystem solutions (e.g., larger buffer protection zones; restauration and conservation actions of headwaters and riparian areas; native forests); and watershed governance solutions.*
	Forestry hydrogeology approach	*Yes*		*Plantations, climate and soils*	*Geomorphology; efficiency; climate; ecohydrology; hydrology; productivity; sustainability, significant-relevant, many uncertainties (many gaps), etc.*	*forestry management solutions (e.g., reduce areas and increase densities and buffer areas of plantations; or choose different tree clones; diversify the use of tree species in forestry plots); and external water-infrastructure solutions.*
Industry	*Forestry hydrogeology approach*	*Yes*	*Watersheds and plots monitoring program; and e.g. the water challenge program*	*Plantations, climate, soils and native forests*	*Productivity, sustainability, efficiency; significant-relevant; biological sciences; climatology; geomorphology; etc.*	*External water-infrastructure solutions (e.g., infrastructures for drinking water such as wells, mini water storage tanks, inter-basin water transfer).*

Source: author. Based on interviews done in 2018-2019 in Chile. (*) Active research in forest hydrology.

6.6. The mobilization of capital: scientific legitimacy and authority

It is argued here that the incipient development of different claims of scientific legitimacy reflect the internal scientific struggles for authority in the forest hydrology field. Those claims are visible in interviews with key actors in Chilean forest hydrology. Different claims may be made strategically, in order to move or keep the borders of legitimacy and scientific authority of the field. Bourdieu (1996) understands different forms of capital as different forms of power, and in turn, the struggles of the field as strategies to preserve/transform that power through criticism and different representations of legitimacy and authority.

Scientific legitimacy and authority are interconnected because without legitimacy it is not feasible to sustain authority (leadership). Participants in Chilean forest hydrology debates have also made different claims regarding scientific legitimacy. Two relevant aspects are found in these discussions. Some claim that there is no legitimacy of any group – or mention the exception of one professor – to make claims about forest hydrology in Chile due to a dearth or irrelevance of these studies. Others claim that there is sufficient research, but take different positions in terms of the legitimacy of different studies and with regard to which institutions have the authority to make pronouncements about Chile's forest hydrology.

The first claims come from State forestry institutions at the national level. About these claims it is argued here, that the contestations about the existence (or not) of forest hydrology studies (knowledge) and its legitimacy (relevance or irrelevance) in Chile which senior government forestry officials state, may be strategically made to divert attention from scientific studies on forest hydrology knowledge in the country, and to protect economic interests of the forestry industry development at stake - for them - when talking about forestry plantations hydrological effects.

Senior (national) government forestry officials claim that that there would be no legitimacy or authority – neither from academia, companies or State forestry institutions nor from themselves – to make scientific claims on forestry plantations and water reductions. The reason for this is because these forestry governmental institutions declare being unaware of the existence of scientific studies, or that there is little, or irrelevant scientific information on forest hydrology in Chile (Interview 8, November 2018; Interview 24, November 2018).

Exceptionally, one professor of Universidad de Talca was mentioned by a senior-ranking government forestry director as the only legitimate academic, investigating issues of interest and relevance to the country's forestry sector (Interview 8, November 2018). This is in line with the official national report on "state of the art of forestry plantations and water" of the Chilean State which concludes that "from the state of the art review it is concluded that the available information (on forest hydrology) is insufficient" (INFOR 2013, p.5). This claim agrees with Barandiaran's (2015) analysis, which found that the work of the Chilean scientists is not part of a winning coalition that ensures their credibility in front of governmental or public institutions. The position of the State forestry institutions must be put into the broader political context, notably the fact that Chilean public institutions are the ones who have been facing legitimacy crises in the country due to political fiascos and the subsequent loss of credibility (Silva 2009). An important example of this governmental legitimacy-crisis, are the recent massive protests against the government in 2019, which in 2020 led to the approval of the creation of a new constitution in Chile.

In the following paragraphs, two examples from senior State forestry officials are given to show how these statements that contest the existence, relevance and legitimacy of previous forest hydrology studies in Chile, may be strategically produced in order to contest and divert attention away from forest hydrology studies and its knowledge on forestry plantations and water reductions. Different strategies are shown which seem to be used in parallel and vary: such as labelling the studies as irrelevant (delegitimising); doubting; ignoring or denying; diverting attention from forestry plantations to other external factors, such as climate change, agriculture, or human water consumption, etc. as sure factors contributing to water reductions; stating forest hydrology sentences with scientific inconsistencies; or the use of certain words or concepts that may lead to forest hydrology misunderstanding or confusion, among others. It is show that State forestry representatives might do so in order to protect the forestry economy in Chile at stake for them. As two senior State forestry representatives exemplifies:

> "*I am not so sure that forestry plantations contribute to water scarcity (...) the study of* [expert] *says that 'forests'* [forestry plantations] *help water production.* (…) *I don't know of a study that supports it* [that forestry plantation activity contributes to water reductions] *(...) scientifically there is no argument (...)* [water scarcity] *it is a bigger problem that affects the native forest, it has to do with climate change, people and their consumption* [of water], *and* [forestry] *plantations should be evaluated,* [but] *not just the plantations*". (chief 1).

The statement of this chief 1, a representative of a forestry plantation department, first of all, raises doubts. Secondly, he ignores or denies knowledge about the existence of a vast number of scientific studies carried out by academics in the country – which could be a possible ignorance – but at the same time, he is also unaware of the development of other statal projects (such as the SHETRAN project) that the institution he represents has developed (see section 4.1.4). Thirdly, Chief 1's statement highlights the use of certain 'expert[18] to support scientifically inconsistent statements such as 'forests (meaning forestry plantations) produce water'. Additionally, in this context the conceptual use of 'forests' to refer to 'forestry plantations' is also confusing and may favour misunderstandings in Chile about the objects (plantations) under discussion, given that, for example, native forests and exotic forestry plantations have indeed different hydrological effects, as well as a mix of both that will be more nuanced than plantations alone (see chapter 5). Access to the document that studies and demonstrates that 'forest plantations produce water' was requested, but was not shared, neither by the aforementioned 'expert'. Fourth, this chief despite declaring himself unfamiliar with the subject, states that the situation of water reduction is an issue with broader and external causes, and not only the forestry plantations. Even so, this chief establishes as a sure cause of water scarcity, the human water (over)consumption of those rural inhabitants facing water scarcity.

The following case of 'chief 2' representative of the central level of a forestry institution also provides an example in the same orientation regarding contestations about forestry plantations and water reductions from senior forestry state bureaucrats in Chile:

> [Regarding water reductions] "*There is no lack of water in the south* [of Chile], *they* ['Corporación reguemos Chile'] *want to take the water to the north* [in a mega irrigation project to transfer water between watersheds]". (Chief 2).
>
> " *When you say that the forestry plantations are established in the areas that have more water in Chile, and even with the drought they are able to have 85% of the water that reaches the sea and they want to take it to the north, that context is to tell you that I*

[18] In this case, from the 'national programme on watershed management and soil and water conservation' of CONAF.

> *do not understand the relevance of why it is an issue that the Eucalyptus forest plantations use water and why it is not agriculture, for example.*" (Chief 2).

For this senior state official (chief 2), what is at stake is not lack of water –which he denies – but what is at stake for him is the relevance or irrelevance of studying and knowing about water use of *Eucalyptus* forestry plantations. Additionally, this senior state official divert attention from the water use of *Eucalyptus* plantations by counter-arguing why there is no research done about water use of agriculture instead.

Complementary, regarding to forest hydrology studies and knowledge gaps in Chile, chief 2 also states:

> *"There are no serious studies here in Chile. No, not one, not one, I don't think, I mean there are studies, about for example the professor* [name] *from the Universidad de Talca, has a study of what happens in the basins with different covers, what happens with the water at different points, that is a good study, that is to say there are good studies of that, but studies of how much a hectare* [of forestry plantations] *uses* [water]... *there are not, I think, in Chile there are not and one of the things I would love to do in the* [Forestry state institution] *is to have a good study of that question.* (chief 2).

This statement first denies – or ignore – the wide existence of scientific studies on forest hydrology in Chile. Ignorance is also possible, but in that case, it would be striking that he ignores forest hydrology and monitoring research that technical agents of his own organisation have produced and were conducting in Chile at the time of the interview. But his argument does not rest on denialism alone and takes a twist in acknowledging that studies do exist in Chile, but he delegitimises them by stressing the sole legitimate exception of 'a good study' from one professor from the University of Talca. It is important to mention that the professor mentioned as the only legitimate academic by this forestry state chief 2 (a former director of CORMA), corresponds to a professor who led the forest hydrology unit at the University of Talca, which faculty was closed in 2022 due to its low scientific productivity (UTalca 2020). Additionally, the aforementioned academic is known to have published reports on forest hydrology at the request of CORMA (the Chilean Timber Corporation).

Additionally, when arguing why most of the forest hydrology studies in Chile would not be legitimate studies, chief 2 states:

> *"They* [other and the majority of academics in Chile] *have limited themselves to studying things that for me are irrelevant. For me, a study, a study, a relevant study. For example, because if I am able to reach the magic hectare* [of forestry production]*, I am not only freeing the Chilean native forest from pressure because perhaps Chilean biodiversity is not even one of the best, I can have the biodiversity of Indonesia, it can be much better and today the world is global. A cubic metre of wood that I produce here* [Chile] *and export to Japan or China, which is where they are consuming, right?... I eliminate one cubic metre that I took in Indonesia*" (chief 2).

The statements of this chief 2, shows his notion of 'legitimacy' and 'relevance' about forestry hydrology studies previously produced in Chile. For this senior State forestry representative (chief 2), the 'legitimacy' of a study and academics is linked to whether the research 'is useful' or able to provide an economic solution to the forestry industry: in this case 'to reach the magic hectare' of forestry production.

An alternative claim regarding the existence and legitimacy of the Chilean forest hydrology studies comes from academia, forestry companies and the same governmental forestry institutions but at regional levels. They argue that since the beginning of forest hydrology studies, such as the work of professor Huber in the 1980s, there are multiple studies and metanalyses on forest hydrology developed in different regions of the country (Interview 2, November 2018; Interview 3, November 2018; Interview 7, January 2019; Interview 17, December 2018; Interview 23, December 2018). For them the issue under discussion is how the legitimacy of the scientific studies is constructed, and who has or should have the authority on forest hydrology issues in the country. As for the discussions on legitimacy and authority among these academic, state and industry actors, it is possible to see that most of the agents agree on many of the criteria that scientific research should consider in order to be considered legitimate.

First, for several academic interviewees, scientific authority was linked to pioneering research on a topic, as is the case for Prof. Huber's group mentioned earlier, and the subsequent, multiple forest hydrology studies and meta-analyses that have been done and published in Chile (Interview 2, November 2018; Interview 3, November 2018; Interview 7, January 2019). In this sense, for academia, being the ones who have done more research on forest hydrology over the years, this would give them the scientific authority in the forest hydrology field. Second, for some academics, scientific legitimacy mainly comes from the peer reviewing of the forest hydrology research. For them, it is essential to participate in the peer review publication process (Interview 21, November 2018; also Diaz 2013). They see it as evidence of legitimacy and authority in the field. Giving priority to blind peer-reviewed publications in international or national journals, they are critical about the use of technical documents or reports on forest hydrology issues that lack scientific rigour (Interview 2, November 2018; Interview 21, November 2018). To them, peer reviewed publications are also an important element of the scientific recognition of academics, because it allows scientists to enrich their curriculum vitae, helping them to apply and obtain funding from the government research agency CONICYT (nowadays ANID) projects (Interview 21, November 2018). Obtaining such national research funding also reflects the recognition from the scientific community, because they are provided by a scientific committee composed of national university professors (Bühlmann et al. 2017). However, on the other hand, another group of academics manifest symbolically their recognition, legitimacy and authority mainly through the publication of forest hydrology reports, commissioned by various national public and private forestry institutions such as CONAF and CORMA, as well as an international organisation linked to education (Interview 12, November 2018; Interview 21, November 2018).

Third, some academics also think it to be important to present the results of studies at national and international conferences because this allows to discuss research results with stakeholders from multiple sectors (Interview 7, January 2019). In this sense, there is a perception in academia that those actors who do not share their research have lower legitimacy in the field (Interview 3, November 2018; Interview 20, December 2018).

Fourth, academics mention the use of official flow stations from the public monitoring network of the Chilean Water Authority (DGA) (governmental institution responsible for water management and water monitoring in Chile) as an important aspect of legitimacy because the DGA monitoring stations are a public hydrological data source that anyone can access and review (Interview 1, December 2018; Interview 7, January 2019).

Fifth, an indicator of scientific legitimacy is also simply the authority to train future researchers and to have a large number of students (Interview 7, January 2019). A large number of successfully trained students would be a sign that your research (as a professor) is valuable and diverse (Interview 13, December 2018; Interview 6, December 2018), permitting access to new ideas, networks, methods/techniques; and to apply to new research funds (Interview 22, December 2018).

Finally, also having international scientific networks is indicated as an important factor of scientific legitimacy, as it would indicate that a researcher is not isolated (Interview 1, December 2018; Interview 7, January 2019; Interview 12, November 2018; Interview 21, November 2018). In this regard, some academics claim that foreign scientific knowledge is sometimes more valued in Chile than local scientific knowledge. This, some of them consider, is a mistake because the scientific quality/legitimacy of research in forest hydrology in Chile positions itself very well internationally (Interview 4, December 2018). This last argument, is in line with what Barandiaran (2015) also notes about Chile, where the credibility of Chilean environmental science is contested in comparisons to foreign/local science.

Government research institutions – at some regional levels – share many of the views on legitimacy mentioned by academics, and especially about the criterion of peer review data and publication in which open access to forest hydrology information is key. As an example, INFOR has focused on convening all participants in the field to jointly map and make public all existing hydrological research data in the country, in order to enable all actors to openly use the forest hydrology data (INFOR 2021c). In this sense, for INFOR at the regional levels, legitimacy is also understood as peer review and open access of forest hydrology information.

The forestry industry shares certain views of legitimacy with academia, yet at the same time, they have their own understanding about scientific legitimacy. It is argued here that the forestry industry through their numerous long-term monitoring sites and these selective national and international scientific collaborations, is seeking to promote its own research agenda, establishing its own scientific legitimacy, and seeking to challenge the authority in the forest hydrology field. In order to do so, on the one hand, forestry industries recognise the relevance of certain elements of the academy's scientific legitimacy. But on the other hand, they incorporate new criteria of legitimacy, with which they seek to position their own research as more legitimate (e.g. more modern and precise studies) than the previous forest hydrology studies from academia and the State. With these legitimacy contestations, the industry seeks to gain authority and leadership in the scientific field of forest hydrology. For instance, on the aspects of legitimacy shared with academia, scientists from forestry companies have begun to participate in national and international conferences on the subject, and plan, in collaboration with national academics and international consultants, to join the peer reviewed publication system (Interview 9, December 2018). Some forestry companies also declare their intention to share forest hydrology data in the future with multiple actors (Interview 9, December 2018). However, the industry also makes other claims on legitimacy to contest the scientific authority of academia. To build their scientific legitimacy and authority on the water and forests subject, industrial actors started their own independent multi-long-term forest hydrology monitoring programme in the country. They recognise that there are many forest hydrology studies, which however are mostly of short duration, and claim that they are currently the ones who mainly have long term studies (Interview 23, December 2018; Interview 2, November 2018). The methodologies used by the industry are also considered by them as more modern, unlike Professor Huber's forest hydrology studies from the 1980s which would be old and less accurate for them (Interview 23, December 2018). Thus, for the forestry industry, aspects such as long-term studies and the use of new technologies, would provide important elements of legitimacy to their studies. Examples of this are the multi-long-term hydrological projects that the two main companies started in 2008, and which monitor more than a dozen small watersheds in different areas of the country (Interview 12, November 2018; Interview 23, December 2018). Additionally, for the forestry industry, a key aspect of the scientific legitimacy of their research is that they are not working alone, because they are working in collaborations with certain members from academia and international consultants, who do research in forest hydrology (Interview 9, December 2018; Interview 23, December 2018). Examples of this are collaborations with some professors from the Universidad Austral de Chile and Universidad de Concepción, among others, and with two forestry hydrology consultants from Australia (Interview 9, December 2018; Interview 23, December 2018).

6.7. The autonomy of the forest hydrology field

In this chapter's final section, the focus is on the external political-economic influences shaping production and circulation of forest hydrology knowledge, and therefore the relative autonomy of forest hydrology science in Chile. Given that neoliberalism is a defining feature of previous decades in Chile (Tironi and Barandiarán 2014), it asks whether the three neoliberal external forces found by Lave (2012, p.376) in her study of stream restoration field in the U.S. are also relevant in Chile. As a reminder (see section 2.4.1 supra), these are (i) increasing privatization in the field, ii) a shift in research to meet market and agency demands, as well as the production of iii) new measurement "metrics to enable market-based environmental management", as main neo-liberal characteristics that influence scientific practices and may reduce the relative autonomy of the field. This allows to focus on neoliberalism not just as an abstract force, but also as specific situated practices, and specifically as political technology applied practices in the country (Tironi and Barandiarán 2014).

It is argued in this section, that external political-economic reforms of neoliberalism applied in the country, have shaped and influenced the production and circulation of forest hydrology knowledge in Chile and its relative autonomy. In particular, by prompting gaps of access to material resources (e.g. forestry land) and gaps of information/circulation (e.g. prolonged time for publication) for certain forest hydrology research. This also has influenced a scientific production trend focused on forestry and private agency needs. It also shows a change of trend in the territorial, collaborative and financial dimension of forest hydrology research that can be carried out in the country. This has been practised through privatisation mechanisms, and reduction of state resources, among others.

One of the most noticeable examples of external forces influencing the scientific production of forest hydrology is related to the birth of the Chilean forest hydrology field itself. That is, in the Chilean case, the field of forest hydrology and its research was born due to the environmental changes and neoliberal transition that the country went through after the introduction of *Pinus* and *Eucalyptus* species – accidentally in some cases – and subsequently of the multiple policy-forestry reforms that introduced and promoted the plantation of *Pinus* and *Eucalyptus* species in the country (see section 4.2.2). Notably, the most important recent reform is granted by Decree Law N°701 which further expanded the practices of *Pinus* and *Eucalyptus* forestry plantations, replacing degraded agricultural land or native forests, among other land uses. Already in the 1960s there were water concerns, and the pioneer State 'Junquillar scientific forest hydrology project' (in the coastal range) was developed in 1970 to address and answer the hydrological effects of landscape changes and forestry management techniques in Chile (see Jones et al., 1975). The coup d'état of 1973 in this respect 'froze and delayed' the scientific development of the Chilean forest hydrology field by more than a decade, and on some subjects even more so. This is especially visible in the Junquillar research project and its topics related to the hydrological effects of native shrub fires and clear-cutting forestry management techniques widely applied in the 1960s and still contentious issues in Chile today. Among other, these are subjects that the 1970s Junquillar project could have addressed, such as the land use change from native shrubs on degraded soils to forestry plantations, construction of predictive forest hydrology equations, etc. (Jones et al., 1975). During the mid-1970s, after following the neoliberal political and economic reforms which were implemented in the whole country through the coup d'état, the forest transitions were strengthened and implemented to promote a new expansion and industrialisation of the Chilean forestry sector (Heilmayr et al. 2016), as well as to apply the privatisation of State forestry lands and industries (see sections 4.1.4 and 4.2.2 supra). Afterwards, in the early 1980s, concerns about water reductions surrounding the new forest plantations emerged and prompted Professor Huber of the Universidad Austral de Chile to approach the forestry company CMPC to begin forest hydrology research on their *Pinus* plantations (Interview 2, November 2018). Thus, the second major event of change in the forestry field occurred in the early 1980s, when the first contract between Professor Huber and the forestry company CMPC was established to gain access to forestry private company lands to do forest hydrology research. Therefore, the environmental and political-economic changes and the water reductions that the country has experienced in different decades of recent history, gave birth to the new scientific practice of forest hydrology in Chile. So, the birth of the forest hydrology field itself constitutes the first evidence of the influence of an environmental change (e.g., the forest transitions that introduced and subsequently expanded the plantation of *Pinus* and *Eucalyptus* trees) and the political-economic forces that promoted and enhanced these changes (e.g., the Decree Law N°701) in the production, consolidation and circulation of forestry science about forest hydrology matters. The Chilean forest hydrology case corroborates the findings of Peet et al. (2011, p.39) that science "is itself a product of both political economy and the changing environment in which it is practiced".

Other aspects related to privatization of the forestry sector in Chile reflect the influence of external neoliberal political-economic forces on the production of the Chilean forest hydrology field. Indeed, as evidenced in section 4.2.3, since 1973 the whole country experienced increasing privatisation and the reduction of state funding for the Chilean universities and national budget for research (Barandiaran 2012; Diaz 2013), and the forest hydrology field itself (see Jones et al., 1975). The forestry sector was one of the first to be extensively privatised, with the transfer of land and tree plantations of *Pinus* and *Eucalyptus*, forestry nurseries, sawmills, industrial pulp mills, among many other elements of the forestry sector produced previously by the Chilean State (Clapp 1995; Arze and Svensson 1997; Frene and Nuñez 2010; Cabaña et al. 2013). These massive forestry privatisations shaped the way in which forest hydrology research could be conducted (or not) in productive forestry plantation trials. This is due to the fact that currently in Chile, private forestry companies hold most of the plantation land in the country, necessary to do any forestry and forestry hydrology research on productive lands (Interview 2, November 2018). Access to lands to perform environmental research is a basic feature in scientific production, yet under the Chilean neoliberal scientific regime, it requires prior authorisation from private entities, which can approve or reject this for some researchers. This is confirmed by certain actors of academia, who state that their request to forestry companies for access to forestry land to perform forest hydrology research, has been selectively and constantly postponed and therefore have not been able to be carried out (Interview 20, December 2018; Interview 22, December 2018). This selection of academics to perform forest hydrology research on forestry company lands, is also confirmed by some forestry companies (Interview 23, December 2018). For those academics, forestry privatization providing authority to the private sector in terms of controlling access to forestry land to perform research has influenced the relative autonomy of scientific production and circulation of the forest hydrology field. This is confirmed by some academic views, which hold the perception that companies sometimes manage more information because they have their own information that is not public, contrary to the information generated by the State which can be access by everyone (Interview 22, December 2018).

Additionally, the increasing privatisation of the forestry sector (Arze and Svensson 1997b) and the reduction of the state investment in research (Diaz 2013), has not only boosted a shift to market-based forestry management, but has also influenced a shift to a market and agency research demands in the country. One evidence of this is the growing interest declared by some academics in developing research more closely/collaboratively with the industry (e.g. Interview 4, December 2018; Interview 5, November 2018; Interview 7, January 2019; Interview 14, November 2018; Interview 21, November 2018), and the fact, that in order to do so, academics must to do research on topics/questions that are attractive/useful to the industry (Interview 4, December 2018; Interview 21, November 2018; Interview 23, December 2018). This, in turn, has conditioned the relative autonomy in the production and circulation of forest hydrology knowledge in the country. Thus, some of the greatest challenges to the internal autonomy of the field are those imposed by the publication of information. This is the case, both with regard to the collaborative work of academics with government entities, or with a forestry company in Chile, as several interviewees revealed. For example, what research will be done (e.g. questions), what and when to publish (or not) is determined by this (Interview 2, November 2018; Interview 3, November 2018; Interview 4, December 2018; Interview 6, December 2018; Interview 28, January 2019). Hence, by setting external conditions on publication outputs in terms of content (e.g. what is a relevant question or not, what to include or not), or timeframe (e.g. in what time frame, months or years), the relative autonomy of researchers is limited, especially for those academics working in collaboration with industry and the State.

Furthermore, the strategy of reduction of the State's investment in science has contributed to the discontinuity of investment in forest hydrology monitoring programs and their inconstant research trajectory (trend of ups and downs), which has promoted short-term forest hydrology research from the side of certain groups of academics and State forestry institutions themselves. Under this neoliberal research policy, the central State has diminished its pioneer participation in forestry and forest hydrology production research, and consequently, diminished also its legitimacy and authority on scientific production in forestry, and therefore in forest hydrology issues. Examples of this are the project of Junquillar with its three monitored watersheds of La Piragua, La Puente Nos 1 and 2, and the lack of follow-up from the State of its SHETRAN project and its four monitoring watersheds of La Reina, Río Clarillo, Minas del Prado, and Chosme catchments (with c.f. Jones et al., (1975); and Bathurst et al. 1998). The former, has been a decision taken mainly by the neoliberal central State in Chile, which is demonstrated by the emergence of regional projects such as the Forest Ecosystems and Water Programme (Interview 18, December 2018), which seek to establish, in a different way, broader and more transversal forms of production and circulation of forest hydrology knowledge through the creation of a national public catalogue that involves diverse national public and private actors. As another result, through scientific collaborations with some members of academia and international forest hydrologists, and the discontinuity of State investment in science (e.g. no or less funding, resulting in greater challenges to give temporal continuity to projects, etc.), the forestry sector has been increasing its scientific capital, legitimacy and authority in the forest hydrology field. These facts also reflect "one of the central characteristics of neoliberal science regimes, [which] is an emphasis on privatizing the production of scientific knowledge" (Lave 2012, p.376). The best example of this are the long-term projects that the two main forestry companies of the country are leading in collaboration with international scientists (e.g. Australian consultants) and some professors from the Universidad Austral de Chile, Universidad de Concepción, and Universidad de Chile.

All of these neoliberal reforms experienced in the national context were a superior force that led members from all parties in the field (academia, companies and governmental institutions included) to adapt to the needs of the new kind of forestry and scientific neoliberal regime. These external neoliberal forces might also explain the recent emergence of the forestry hydrogeology trend, whose research orientation focuses on the heteronomous (external) pole of the forest hydrology field. Thus, the impacts and dynamics on forestry which have also impacted the development of the forest hydrology science and its autonomy in the production and circulation of scientific knowledge, cannot be analysed without attention to political-economic relations.

6.8. Conclusions

Understanding the production and circulation of the Chilean forest hydrology knowledge has allowed us to identify a rich diversity of institutions, environmental change, and political-economic processes, which over time, have given origin and shape to the scientific field. Through the analysis of the field, it has been possible to show how in Chile, there have been contestations about the existence (or not) of forest hydrology studies in the country. One clear example of the former, is the case of Chilean State forestry institutions at the national level, who by ignorance or by bordering denialism, have diminished the existence of forest hydrology research and ignore the effects of forestry plantations on water reductions in the country. Senior State forestry representatives, do so by stating that 'there are not studies', that 'they are not aware about studies on the subject', or through a discursive shift that subsequently acknowledges the existence of studies but delegitimises them. These statements which are contradictory with the facts have complexified the forest hydrology debates in Chile. For those field participants who do recognise – or do not refuse – the existence of extensive research on forest hydrology, discussions focus, among others on contesting the relevance of certain forest hydrology objects, or the legitimacy and authority of the forest hydrology field.

As for the habitus dimension, despite the existence of a diversity of research, it demonstrates the existence of two main scientific trends or approaches within the scientific production of the Chilean forest hydrology field. These are the ecosystem and forestry hydrogeological trends, which respectively, focus either more on the internal role of forestry plantation/land uses, or on the external role of hydrogeological factors (clime, soils, aquifers, snow, etc.), agricultural and human water consumption, among others, in influencing the phenomenon of water reductions in forestry landscapes in Chile. Thus, each trend presents different research directions on internal or external aspects, frameworks and concepts to forestry plantations.

Regarding the internal dimension of capital, this chapter shows the different ways in which actors maintain (academia), or challenge and/or build (State and industry) the boundaries of scientific legitimacy and authority of the field of forest hydrology in Chile. In this sense, on the one hand, the central level of the State stands out for self-diminishing its authority and the legitimacy of its own and most academic forest hydrology studies in the country. Some senior State forestry representatives do so by delegitimising the existing research as 'irrelevant scientific studies' because they would not provide economic solutions to the forestry sector, and which economy is at stake for them. In doing so, the Chilean central State has likely strategically diverted attention– by ignorance or bordering denialism – from its own forest hydrology scientific knowledge and the knowledge of most academics produced in previous years. Furthermore, national forestry State representatives have pointed to external causes to forestry plantations such as climate change and the increase in rural population as the only sure factors involved in water reductions. By doing so, they have likely diverted attention from forestry plantations too. On the other hand, participants from academia, industry, and regional state forestry departments struggle argumentatively to keep or move the boundaries of scientific authority and legitimacy of forest hydrology studies in Chile. Both tendencies of forest hydrologists highlight elements of legitimacy on which they are stronger than the other field producers. For academics, having most blind peer-reviewed scientific publications and being one of the first to initiate studies in Chile, and those who have been doing research for the longest time, among other aspects, provides greater legitimacy and authority. While for other industrial forest hydrologists with no scientific publications (at the time of these interviews in 2019), they build their legitimacy on the use of new technologies, or on the impressive deployment and investment in long-term forest hydrology studies, which other forest hydrologists from academia also possess but in a more modest way. The different aspects mentioned above become more relevant when, subsequently, it is time to evaluate what scientific information to use or not for the formulation of public policies and, what measures should be applied or not as future forest hydrology solutions in Chile's forestry territories.

Regarding the autonomy of the field and in particular the external politico-economic forces that influence the production and circulation of forest hydrology in Chile, it has been shown that the landscape and neoliberal transformations have had a profound impact on contemporary Chile (Altieri and Rojas 1999; Ffrench-Davis 2002), its science (Javiera Barandiaran 2018a) and environmental and political-economic changes in forestry (Heilmayr et al. 2016). In turn, these landscape and political-economic transformations have influenced the creation of the field of Chilean forest hydrology itself and shaped scientific practices of its production and circulation; and therefore, the relative autonomy of the field. This has been practiced since 1973 through mechanisms of privatisation, and the withdrawal of State resources for forestry and research, which has subsequently shifted forestry research trends – in some cases – towards topics oriented to the needs of the forestry industry. This has been demonstrated in Chile through practices beyond the will of researchers, such as the control by the forestry industry to decide (and so the possibility to reject) on the access to forestry land to carry out research by some academics. But also, it has been demonstrated through forest hydrology knowledge circulation/publication practices over some academics who collaborate in forest hydrology scientific production and/or circulation with some forestry industries and forestry representations of the state. These facts might promote the generation of knowledge gaps in forest hydrology in Chile. Additionally, these neo-liberal forces have very likely given rise to the heteronomous (external) forestry hydrogeology trend. It is therefore possible to conclude that the neoliberal dynamics of the forestry sector and the neoliberal science regime in Chile, have in some cases influenced the autonomy of the forest hydrology field, and that its production and circulation cannot be understood without attention to the country's political-economic and environmental relations.

This chapter also joins and contributes the literature in STS and political ecology interactions working on the production and circulation of environmental knowledge; arguing that scholars could benefit from the theoretical concept of the field to deepen the comprehension of the social aspects of structure, habitus, legitimacy and autonomy that underpin scientific production. As this study has shown, the inclusion of those social aspects in the analysis of science studies may help highlight the multiple internal social relations and external political-economic forces involved in producing, transforming and shaping knowledge circulation, and the consideration of which can enrich discussions on contested issues.

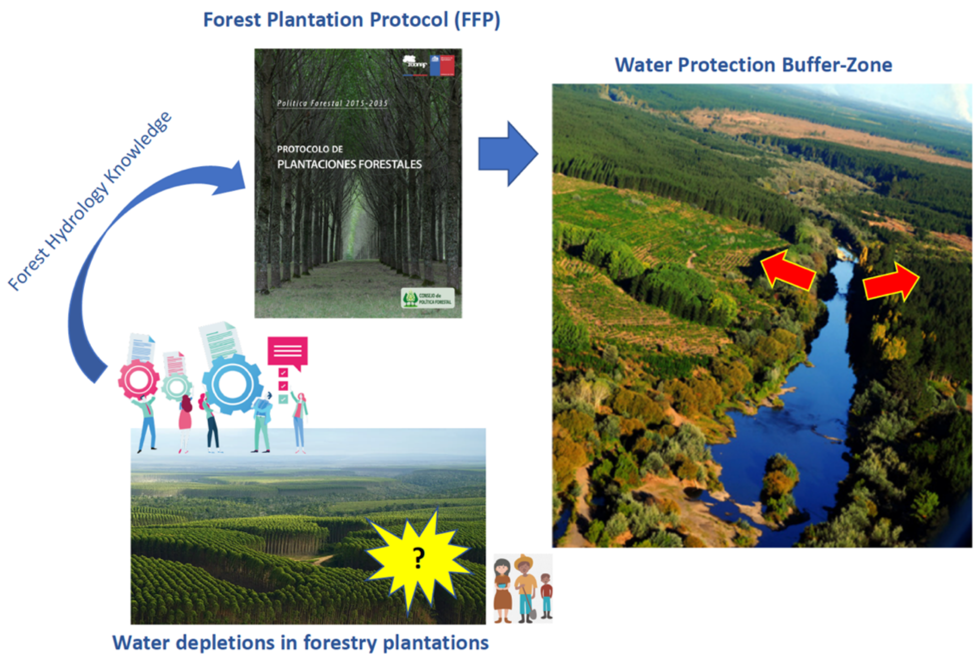
Chapter 7

Circulation and application of scientific knowledge in policy-making: forest hydrology governance in Chile

This chapter investigates how forest hydrology knowledge has been circulated and applied in a policy-making process in Chile. Specifically, the production of the Forest Plantation Protocol (FPP) policy, and its policy-outputs for plantations and water issues are analysed. Four questions are investigated: (C1) What scientific knowledge has been listened to and what are the actors' coalitions in the policy-making governance? (C2) How have relative stable parameters influenced the forest hydrology policy-governance? (C3) How have external system events influenced the forest hydrology policy-governance? And, (C4) how has scientific knowledge been applied and what have been the paths to policy change?

To address these questions, the chapter operationalises the concepts of the advocacy coalition framework (ACF) (Sabatier 1988; Jenkins-Smith and Sabatier 1994; Sabatier 2007) presented in section 2.4.2. The chapter is composed of 7 sections, which address the creation of the Forest Plantation Protocol (FPP). Section 7.1 introduce the overall governance of the FPP. Section 7.2. presents the initial context of the political process (before the forest fires) in order to understand what and how the policy process adapted later on. Section 7.3 presents the experts and actors involved in the plantations and water debates. Section 7.4 demonstrates what scientific knowledge was listened to, with what bases, approaches and its coalitions. Section 7.5 analyses relative stable parameters and specifically the decree 82, in order to understand how scientific knowledge was applied in policy-change (decision-making), and what the margins of that change were. Section 7.6 reflects empirically and theoretically about Sabatier's paths for policy change. This analysis is reinforced by previous ACF scientific literature on the Chilean forestry sector and policy-making in Chile. Finally, Section 7.7 concludes by summarising the main theoretical, methodological and empirical findings of this research.

Figure 29. Schematic representation of the process of creating the 'water protection buffer-zones', which was one of the main outcomes discussed by the experts in the Forest Plantation Protocol (FFP).



Source: author. Water protection in forestry plantations was one of the four topics addressed by the FPP. One of the major outcomes discussed by the Soil and Water Expert Commission (SWEC) was the creation of water protection buffer-zones (WPBZ) in all forestry plantations in Chile. WPBZ consists in a buffer area around water bodies, where no new tree crops can be planted in order to protect water and soil resources.

7.1. Introduction

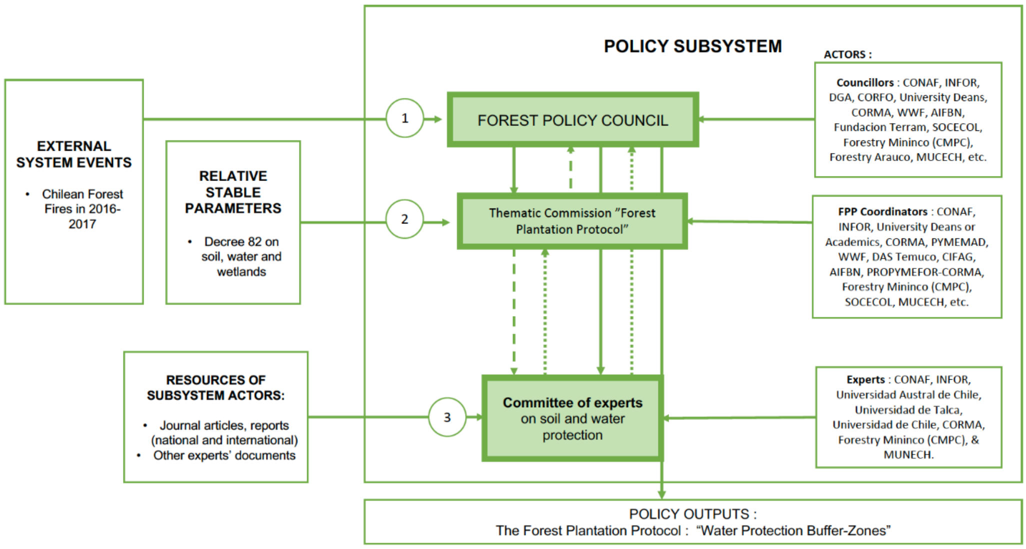
Between January 1 and February 10, 2017, central-southern Chile was ravaged by several mega-fires, which were considered the second largest in the country's history with more than 500.000 hectares affected (de la Barrera et al. 2018; Pliscoff et al. 2020). The mega-fires were enhanced by extreme weather conditions, increased by the effects of a mega drought which had been going on since 2010 (Bowman et al. 2019). The fires affected mostly forest plantation areas (McWethy et al. 2018; de la Barrera et al. 2018; Bowman et al. 2019) but also had devastating effects on human lives (Pliscoff et al. 2020; Bowman et al. 2019), settlements, infrastructures and native forests (Valderrama et al. 2018; McWethy et al. 2018; de la Barrera et al. 2018). Particularly affected were the settlements of Navirilo and Santa Olga. The latter settlement, with more than 1000 inhabitants, was totally destroyed due to the effects of the fire that consumed houses and surrounding forest plantations alike (Toro and Valenzuela-Beltrán 2018; Pliscoff et al. 2020).

Given the severity of the mega fires in the country, the Chilean government, through the Ministry of Agriculture and the country's Forestry Policy Council composed by governmental institutions, forestry industries, and social organizations, gave urgent priority to the elaboration of new guidelines and standards to regulate the establishment and management of the forthcoming forestry plantations in the country. This process resulted in August 2017 in the country's first Forest Plantation Protocol (FPP) (CONAF 2017a) agreed upon by the State, academia, forestry industry and social organisations at a national level. Four themes were addressed by the FPP: (i) soil and water protection, (ii) interface and management of forest fires, (iii) ecological functionality, and (iv) partnership (see figure 7, in chapter 3). In order to address aspects of soil and water resources, the thematic commission of the Forest Plantations Protocol (TCFPP) convened a "Soil and Water experts commission (SWEC)" composed of forest hydrology experts from academia, forestry industries and governmental institutions. Their task was to scientifically address soil and water aspects in forest plantations in the production of this forestry protocol.

The SWEC was relevant, because despite the existence of some previous initiatives related to forest plantations and water protection in the country (e.g. Decree 82, a special agreement in the Araucania region or certain guidelines in the FSC certification, etc.), until the development of the Forest Plantation Protocol there was no agreed joint national framework between the State, the forestry sector, academics and social organisations regarding soil and water aspects in forest plantations (CONAF 2017h). However, as is common in processes of political production, different actors try to influence the outcomes of political process (Sabatier 1998), and in this process of policy formulation, it is crucial to understand the role which scientific and technical knowledge plays in it (Sabatier and Weible 2007c). In the FPP's case, forest hydrology science was evoked to support the development of policy-outcomes. Within the work produced by the Forest Plantation Protocol, two main groups of forest hydrology experts emerged, arguing for increasing, keeping or reducing current standards on water and soil protection regulations. Both groups circulated their scientific approaches in the competition to be heard in policy making.

Inspired by these issues, I look especially at the Soil and Water experts commission, as well as the Thematic Commission on Plantations Protocol (CTFPP), and at plenary sessions of the Forest Policy Council (FPC), which produced the Forest Plantations Protocol (see respectively '3', '2' and '1' in figure 30). This is done in order to follow the debates on water and forestry plantations, in particular on the policy output of the Water Protection Buffer-Zone (WPBZ). By doing so, this chapter focus on policy-making governance in order to analyse the circulation and application of forest hydrology knowledge in the policy-production that seeks to develop water and soil protection measures for Chilean forestry plantations. Based on empirical evidence – such as the minutes of the commission and council meetings, and interviews with policy participant – and embedded in a case study approach (Creswell 2014), the Advocacy Coalition Framework (ACF) concepts are applied to assess the environmental scientific knowledge and policy-making interactions in the FPP as a case study. This chapter argues that ACF can enrich studies focused on the circulation and application of knowledge. ACF does this by providing theoretical tools to analyse what knowledge is listened to and how this may (or not) change policy production. Concepts such as external system events, relatively stable parameters, or policy subsystem, among others, can help to enrich these analyses (see section 2.4.2). Empirically, to date no study in the field of forest hydrology has addressed the circulation and application of scientific or expert forest hydrology knowledge in policy making in Chile, which provides interesting insights from practice to theory.

Figure 30. ACF' concepts and main actors involved in the production of the Forestry Plantation Protocol



Source: author. Figure 30 summarises the structure and actors of the FPP (see also figure 7), and the ACF concepts operationalised (see figure 5) in the analysis of this chapter. Some of these actors are also further described in sections 4.1.4 (chapter 4) and 6.4 (chaper 6) (actors linked to the production of forest hydrology knowledge in Chile) and in the following section 7.3 (Chilean experts in forest hydrology who participated in the soil and water discussions).

7.2. Forest Plantation Protocol (FPP): origins and adaptations

This section demonstrates how an external system event, or environmental 'shock', can constitute a force that shifts the balance of the traditional political forces and thus can be used as an opportunity to push for policy change. The section begins by presenting the origin of the process (section 7.2.1) and then goes on to discuss how the overall governance of the process subsequently changed after the Chilean mega-fires in 2016-2017 (section 7.2.2). It is argued here that the inclusion of ACF might enrich political ecology analysis from a policy-making analysis perspective, while contributing to address an environmental governance and geographical analysis in policy production. This is done by providing the theoretical tool of 'external system events' that allows to analyse how external events (social, environmental or economic events, etc.) can act as mechanisms that shift a governance process in the policy production, which has not been a traditional strength or focus of political ecology analysis.

As the case of the Forest Plantations Protocol (FPP) demonstrates, external system events can become an opportunity for changing traditional forces and trends of policy production, but this strength is not unlimited.

7.2.1. Initial context: the thematic commission management of plantations

How did the Forest Plantation Protocol process start? On June 14th 2016, the 8th Plenary Session of the Forest Policy Council agreed to work on a shared vision for the establishment and management of the forest plantations in the country. To achieve this, the 'Thematic Commission Management of Plantations' (TCMP) was created (CONAF 2016b). Subsequently, the time-schedule for starting TCMP activities was discussed in December 2016 (CONAF 2016c). The first TCMP meeting was hold in January 2017 to "define actions that respond to the strategic axes set out in the Forestry Policy 2015-2035 related to the establishment of forestry plantations that meet high social, technical, economic and environmental standards" (CONAF 2017b, p.1). At that date, several forest fires had already broken out in the country, but these had not yet reached the category of 'disaster zones'.

During this first meeting of the TCMP, participants discussed and highlighted different concerns about the future of forestry plantations in the country. In general terms, government actors were looking for ways to improve and strengthen the social and environmental dimensions of the forestry sector, while forestry-industrial actors were looking for ways to improve the social views on plantations and searching for political and economic support from the State after the forest fires. For instance, CONAF proposed to start by identifying the problems that society was assigning to plantation forestry, including for instance the issue of water, and then to analyse the possibilities for mitigation (CONAF 2017c). CORMA and representatives of large forestry companies, on the other hand spoke about the political challenges that plantations were facing, given society's negative perception of the forestry sector. In this regard, they called for a public defence of plantations by the State; for the creation of a new forestry economic fund; and for a post-fire policy of reforestation with productive tree species (CONAF 2017c) thereby showing concerns of a productivity-related character. In response to the idea of a post-fire policy, representatives of the Forestry Policy Council stated that people could not be forced to reforest if they wanted to use their land for (e.g.) agricultural purposes (CONAF 2017c). Academics based at universities, from their side, proposed to address forestry plantations through environmental and restoration objectives and meet the productive-commercial, environmental and social aspects. In the same way, academics mentioned the importance of indicating positive aspects of plantations too (CONAF 2017c). In this way, to close the meeting, CONAF and INFOR proposed to identify positive and negative aspects of plantations, then to define how to address them and thus help to improve civil society's image of plantations (CONAF 2017c). The commission closed its work by agreeing on the next meeting dates and concluding that at the end of its work the TCMP would present a report to the Forestry Policy Council for validation (CONAF 2017c). However, at that moment, the TCMP had not yet defined other work themes and only political councillors elected by the Forest Policy Council were participating in this TCMP meeting.

7.2.2. External system events: "the firestorm" and the forest plantation protocol

By February 2017 the fires had increased in magnitude and became the second largest ever recorded in the country, thus earning the name of 'mega-fires' (Pliscoff et al. 2020). These fires became a national emergency with areas declared 'Disaster Affected Zones' and 'Disaster Zones with Constitutional Exception' (ONEMI 2017). During the time of the emergency, the President instructed the Ministry of Agriculture and the Forestry Policy Council to propose an action plan to urgently recover and restore the country's patrimony affected by the forest fires (CONAF 2017d). Four thematic lines of action were proposed: a) assisting small and medium forest enterprises to recover their productive resources; b) supporting farmers to recover damaged forest plantations and native forests; c) designing participatory ecological restoration plans, including the recovery of streams, protection against erosion, protection against forest fires and priority areas for conservation; and d) developing environmental education and innovation plans on forest fires (CONAF 2017d).

Thus, in February, while the country was still in a state of emergency, the Forestry Policy Council held an extraordinary plenary session where it was announced that the "Thematic Commission on Plantation Management" (TCPM) was to change its name to "Forest Plantation Protocol" (FPP), which was to have as its main objective the establishment of a set of criteria for the development of new forest plantations (CONAF 2017d). In this way, the social, environmental and economic national shock resulting from the fires emergency became a major opportunity to shift the governance process. This is demonstrated by changing the name from TCPM to FPP, and the structure of the governance process by incorporating the four lines of action previously proposed by the country's presidency as a response to the emergency. This was relevant because with the introduction of these four themes (see 'a', 'b', 'c' and 'd' thematic lines mentioned in the foregoing paragraph), also 'scientific or expert knowledge' was introduced into - and modifying the governance process by creating four Committee of Experts (see figure 7). So, at the second meeting of the now called "Thematic Commission on Forest Plantations Protocol (TCFPP)" (previously called TCMP), the TCFPP presented these 4 axes of work and agreed upon the creation of four additional expert commissions. Among these commissions was the conformation of the 'Soil and Water Experts Commission (SWEC)'[19] (see figure 30).

In the same way, the external shock shifted the traditional balance of forces among the actors in the governance process of the Forest Plantation Protocol. This was demonstrated through the management of working time in the creation of the FPP. Traditionally, forestry power relations in Chile have been described as a "highly asymmetrical relationship, where a minor State agency confronts powerful business groups" (Silva 2004, p.268). One evidence of this power dynamic is that since the 1980s, policy-making processes in the forestry sector in Chile have traditionally taken years of lengthy negotiations before producing a policy-output to regulate the forestry sector. An example of this was the production of the Native Forest Law in Chile, which took more than 15 years of discussions in the Congress (Arnold 2003; Frene and Nuñez 2010a; Biblioteca del Congreso Nacional de Chile 2020). However, unusually fast, the FPP was discussed and approved in eight months of collective work, despite the fact that the forestry sector and environmental actors sometimes requested more time for the production of the FPP' outputs (CONAF 2017p). This power-shift in the FPP process was demonstrated due to the fact that the fires spread mainly through the forestry plantations (see e.g. McWethy et al. 2018; de la Barrera et al. 2018; Bowman et al. 2019) and caused many human injuries and damages to properties (Toro and Valenzuela-Beltrán 2018; Bowman et al. 2019). The fires symbolically affected the power of the forestry sector, due to the fact that this unfortunate and dramatic event 'reinforced unfavourable perceptions in public opinion on forestry plantations' (CONAF 2017p). This reinforced the urgency and therefore the strength of the FPP's regulatory initiative. This exceptional political force was

[19] The TCFPP agreed to the creation of the four expert commissions on: 'Soil and Water'; 'Fuel Discontinuity Management and Interface'; 'Recognition of Ecological Functionality'; and 'Partnership' (see figure 7).

demonstrated during the production of the Protocol through the priority and urgency characteristics of which governmental representatives constantly reminded the actors during the multiple working commissions meetings (see e.g. CONAF 2017d; 2017e; 2017j). For example, at the 16th plenary session of the Forest Policy Council which first discussed the results of the SWEC, stakeholders from CORMA and PROPYMEFOR-CORMA requested an additional 4 months to discuss the FPP' outcomes. In response, stakeholders from TERRAM Foundation, INFOR and CORFO (the latter two governmental organisations) among others, argued that 4 months was too long and supported CONAF's initiative of 1 month more. Finally, the members of the Forest Policy Council agreed with majority to one additional month of work to close the issues of disagreement in the protocol. In this way the so-called "firestorm" created a political opportunity that gave exceptional strength to governmental actors to accelerate the working time of the FPP.

Being able to define the time of work or time horizons, is recognised by some governance' theorists as a manifestation of power (e.g. Jessop (2003)'s *time sovereignty*). In this case, this was applied with the outbreak of mega-fires and shown by the exceptional force of the Chilean government in dealing with actors from the forestry sector when proposing themes and working times. Likewise, this finding is consistent with the original ACF hypotheses, which argue that policy changes require external shocks (Sabatier and Weible 2007).

> "*The most important effect of external shock is the redistribution of resources or opening and closing venues within a policy subsystem, which can lead to the replacement of the previously dominant coalition by a minority coalition*" (Sabatier and Weible 2007, p.199).

However, while the general working themes and commissions were defined, it still remained open what and how the environmental standards would be applied in the FPP's expert commission of soil and water. It would be the role of the scientific experts to define the environmental standards to apply on the soil and water aspects in forest plantations of the country.

7.3. Actors of the soil and water expert commission (SWEC)

This section shows the main actors involved within the Soil and Water Expert Commission's (SWEC), and others that later on will appear in the forest hydrology discussions. The SWEC (see figure 30, box 3), was the policy sub-system responsible for providing scientific knowledge to the FFP on water and soil issues. It was composed of four key actors or institutional groups. Some of the experts who participated in the SWEC knew each other from previous forestry work and forest hydrology publications carried out between them.

First, the Government was represented by the National Forest Corporation (CONAF) and the National Forestry Institute (INFOR). They are the two main governmental forestry institutions that have carried out – in different periods – forest hydrology research in the country. During the SWEC process, some representatives of CONAF seemed to act as intermediary agents or mediators between INFOR and the forestry sector. For example, some members of CONAF called for prioritizing an adequate relationship between social and economic products from the watersheds, as the forestry sector also stated at some point (CONAF 2017i). Other members of CONAF proposed to focus the discussion on defining criteria for critical watersheds for human consumption, and specifically in buffer-zones for soil and water protection, as also INFOR supported (CONAF 2017h). This led to contradictions among CONAF's actions in the SWEC process, where sometimes CONAF and INFOR seemed to act as a governmental coalition, and sometimes as opposing coalitions. This situation is exemplified in more detail in section 7.4 about the discussion of the widths of water protection buffer-zones.

Second, there is the forestry industry sector, represented by agents of the National Timber Corporation (CORMA) (e.g. the forestry company MININCO). CORMA is the business association that represents the country's small, medium and large forestry producers, such as MININCO, ARAUCO, Masisa, AnChile, among others. ARAUCO and CMPC (MININCO) forestry companies are the two largest forestry companies in Chile, among which ARAUCO constitutes the second largest pulp producer in the world (LaTercera 2017). These firms have therefore historically been very influential actors with national and global relevance. CORMA has previously commissioned some of the academics participating in the SWEC to produce reports on forest hydrology that have been published online in the country.

Third, we have groups of academics working on forest hydrology and forestry management from the Universidad de Chile, Universidad Austral de Chile, and Universidad de Talca (the academic from Universidad de Concepción is not noted in the minutes meetings). These academics have been trained in Chile and/or abroad. Furthermore, all the academics invited in the SWEC are academics who carry out diverse forestry or forest hydrology studies in collaboration with CORMA or the larger two forestry industries of the country. Some of them have published reports with CORMA, and just recently (2021) also scientific articles in collaboration with the forestry companies of Arauco and Mininco (CMPC). In the same way, some of these academics have been previously commissioned by senior CONAF officials to write official reports on the state of the art of forest hydrology in Chile. The only academic who did not show up to participate in the SWEC meetings was from the Universidad de Concepción (not mentioned in the SWEC minutes). The above facts demonstrate that the groups of academics listened to in the SWEC process were those academics with collaborative work-links to the government and/or forest industry on forestry or forest hydrology issues.

As a fourth actor, there was one representative of the Peasant Farmers' Movement (MUCECH). However, he only attended one SWEC meeting, and his organisation is recognised in previous ACF studies as a solitary organisation and an opponent of CORMA in the case of the Chilean Native Forest Law policy-production (Arnold 2003). This representative was not a scientific expert on the subject and did not share any publications, reports or documents. But, he requested that knowledge of forest hydrology studies be disseminated in rural localities.

7.3.1. Other actors

Later and after the first SWEC report on soil and water protection measures, other actors were going to discuss the results of the SWEC. These actors were going to meet at the Thematic Commission of the Forest Plantation Protocol (TCFPP) and the Forestry Policy Council (FPC) meetings (see figure 30, green-boxes 2 and 1 respectively).

Other actors, such as the forestry representatives from small and medium forestry enterprises (SMEs) – a wing of CORMA – called PROPYMEFOR-CORMA; the Ecological Society of Chile (SOCECOL); TERRAM Foundation; and Forest Engineers for Native Forests (AIFBN); WWF (World Wide Fund for Nature), and the Department of Social Action Bishopric of Temuco (DAS-Temuco), among others were going to join too.

Some of those organisations have members who are academics and professionals from multiple institutions. For example, an academic participant in the FPC explained his participation as a representative of AIFBN in the following way:

> "*The only one who could... who could have independence, and that if any kind of tension happened... somehow one said, from here, from the university no... they couldn't put pressure on me. And that's why I ended up*" (Interview 8, November 2018).

AIFBN did not participate in the SWEC but its organisation was mentioned in a previous ACF study, together with other environmental organisations, as an opponent of CORMA (Arnold 2003).

7.4. What scientific-expert knowledge is listened to?

As the case of the Forest Plantations Protocol in the SWEC demonstrates, opposing coalitions may circulate and apply diverse environmental knowledge approaches in policy production, and other strategies. Specifically, it was a mix of forestry hydrogeology and ecosystem science approaches (as found and described in the previous chapter 6 as well), which were listened to, circulated and applied, in different ways and by different group of actors. Additionally, this section demonstrates that various environmental statements may or may not be supported by scientific documents, and that sometimes the denial of knowledge might occur. In this way, the policy subsystem of the SWEC analysed by the ACF helps to enrich the analysis of the studies' focus on the circulation and application of environmental scientific knowledge, by helping to understand what kind of scientific approach is listened to and on what basis it is applied.

As a general context, the experts convened in the SWEC were mandated to analyse the role of plantations in affecting soil and water and how to protect them, while reviewing the particular case of 'critical watersheds' – in terms of water reductions – from the point of view of water supply for rural inhabitants (CONAF 2017h).

> "*Issues to be analysed for plantations and responsibility for soil and water conservation: critical watersheds, from the point of view of water supply for local populations, Strips around watercourses;*

zoning in the watershed, classification of sites where there should be no plantations or where there should be lower densities or greater distances from watercourses, among others" (CONAF 2017g, p.4).

The SWEC would need to agree and write the guideline for future management and operationalisation of the soil and water protection measures in the country. To do this, and as an orientation, CONAF communicated that the Thematic Commission of the FPP (acting as general coordinator of the 4 Experts Commissions) proposed to base the expert discussions on the existing Decree Law 82 on soils, water and wetlands because this is a regulation in force in these soil and water matters (see following section 7.4).

Subsection 7.4.1 shows what kind of documentation was circulated and applied by SWEC experts to support their forest hydrology arguments. Subsection 7.4.2 demonstrates the circulation of two forest hydrology approaches in the SWEC. Subsection 7.4.3. delves into the forest hydrology discussions to demonstrate the coalitions, strategies and the policy core beliefs they hold in the discussions.

7.4.1. Documents presented by the experts in support of their statements

As mentioned in section 7.3, actors from government, academia, the forestry sector and other social organisations participated in the SWEC discussions. This section reviews the type of documental material circulated by the experts in the SWEC to support their statements, according to the SWEC archives and minutes.

INFOR governmental representatives presented a PowerPoint document summarising the major findings in forest hydrology from Chilean and international peer-reviewed scientific journals. This presentation also included publications by academics present at the SWEC. INFOR and CONAF furthermore presented their internal institutional documents on forestry and forest hydrology. A scientific article published by an INFOR expert was also used.

The academic group – most academics – for its part presented a forest hydrology report, defined as a 'draft version' and dated 'April 2017'. The report presented in April 2017 was based on one report previously requested and published by CORMA[20] in January of 2017, which some of those academics wrote in order to answer forest hydrology questions based on the international and national literature. Both the January and April 2017 reports answer the same number of fifteen questions, but some questions were slightly modified in the second report. Additionally, the report presented at SWEC in April 2017 removed in its introduction that it had been commissioned by CORMA (but not in the entire document) and expanded the co-authorship of academics who endorsed the report at the time of submission to SWEC as a draft version. Academics also presented other forest hydrology documents they prepared themselves, as well as other reports developed by other academics who collaborate with the national State and forestry industry in previous years. A scientific article published by a UACH academic was also used.

The forestry company Mininco (CMPC), CORMA and MUCECH stakeholders for their part, did not present documents to support their forest hydrology arguments at the SWEC in 2017.

7.4.2. Forest hydrology approaches in the SWEC

It was possible to identify the presence of two approaches to forest hydrology. The 'ecosystem approach' and the 'forestry hydrogeology' approach. As mentioned above, the two approaches differ mainly in the internal and external objects that are highlighted in the forest hydrology discussions. On the one hand, for the 'ecosystem approach' the tree species used, diverse land uses, land use changes and forest harvesting are factors contributing to water fluctuations and reductions in watersheds with forest plantations. On the other hand, for the 'forestry hydrogeology approach' the most relevant factors contributing to water fluctuations and reductions are factors external to land use covers or tree species, and these correspond mainly to soil, geology, precipitation, snowfall characteristics, or – for some actors – the increasing water consumptions from agriculture or rural inhabitants. According to them these are more relevant factors to consider with regard to water fluctuations and reductions than diverse forest covers, tree species or harvesting.

[20] This report, first published online by CORMA in January 2017, mentions that it was requested by CORMA. The same report, dated April 2017 and presented at SWEC, includes more academics and leaves out that it was demanded by CORMA.

In this respect, the 'ecosystemic approach' and the 'forestry hydrogeology approach' are complementary in recognising environmental complexities. For instance, both approaches recognise climate change, rainfalls, location, age, and geology, among others, as basic features for the determinant hydrological regulation of basins (CONAF 2017h). Additionally, both approaches recognised the importance of including soil and water conservation works (infrastructures), which reduce sediment transport and increase water infiltration (CONAF 2017i), and in focusing the discussions on catchment areas associated with human water consumption (CONAF 2017h). They also agreed on the importance of size of harvested areas, or the impact of roads, among others in affecting water resources (CONAF 2017i).

But the two approaches differ in their understanding of the relevance of what topic to apply as soil and water protection measures, such as (i) diverse forest land covers (e.g. *Pinus* vs *Eucalyptus* trees), and (ii) the management of harvesting. They also do so with regard to whether or not (iii) forest plantations contribute to groundwater recharge. Each approach mobilised its arguments through different strategies, and differed with regard to the type of actors that circulated these arguments in the coalitions (see section 7.4.3). For instance, some academics, directly denied knowledge and presented hypothesis as facts, thus generating misunderstanding as a strategy. Further details of the two forest hydrology approaches and their discussions, are presented and exemplifying in the following subsection 7.4.3 for governmental, academics and forestry industry SWEC experts.

7.4.3. Coalitions, strategies and policy core beliefs

Through the analysis of the forest hydrology discussions, diverse strategies and policy core beliefs about the effect of forest plantations on water and soil resources in the SWEC are observed. This subsection demonstrates, that core policy beliefs at stake on the part of the government coalition represented by INFOR and CONAF, are to advance a common regulation – prioritising a precautionary principle – to protect all waters in the country's forested watershed territories; versus a policy core belief on the part of the forestry industry coalition represented by CORMA and invited academic allies, which seeks to avoid a unique regulation to protect all waters in the country's forested watershed territories, and promotes case-by-case assessment of punctual territorial situations that need water protection measures in forested territories. Additionally, this section shows that the argumentative contestations of certain topics, and certain strategies are mobilised to advocate 'for avoiding' the inclusion of certain topics in the policy-making governance, especially in the forestry coalition. Additionally, this subsection shows that focusing on common understandings on topics between actors may favour the agreement on policy-outputs, but does not necessarily favour major policy changes.

First, both governmental institutions of INFOR and CONAF – but mostly INFOR – advocated for an ecosystem approach to forest hydrology discussions (INFOR 2017a). This approach pays more attention to the need for a permanent (non-harvesting) tree cover – of native forest, *Pinus* or *Eucalyptus* trees – to maintain the hydrology of a site (CONAF 2017h). This mean to prevent rises and falls in water levels. Moreover, regarding forestry tree species, experts from CONAF and INFOR recognised that *Eucalyptus* is one of the most evapotranspiration efficient tree species (CONAF 2017h; CONAF 2017g).

> "*Eucalyptus is one of the most efficient species in terms of evapotranspiration. Trees are made up of 85% water, so we can see the tree as a source of water and the faster the tree grows the more water and nutrients it consumes*" (CONAF 2017h, p.10).

Both governmental institutions agreed that despite forestry plantations of *Pinus* and *Eucalyptus* trees not being the unique cause for the water shortages in the country, forestry plantations are also responsible for the hydrological effects on watersheds (CONAF 2017h), as a water consumer that affect streamflow and also soil water infiltration through water transpiration of trees (CONAF 2017g; CONAF 2017h). Likewise, if a watershed with plantations occupies a good proportion of the surface area, the watershed will have a lower water yield (CONAF 2017h).

As for policy core beliefs, both governmental institutions of CONAF and INFOR also called for a general criterion that would regulate and support CONAF's forest management work, despite the fact that nature is indeed complex and diverse. In this way, the governmental coalition mostly advocated for a common policy regulation to protect all waters in watersheds of the country with a good proportion of forestry plantations:

> "*While it is true that nature is very diverse, nevertheless general criteria should be used to develop the protocol*" (CONAF 2017g, p.5).

But stakeholders from CONAF and INFOR also differed on some points. One expert from CONAF mentioned that the services of forestry plantations may be in competition – while helping to control erosion[21], at the same time they consume water – and that this depends on climatic and geological particularities (CONAF 2017h). Also, this governmental expert of CONAF called for a balance between water production and the productivity of other goods and services in the basins, and mentioned the case of South Africa, where scientists have recommended not having more than 50% of a watershed covered with plantations (CONAF 2017h). On these last points, CONAF was close to the forestry hydrogeology approach and the arguments of the representatives of the forestry industry, who also argued for a balance between productive and conservation aspects in the watersheds (more details on this in the following paragraphs). On this last point CONAF and INFOR differed. For governmental experts of INFOR, catchments that supply water for human consumption should have a permanent forest cover (unharvested) (CONAF 2017h), with native forest or a mix with tree plantations because this helps to better regulate hydrology in the watersheds (Interview 3, December 2018).

> "[A] *watershed that supplies water for human consumption should have permanent forest cover, therefore industrial activity, which is based on short rotations of high* [water] *consumption, causes a series of hydrological impacts*". (CONAF 2017h, p.9).

This means that with a permanent vegetation cover in a catchment, water level fluctuations – from floods and water reductions – which in fact do occur after the harvesting and (re)growth of young trees in productive plantations, are avoided. In this regard, there is also a cumulative effect over time (temporality) to consider (CONAF 2017h).

Thus, for INFOR, the understanding of forestry plantations as a factor that highly contributes to water consumption is applied to argue for the development of a precautionary principle in the policy formulation.

> "*The issue of plantations and water consumption had been discussed at length, and at INFOR they had made a pronouncement by exhaustively reviewing the existing literature at national level, which*

[21] As for the statement that productive forestry plantations contribute to sediment control in streams, this is not consistent with what was observed during field visits and in a forestry plantation monitoring catchment in Chile (see figure 31).

coincided with international information. Therefore, existing literature agrees that on the water issue, small basins should be addressed – considering the precautionary principle, which is relevant and required by some companies – where fast-growing forestry plantations that occupy a good proportion of a small basin generate a lower water yield, especially in the summer season. This compares to grassland, scrub and native forest in Chile" (CONAF 2017g, p.9).

Second, academics, for their part, mostly advocated for a 'forestry hydrogeology approach'. This approach pays more attention to external factors, such as soils, geology, or climate characteristics in analysing hydrological effects of forestry plantations. In the forest hydrology discussions, some of these academics argued that although tree forests and plantations do indeed contribute to the reduction of water resources, land cover is not the most relevant variable. For them, external climate, hydrogeological and human water consumption factors are more significant to consider than forestry plantations in the policy-measures (CONAF 2017h). As one academic stated:

"*Land use is not the most relevant variable* [in water reduction phenomena], *but rather are hydrogeological and climatic variables. According to isotopic studies – led by forestry companies – the behaviour of metamorphic rocks, the residence time of water in the rock is 8-9 years. When there is a continuous flow in a non- surface watercourse, and as there is a period in which there is no precipitation, it is evident that there is a mixture of surface and recessive flows. Additionally, the data from the DGA establishes that water consumption has increased three times since 1990 to date, so there is no ecosystem that can resist*" (CONAF 2017g, p.7).

In doing so, they argue that as 'trees' do indeed have effects on the hydrological distribution, it is always more beneficial for water production to have 'smaller vegetation' in catchments (CONAF 2017i), by which they mean vegetations such as grassland but not trees.

Concerning tree forestry plantation species, one academic stated as a research gap the need to identify whether there are hydrological differences between *Eucalyptus* and *Pinus* species (CONAF 2017h), although in another report published by the same author(s) and presented at the SWEC, this academic acknowledged that *Eucalyptus* are higher water users compared to *Pinus* and native forests (CTHA and CFCN 2017). In doing so, this academic (or these academics[22]) has been inconsistent between what he declares and writes, and likely as a strategy, has presented as a research gap (a need to know) a fact of his own forest hydrology written knowledge (document written in 2017) and which was presented as a backup of the forest hydrology discussions held in the SWEC in 2017.

Similarly, some of these academics argued that plantations also contribute to groundwater and soil water recharge (CONAF 2017g; 2017f). This group of academics even develop the proposition of a new hypothesis (called by them a theory) unique to Chile. For them, the results of international forest hydrology studies – which demonstrate the effects on water reductions of *Pinus* and *Eucalyptus* forestry plantations – could not be compared with Chile, given the country's Mediterranean climatic and hydrogeological characteristics (Interview 4, November 2018; Interview 5, December 2018). In this way, these academics, likely as a strategy, challenge the international and national state of art in forest hydrology, which recognises how *Eucalyptus* and *Pinus* plantations contribute to water reductions. Part of this hypothesis also argues that forest plantations contribute to groundwater recharge in climates where it only rains in winter such as in Chile. In these ways, these academics believe in the impossibility of comparing forest hydrology knowledge from different locations and this argument is used to advocated (policy core beliefs) for avoiding a common regulation to protect all waters in forested watersheds of the country, and by analysing case by case the hydrological effects:

> "*I agreed* [with the other academics] *that a common* [forestry] *policy could not be applied to all the watersheds. A book* [it is a report] *has just been published with Unesco where 13 countries were contacted, which were world powers in the forestry sector, have been contacted to find out what policies they were applying in the sector and what they were applying to protect water resources. One of the conclusions reached was that what happens in one climate cannot overlap with what happens in another place. Similarly, the forest management carried out in one basin would not necessarily work in another, as it depends on the hydrogeological characteristics of the basin. It is important to know that in climates where it only rains in winter, as in much of Chile, if forest plantations are well established territorially, far from the water table, in the upper parts of the basins, it helps to*

[22] This statement was declared by one academic, but other academics - who were also present at that SWEC meeting and are co-authors of the aforementioned report presented at the SWEC – kept silence and did not clarify this inconsistence between his oral and their written statements neither.

> *produce water* [probably he meant due to groundwater recharge ?], *as is the case in South Africa*" (CONAF 2017g, p.5).

In this regard, it is important to mention that the statement that forestry plantations 'help to produce water' by recharging groundwater was not found in the literature references reviewed in chapter 5. On the contrary, concerning *Eucalyptus* tree species in Australia and South Africa, it was noticed how forestry plantations contribute to reduce soil water content and groundwater levels, and these trees are in some cases used to reduce the groundwater levels in aquifers facing salinity problems in Australia (see section 4.1.3). In addition, considering the findings in chapter 5 of this research, Chile has no scientific publications about the hydrological effects of *Eucalyptus* plantations [as to my knowledge, neither about *Pinus* plantations] on their aquifers water use and/or groundwater recharge by these trees; making this topic a key knowledge gap in Chile. In this context, the statement that 'plantations help to produce water' is an inconsistency. Additionally, the aforementioned statement seems to use the 'groundwater' gap of knowledge (a need to know in Chile) likely as a strategy to present as facts, hypotheses not proven yet or rejected in Chile.

The issue of whether or not forest plantations of exotic species help (or not) groundwater recharge was an issue on which INFOR experts asked for clarification, and about which INFOR and academics did not reach common understanding (CONAF 2017h). This could explain the scientific inconsistencies reported in the SWEC minutes summary:

> "*A reference is made [in the meeting] to the lack of existing research for providing answers to the many questions (…) given that there are many claims regarding the effects of plantations on waterbodies that have no scientific background*" (CONAF 2017h, p.2).

Furthermore, some of these academics usually stress as an argumentative strategy, that as all watersheds are different (climate, soils, groundwater, etc) and complex, there are no homogenous hydrological effects and many uncertainties. They also pointed out that the summer water present in a basin is not strictly concordant with the water that fell in the preceding hydrological year, and that this water is explained by the water that fell in previous seasons; as well as that basins and aquifers do not always overlap (CONAF 2017i), thus stressing the complexities of forest hydrology phenomena. Furthermore, given the large number of external and significant factors such as climate change, increasing human and agricultural water consumption, etc. which also play part in the water production of watersheds (CONAF 2017g; 2017f), generally these academics circulated and applied these arguments to advocate that it is not so simple to subject forestry plantations to a single forest policy, and more research is needed in collaboration with public and private actors. In these ways, as for the policy core beliefs of these academics, their understanding of the environmental complexity, diversity, and uncertainties or gaps of knowledge is applied to advocate against a unified policy formulation for all forestry plantations. As another academic also stated:

> "*The answer to the questions posed are not unique and what to do in all these cases to strengthen public policy is not so simple and there must be more research on this issue and greater collaboration between different public and private bodies. Moreover, in the national parks there should be monitoring of these basins. Define well what is critical in relation to current and future demands, in order to clarify what will be investigated. If the existence of vegetation is conflicting within the basin in relation to water supply and demand, then let's study that issue and make the results known to society*" (CONAF 2017h, p.9).

As for argumentative coalitions, these academics agreed to distinguish and look more carefully at cases in the so-called 'water supply watersheds' (CONAF 2017h) instead of distinguishing/calling them 'critical watersheds' (CONAF 2017i). With all these arguments, these academics show points in common with CORMA representatives who also advocated for calling them 'water supply watersheds'. Additionally, some academics recommended reaching some kind of agreement, giving the example of the case of South Africa, where watersheds are not completely forested in order to provide opportunities for other uses (CONAF 2017h). Thus, they show points in common with a CONAF expert who also mentioned the example of South Africa. In this case, the example of South Africa was applied as a common strategy from these actors, to advocate for the presence of productive plantation forestry (harvested) in 'water supply watersheds. In this way, these actors advocated for common elements in the policy-process, demonstrating signs of a coalition.

Third, forestry industry representatives for their part, presented a forestry hydrogeological approach too. Forestry actors indicated that they have done forest hydrology research on the subject for more than 5 years, with significant advances (CONAF 2017i). Based on their forest hydrology knowledge, the forestry industry – while acknowledging that land use and management are factors that influence water dynamics – advocate that water reductions in forestry areas are mostly due to external factors, such as climate change (less rainfalls), soil characteristics or higher water consumption by agriculture. As a forestry representative stated in the forest hydrology discussions:

> "*There are things that have already been said, less rainfall, less water, origin of the soil and now we are facing a third element, the use of the soil and we must recognise that agricultural crops consume more than forestry crops and this must be made known to society as a whole*" (CONAF 2017h, p.6).

> "[Additionally, he] *raises two issues. The first is that you cannot look at water independently without considering the existing vegetation over the watershed, water production is not independent of watershed management. The second is that the size of the watershed and the size of its intervention affects how much or how little road construction and how much or how little sediment is washed away by roads*" (CONAF 2017h, p.8).

Additionally, similar to the group of academics. forestry industry stakeholders also preferred to work with the concept of water supply basins, rather than critical basins (CONAF 2017i). Likewise, the forestry industry argued that it is important to maintain a balance between the production of goods and services (timber and water, etc) in watersheds, showing accordance in this regard with CONAF. Additionally, forestry experts stated that a well-applied clear-cutting (harvesting) could be a management technique in forestry watersheds that provide water to communities as well (CONAF 2017i), differing on this point with INFOR.

> "[A forestry representative] *raised the importance of maintaining the productivity of multiple goods and services in water-products of watersheds, and argued that well-applied clear-cutting could also be a management alternative for these watersheds, especially when we are in coniferous plantations due to silvicultural management issues. He indicated that a balance should be maintained between environmental, social and economic aspects*" (CONAF 2017h, p.10).

With these arguments, representatives of the forestry sector also called for a protocol that does not modify productive forestry management of plantations, especially harvesting, in 'water supply catchments'.

At the same time, the forestry sector equally mentioned the complexity of regulating all the watersheds with the same policy-measures, when – according to them – the existing critical cases for human water consumption are a minority (CONAF 2017i). In this sense, as for the policy core beliefs for this representative of the forestry sector, the statement that the cases of forestry watersheds affected by water reductions would be a minority in the country, is used to advocate for a case-by-case management-solution, and against a unique policy formulation for all watersheds with forestry plantations. As a forestry industry expert stated:

> "[He] *points out that the catchments that we are talking about, at the national level are very few and it is not possible to regulate for all cases when it comes to a minimum number of situations*" (CONAF 2017h, p.9).

In this way, this forestry representative proved to share policy core beliefs and make a coalition with most of the invited academics in: a) advocating together against a unified national policy regulation to protect all waters in the country's forested watersheds in Chile, and b) in favour of a case-by-case analysis, to assess whether and where it is necessary to safeguard water and soils in certain forestry plantations in Chile.

Forestry industry experts thus, on the one hand, expressed common ground with both CONAF and academic representatives on certain aspects mentioned above. But, on the other hand, forestry actors also differed with INFOR actors on other aspects, such as on the relevance of considering (or not) harvesting (clear-cutting) practices in watersheds for human water consumption in the country (CONAF 2017i), and later, on the 'widths' of water protection buffer-zones (CONAF 2017q). The specific discussion among actors on the issue of the water protection buffer-zones, is addressed in greater detail in the following section 7.4.

MUCECH representatives for their part, did not actively participate in the development of protocol agreements (see e.g. CONAF 2017f; 2017i; 2017b; 2017k). However, during their interventions in the process, they advocated for the rural peasants' and indigenous communities' views. They mentioned being affected by forestry activities (land properties, or chemicals, among others); and requested support for rural peasant production, as well as called for an integrated management policy that could ensure a permanent water availability in the watersheds (CONAF 2017i). During the process they did not report conducting research on the subject, but called for the knowledge about soil and water studies to be diffused in rural communities (CONAF 2017i).

In this regard, inspired by the Decree 82 on soil, water and wetlands regulation, and based on the previous forest hydrology discussions, academics mentioned three concrete measures for soil and water protection. These were agreed on and then taken up by governmental and industrial actors too, to advance the production of the FPP: 1) manage the exclusion intervention buffer zone with low vegetation that has low water consumption rates, 2) define riparian zones, do not plant in these zones and do not thin trees as this would increase the water consumption of remnant trees; 3) establish mosaics of different ages of trees and look at their plot sizes so as not to increase the density of roads (CONAF 2017i); as well as other soil protection measures to be taken into account during harvesting operations (CONAF, n.d.). These proposals demonstrate how common understandings among experts about certain topics were key to move forward the production of the SWEC outputs. Such is the case, for instance, for the three measures proposed by academics (above), and where actors from industry and government reached a common understanding of identifying these as relevant management practices to consider in the SWEC proposals. Conversely, most contested issues such as the harvesting practices in 'water supply catchments' were not addressed in depth. Subsequently, only the horizontal width of the exclusion intervention buffer zone was later contested in the final outcomes of the Soil and Water Commission. This finding is consistent with the ACF theory, which states that a minimum of consensus on issues is required for policy making (Sabatier and Weible 2007).

After their second and third meetings, the SWEC experts started dividing themselves into smaller sub-working-groups to more efficiently develop the topics defined by consensus in the commission. INFOR and CORMA worked to define the conceptual framework for the work of the SWEC (CONAF 2017i), and the issue of buffer protection zones was discussed at the meetings of the experts (see e.g. CONAF 2017g; 2017i; 2017m). Academics worked with CONAF and CORMA on the development of a soil fragility index (see e.g. CONAF 2017k). Furthermore, academics worked with INFOR and CONAF on the development of drainage works and roads (see e.g. CONAF 2017i; 2017k). They also worked on a proposal for harvesting and establishment issues (see. CONAF 2017j), and a proposal for harvesting machinery was made by CORMA (see CONAF 2017l). During this process, the participants had the possibility to exchange views between the groups before the complete proposal was sent to the CTFPP, and subsequently to the FPC (see CONAF 2017m). With these measures, it was hoped to ensure that all views were represented for each topic of work (Interview 2, November 2018).

As reported in the minutes, after discussions, many of the issues worked on in the SWEC reached consensus despite some differences. However, in the following section I explore in particular the work on the definition of the minimum width required for soil and water buffer protection zones in forestry plantations, as this was one of the most difficult issues to reach a final agreement on in the entire FPP. Through this example, it is possible to demonstrate more clearly the existence of two opposing coalitions in the production of the FPP on the soil and water protection issues: INFOR and CORMA, who confronted their scientific approaches to negotiate the minimum width of the country's soil and water buffer protection zones.

Figure 31. Catchment monitoring station in a *Pinus* forestry plantation under the influence of harvesting and forestry roads

Source: author, 2018. The weir is full of sediment which has covered part of the water level sensor (metal vertical pipe visible on the left-up of the picture). This basin had a buffer zone of native forest and shrubs – of a few meters – around its watercourse. Biobio Region, Chile.

7.5. Decision making in the governance process: the soil and water protection buffer-zones

In this section, I argue that Sabatier's advocacy coalition framework (ACF) can enrich studies focused on the application and circulation of scientific expertise in policy change. It does so by helping to understand how the relative stable parameters (previous policy or rules) play a role in defining the margins for policy change. Additionally, ACF contributes to understanding the role that scientific knowledge plays in the production of the policy outputs within those stable parameters. I do so by analysing how scientific knowledge can move or change those parameters, or not.

As it is demonstrated by the discussion on width of buffer zones in the FPP, on the one hand, knowledge played an important role in policy production by providing scientific evidence to advance the negotiation margins. In this respect, two scientific papers were applied in the SWEC concerning buffers widths in Chile. On the other hand, it is demonstrated that the request to apply the same measures to small-medium and large-sized forestry entrepreneurs was used as strategy to advocate for conservative buffer-widths options in the policy discussions. This contributed to the fact that the main path to policy change in this respect was a process of negotiation, where environmental and economic aspects were negotiated.

At the same time, this discussion shows the importance of the existence of previous laws and agreements (relative stable parameters) in defining the possible margins of negotiation. As the case of the width of the buffer zones demonstrates, the overall margins did not move beyond the previous legal margins of Decree 82, but did change within those margins. Additionally, it confirms the existence of two opposing coalitions in the process of producing the final outputs of the Soil and Water Experts' Commission (SWEC) in the FPP: the forestry industry, and a governmental coalition. This section looks in particular at the case of the negotiation on width for soil and water protection buffer-zones, as this was the most discussed output of the SWEC and one of the two most discussed topics in the entire production of the Forest Plantation Protocol (FPP).

Section 7.5.1 first presents the background of existing regulations in Chile on buffer zones in forested territories. This allows to analyse a subsequent policy change or not. Section 7.5.2

demonstrates which coalition actors advocated for advancing or preserving buffer distances and their arguments circulated and applied for doing so.

7.5.1. Relative stable parameters: The Decree 82 on soil, water and wetlands regulation

During the creation of the SWEC, the Thematic Commission of the Forest Plantation Protocol (TCFPP) discussed which regulations to use as a guide for the experts' discussion. In its third meeting, the TCFPP proposed to use the Decree 82 on soil, water and wetlands regulation (Ministerio de Agricultura 2010) as the basis for the analysis of the issue of water and soil protection (CONAF 2017g). It was also decided that the Forest Plantation Protocol would be an indicative and non-normative document since its production was part of the FPC which is also a consultative political body (CONAF 2017g). In this way, at the first meeting of the SWEC, government representatives presented the decree 82 as a guideline for the development of SWEC's work themes, among which protection buffer-zones are specified (CONAF 2017h).

Decree 82 on soil, water and wetlands regulation (Ministerio de Agricultura 2010) is the Chilean regulation that sets out the criteria for protecting soils and water bodies in the country. It focuses on native forest recovery and forestry incentives. Decree 82 addresses the issues of protection buffer zones, harvesting, use of machinery, road construction, soils, erosion, slopes, among other topics that were addressed at the SWEC as well.

Regarding protection buffer zones, Decree 82 defines two types of zones. First, an 'intervention exclusion buffer zone' of 5 and 10 metres on both sides for watercourses between 0.2 - 0.5 square metres, or larger than 0.5 square metres respectively. In the intervention exclusion zone, the harvesting of native trees or forest plantations is prohibited, as well as the construction of any structure, roads or the entry of any machinery. Second, there is a 'limited management protection buffer-zone', which is contiguous to the intervention exclusion zone. The limited management buffer zone has a width of 10 metres for slopes between 30 and 45%, and 20 metres for slopes steeper than 45%. In the limited management protection zone, it is possible to intervene leaving a land cover of at least 50%. But this zone does neither allow the construction of structures, nor the deposit of forest harvesting waste, among others. Combined, both intervention exclusion and limited management buffer zones add up to a maximum of 30 regulated metres as a protected buffer zone.

7.5.2. The FPP and the discussions on the width of water protection buffer-zones

According to the SWEC's minutes, participants at their first meetings agreed to consider 10 metres as a minimum width for the exclusion intervention zone around permanent and temporary watercourses (CONAF 2017g; 2017i). This progress was made due to the fact that INFOR argued that the 5-metre minimum distance defined by the Decree 82 was insufficient to protect the quality and quantity of water in the estuaries or headwaters of the watersheds (CONAF 2017h). Likewise, during the process, INFOR reported that published Chilean research indicated that 36-metre buffer strips bordering water bodies covered with forests and plantations on the sides works for purposes of water yields (CONAF 2017h). At the same time, CONAF clarified to the SWEC experts that the width of the buffers would be considered primarily as a criterion for water quality protection (CONAF 2017h), and representatives of the forestry companies promised to send a watershed management protocol that they had developed 5 years before with one of CONAF's regional office's in the south of the country (CONAF 2017i).

However, between the fourth and sixth SWEC meeting, no further progress on buffer zones was reported in the SWEC minutes. In this regard, accounts from some SWEC experts also mentioned that in the discussions on buffer widths, at least one academic has referred to the need for a buffer of at least 100 metres wide, with the buffer area being extended depending on the type of vegetation, topography, slope, etc. inspired by international laws (Interview 7, November 2018). The above, although a minority, is also proof of a diversity of positions on the discussion of buffer widths within the group of academics in the SWEC. Some SWEC experts also would have referred to the old Chilean forest law of 1931, which had buffer protection widths of 100 metres (Interview 6, November 2018). Nevertheless, these discussions were not found in the FPP' minutes, possibly because they were made outside SWEC's meetings (e.g. emails). However, some comments made by governmental and academic actors were found in the minutes of the meetings, suggesting to analyse percentages of afforestation in the watersheds (CONAF 2017h). All of the above could suggest that at one point in the SWEC, major measures on afforestation were also discussed, such as the protection of all or major percentages of the watersheds involved in human water consumption.

But at the seventh SWEC meeting – the last meeting before submitting the SWEC report to the coordinators of the Thematic Commission of the Forest Plantation Protocol (TCFPP), it was agreed between CONAF[23] and forestry industry representatives of MININCO and CORMA – INFOR and academics did not attend to that meeting – to include as a criterion the previous "Protocol of agreement for the protection of watercourses and soils of the IX region". This protocol had been signed by CONAF-Araucania (IX region) and forestry companies years earlier. This CONAF-Araucania document was added as an argumentative baseline for categories and buffer width ranges in watersheds with plantations for the SWEC-outputs. This CONAF-Araucania document included different waterbody categories and defined that the width of the water protection zones in general areas had a minimum distance of 5 metres (see CONAF 2017m), which were not previously discussed by all the SWEC experts. In this way, the 10 metres minimum as water protection zone width were adjusted only to the watersheds identified under the category of water supply watersheds (see annex 1) (see CONAF 2017m). This change demonstrates, on the one hand, the importance of relatively stable parameters, such as the existence of prior agreements between actors (e.g. CONAF-Araucania agreement), to avoid policy change and try to keep current policy-environmental standards within the general margins in force by law (e.g. Decree 82) that had been previously established. In this case, the CONAF-Araucania document signed earlier by CONAF and large Chilean forestry companies, was applied to keep the previous margins of regulation in the SWEC policy-production process. On the other hand, with the inclusion of the CONAF-Araucania document some members of CONAF demonstrated being allies with forestry companies, and CONAF showed contradictions within the actions of the government coalition (e.g. with INFOR). This is probably due to the fact that within CONAF there are different views on the soil and water issue in the country (Interview 9, January 2019). Additionally, this situation demonstrates the power of the forestry sector in the FPP and SWEC negotiations, and evidences that the power of the governmental institutions – who generally sought to advance forestry sector regulations in different topics

[23]The Watershed Unit, Department of Plantations, and the Department of Standards and Procedures. Both from of the National Forestry Corporation (CONAF).

in Chile to date – was not absolute in the production of the FPP, despite the fact that the regulatory power of governmental actors had been encouraged by the 'firestorm'.

This situation of the buffer-zones' width led to a series of misunderstandings among the TCFP councillors when they afterwards reviewed the SWEC's first-output report. The TCFPP was responsible for reviewing this first full draft of the Forest Plantations Protocol, including the first SWEC report with the buffer zones, among others, before transferring it to the Forestry Policy Council (FPC) for approval. During this process, the existence of SWEC's main opposing coalitions became more evident: forestry industry and governmental coalitions. Regarding SWEC's work, at this TCFPP meeting INFOR representatives questioned that the minimum widths should be 10 metres for all permanent and temporary brooks according to the SWEC agreements (CONAF 2017n). INFOR also advocated that other category of water bodies should be included as well, giving the example of lakes that could vary in water level where 10 metres would not be sufficient. For this reason, INFOR considered that in those cases, it should be a minimum of 20 metres (CONAF 2017n) and thus the minimum buffer zone widths for these cases should be increased. At the same time, CORMA argued that 10 metres should only apply to water supply catchments as agreed at the SWEC. They also advocated that large water bodies such as lakes were not located in plantation areas, and that Decree 82 only refers to rivers, springs and water bodies (CONAF 2017n), and no other categories of water bodies as INFOR proposed should be included. At the same time, CORMA argued that the water bodies categories of the SWEC report had been taken from a protocol previously signed between forestry companies and CONAF in the Araucania IX region (CONAF 2017n) to demonstrate that these categories were based on previous agreements between these institutions. In this sense, the previous agreement of CONAF-Araucania, was what the forestry companies could circulate to contest the extension of the buffer widths. This again demonstrates the role of prior agreements for policy-change within relative stable parameters (Decree 82), when some coalitions do not pursue policy-change and seek to preserve previous conditions. At the same time, it demonstrates the process of negotiations as an important path to avoid policy-change, especially when some actors had no publications or documents to back-up their arguments on a subject with knowledge.

INFOR and CORMA councillors and invited experts could not reach an agreement at this meeting about the issue of minimum widths of the water protection zones and water-categories. Therefore, the CTFPP participants agreed to reconvene the Soil and Water Experts group with members from CORMA, INFOR and CONAF to re-analyse the proposal on minimum widths (CONAF 2017n). However, this meeting did not take place. INFOR reported requesting a meeting and having no response from the forestry representative (CONAF 2017p), and the issue of minimum protection widths of 5 and 10 metres passed on to be discussed in the plenary chamber of the Forestry Policy Council (FPC).

In this context, a confrontation between the visions of INFOR and CORMA coalitions on the minimum width of the buffer protection zones also took place in the 16th plenary session of the Forest Policy Council (FPC). In the process of revising the document, some experts and councillors made their suggestions and requested more time to analyse the first draft Protocol. In response to this, the president of the council, led by CONAF, said that it was not possible to reconstitute all the expert committees again, so the FPC counsellors should focus on resolving only those issues on which there were discrepancies (CONAF 2017n). In this way, two main issues emerged as non-agreed topics in the protocol: minimum widths of soil and water protection buffer-zones in the work of the SWEC, and the topic of undergrowth vegetation in forestry plantations in the work of the Commission on Ecological Functionality (not analysed in this study).

At this plenary meeting, stakeholders such as INFOR, SOCECOL and PROPYMEFOR-CORMA requested to increase either more, or less, the minimum and maximum of the protection buffer-zone widths. They applied different strategies. At this point in the discussion, some actors also used the existence of different previous agreements as a main argument for political change. This reinforces the importance of the existence of relative stable parameters, such as, for example, the existing legislation (Decree 82), the FSC certification, or previous agreements (Araucania IX, or in the CTFPP meetings), in order to keep previous policy conditions. For instance, SOCECOL asked whether or not the SWEC buffer proposal changed the margins of the current regulation (Decree law 82). If not, SOCECOL proposed to go beyond the status quo and surpass the established minimums in the policy (CONAF 2017p), thereby supporting INFOR. The counsellor of PROPYMEFOR-CORMA (representative of CORM's micro-enterprises), for his part, requested that 15 meters should be considered as a maximum goal, arguing that the Forest Stewardship Council certification (FSC) requires forestry companies to have 15 meters of exclusion and subsequent fencing, which is not easy to achieve (CONAF 2017p). In response to PROPYMEFOR-CORMA's comment, CONAF argued that for micro enterprises a particular discussion should be held, in order to operationally move forward with a general rule for all actors (CONAF 2017p). This exchange between PROPYMEFOR-CORMA and CONAF evidences a recurring aspect in the construction of the protocol in which for CONAF and forestry companies general measures for large, medium and small forestry entrepreneurs had to be found. In this way, CORMA representatives invoked social and economic criteria by mobilising the argument of inclusion of small and medium forestry landowners, and asked that an 'equal regulation to all forest entrepreneurs should be applied' as an argument in favour of lowering the environmental standards of the buffer widths under discussion. A similar case was reflected in the discussion on the slope and construction of forestry roads (see section 4.1.1), as well as in the final discussion on buffer zone widths at the 8th session of the SWEC (see below). Here too, the existence of small and medium forest owners was used as a socio-economic criterion in the width-buffer evaluation. In this sense, forestry industry stakeholders showed inconsistencies in arguing that a unique/general policy should not or should be applied, or at least not to all forestry plantations, depending on whether environmental-water or socio-economic aspects were discussed respectively. Finally, in both cases of general basins and water supply basins, INFOR argued for including ranges of 20 and 30 meters according to different water bodies' categories (CONAF 2017p). In this way, environmental and economic stakeholders were generally more or less in favour of advancing the standards of the protocol, thus generating opportunities to support the INFOR and CORMA coalitions respectively.

Other environmental stakeholders too gave their views on soil and water outputs. AIFBN mentioned that it was a simplification to see SWEC's differences only to exist between INFOR and CORMA. In response, CONAF agreed but said that it was better to reduce the number of stakeholders to facilitate the SWEC's agreement. In addition, TERRAM Foundation advisors requested to distinguish the measures to be taken between plantations and native forests. In response, AIFBN argued that it was not the species that was relevant, but the type of forest harvesting applied, and advocated for basing the protocol on Decree 82, given that D.L. 701 had anomalies. Subsequently, AIFBN offered to be part of the drafting team of the protocol, replacing SOCECOL in common agreement and taking the position that had initially been assigned to it (CONAF 2017p). In this way, SOCECOL and AIFBN appeared to coordinate their actions, and evidenced support for INFOR (e.g.

increasing buffer widths and the issue of plantation harvesting, respectively). The other social and environmental organisations such as WWF and DAS-Temuco, were present in the meeting but they kept silent on the discussion of buffers. And, since no agreement was reached at plenary session 16th either, the FPC instructed that CORMA and INFOR experts from SWEC re-examined the protection buffer-zone width proposal to reach agreement. Thus, INFOR and CORMA experts from SWEC met for their 8th, and last meeting to define the minimum buffer widths (CONAF 2017q). In this last discussions of the SWEC, the minimum widths of the buffer protection zones did not vary much from the first version of the draft proposed by CONAF and forestry industries, remaining at 10 and 30 metres minimum depending on slopes for water supply catchments, as well as 5 and 30 metres minimum depending on the slopes for other water protection zones in common basins (see annex 2) (CONAF 2017q; 2017a). However, within the general benchmarks of the Decree Law 82 and the Araucania agreement (5 and 30 meters), changes were made. For instance, increasing the minimum widths of the protection buffer zones from 5 to 10 meters in catchments for human water consumption, including new categories of water bodies, and the category of water supply watersheds. This reveals that although the scientific knowledge discussed at the SWEC could not change the previously established legal bases (for example, go beyond the range between 5 and 30 metres established in the Decree 82), these discussions enabled all the actors to make changes to the Decree 82, but without changing its overall benchmarks.

To finally define and justify the widths of the protection buffer-zones, a combination of scientific publications from diverse SWEC experts advocating for opposed coalitions were used (applied) (see CONAF 2017q). This was materialised through the incorporation of two scientific peer-reviewed journal publications referring to buffer zones in forestry plantations in Chile. One of the articles was published by INFOR experts who in the SWEC advocated for an ecosystem science approach. Another article was published by an academic from the Universidad Austral de Chile[24], who in the SWEC advocated for a forestry hydrogeology approach. As the last SWEC minute reported:

[24] The existence of these publications is mentioned in the minutes, but they were not cited for more precise identification.

"*The proposal considered research work carried out by [professor], who studied sediment control for slopes less than 24%, in areas with clear-cut harvesting and waste burning. For steeper slopes, a study by [INFOR] was considered. Both studies were carried out near to Valdivia*".

In this way, each one of these scientific articles was circulated and applied by the opposed governmental and forestry industry coalitions. This is a relevant finding, as this shows how actors of different coalitions can circulate and apply different scientific approaches that may be more familiar or useful to them in the policy making processes. This also shows, that each coalition can circulate and apply their own scientific publications in policy-making. For example, in the case of the forestry companies represented by CORMA, they circulated and applied a scientific article published by an academic working with them.

Additionally to the two scientific studies from both approaches, in the protection buffer-zones evaluation also factors such as rainfall, slope, and the amount of surface area available for soil and water protection for small and medium-sized forestry companies among others, were considered (see CONAF 2017q).

"*The proposed metrics are extensively analysed on the basis of a number of factors such as slope, rainfall, amount of land area devoted to soil protection and water in the hands of small and medium-sized landholders, among other factors*". (CONAF 2017q, p.2).

This last SWEC discussion also demonstrates other aspects relevant to understanding the application of knowledge in policy-making. On the one hand, this demonstrates that, while Chilean forest hydrology knowledge played an important role in policy production by providing knowledge through two articles to support the changes within the policy benchmarks of the Decree 82, the path to policy-change in the protection buffer-zone was also a process of negotiation, where studies and bio-physical factors, but also some socio-economic criteria were considered. This also demonstrates that this forestry policy concerning environmental standards was largely contested by industrial coalitions. However, the inclusion of socio-economic criteria, was not contested by the industrial coalition and was also supported by the government coalition. Additionally, the inclusion of this socio-economic criteria did not require documentation to backup evidence either.

On the other hand, given that the minimum negotiation margins of the buffer protection zone never exceeded the margins established by Decree 82, this confirms the importance of relative stable parameters in defining the possible negotiation margins of the policy change of this Chilean forestry policy. This is despite the fact that some stakeholders suggested surpassing the 30 metres. Likewise, the later inclusion of the 'CONAF-Araucania agreement' confirms the importance of previous agreements in the negotiation process, in order to keep previous policy-conditions. Because it was thanks to this agreement that a width of 5 meters was kept as a minimum in water protection zones in general. This demonstrates that in the absence of scientific evidence (e.g. publications) for maintaining or lowering environmental standards, the existence of prior agreements between actors in a coalition can be circulated and applied as support for the maintenance of policy-making margins, in other words, as a negotiation strategy.

In this way, the scientific discussions supported by those two scientific articles and the other socio-economic arguments have allowed to move the buffer-zone' widths (margins) within the previously agreed general benchmarks (of 5 and 30 meters indicated in the Decree 82), but not to move the margins beyond them. At the same time, it shows that the power of the governmental actors was not enough to push for major environmental policy changes regarding soil and water protection buffer-zones in productive forestry plantations. This could be explained by the fact that, according to one academic, the SWEC was rather a process of agreement building where an acceptable middle ground was sought between all actors (Interview 6, November 2018).

7.6. Pathways for policy change: previous ACF studies and the FPP

Research on ACF presents a smaller number of scientific publications in the South American continent, in comparison with Europe or the USA (Weible et al. 2009; Pierce et al. 2017; Ma et al. 2020). However, in this scenario, Chile stands out in the continent with publications on ACF on the forestry sector (see Arnold 2003; Manuschevich and Beier 2016). In this sense, the study of Arnold (2003) is the first ACF case developed on the Chilean forestry sector. In his study on the production of the Native Forest Policy in Chile, Arnold reports the existence of two main opposing coalitions: the forestry industry (forestry companies represented by CORMA) and environmental groups (among which were the Committee for the Defence of Fauna and Flora, CODEFF, National Ecological Network, RENACE, Forest Engineers for Native Forests, AIFBN), as well as their respective allies, such as professionals and academics supporting both coalitions. He also mentions the participation of the Peasant Farmers' Movement (MUCECH) as a separate actor. According to Arnold (2003), the core beliefs of these two main coalitions are based on forestry economic theory in the case of CORMA, and on an ecosystem approach for the environmental groups. Furthermore, Arnold reports that the role of governmental institutions – Ministry of Agriculture and CONAF – was that of a neutral moderator, seeking to find common ground between the two coalitions. Subsequently, the study of Manuschevich and Beier (2016) also confirms the existence of two coalitions in the debate for the creation of the native forest law in Chile, which they identify as the industrial forestry coalition and the forest conservation coalition, where the opposition of economic vs environmental or conservation aspects, is one of the most typical between the opposite coalitions found in the ACF studies (Sotirov and Memmler 2012).

In the Chilean case of the Forest Plantations Protocol, there were two scientific approaches circulated and applied in the SWEC: forestry hydrogeology, and ecosystem science approaches. But this research also found a forestry economic approach, applied by industry agents, CONAF and some academics.

The government representatives, for their part, mainly presented ecosystem and socio-environmental approaches to forest hydrology discussions. Forestry companies on the other hand relied on a forestry hydrogeology approach, which was mainly circulated by academics. These findings are not completely consistent with the findings of Arnold (2003) regarding CORMA using an approach solely based on forestry economic theory, or CONAF only acting as a mediating actor. During the SWEC process, industry stakeholders and other actors such as CONAF and academics did indeed mention economic concerns, but not just that. The novel finding of this research is the forestry hydrogeology approach circulated by these academics and forestry companies, despite industrial actors did not present evidence/document to support their expert' forest hydrology statements. This change could be explained by the scientific specialization that the industry has developed in collaboration with most of these SWEC academics through conducting their own forest hydrology research program during the last years (see CONAF 2017h).

The findings of Arnold (2003) are concordant in finding the ecosystem approach, but on this occasion this approach is circulated by the government coalition through INFOR. In addition, this research is in line with Arnold's (2003) findings, as both the INFOR and CORMA coalitions had academic allies in their coalitions. But as the SWEC case demonstrates with regard to the discussion on buffer widths, most of the invited academics were allied with CORMA's coalition, with the exception of a single academic who would have pointedly argued for buffer widths of at least 100 metres wide.

In this sense, the impossibility of reaching an initial agreement on SWEC' outcomes between coalitions was more evident between the industry coalition represented by CORMA, and the government coalition represented by INFOR. They presented arguments from these two different scientific approaches, which differed on certain topics as mentioned above. Also, the arguments that each coalition used in policy production were applied in different ways. In this case, these approaches were applied for advancing, keeping or reducing current soil and water protection regulation-standards. Moreover, some actors were scientifically consistent and presented documents to back up their statements, while others did not.

In the TCFPP and FPC working meetings other actors also appear on scene. These are the PROPYMEFOR-CORMA, the MUCECH and AIFBN groups, where the last two have formed an opposing coalition with CORMA in previous political productions (Arnold 2003). Because according to Arnold (2003), AIFBN had advocated for an ecosystem approach in past policy-making, it is likely they continued to advocate for this approach, as they showed certain similarities with INFOR (e.g. forestry harvesting). This suggests that the ecosystem approach is more long-standing in Chile than the forestry hydrogeology approach.

Similarly, political economy literature on forest policy in Chile confirms that each one of the opposed coalitions in forestry policy production, have sought political allies at different institutional levels of the government in previous policy-making processes, such as in the case of the native forest law (Silva 2004). This corresponds to the classic political process described by Sabatier and Weible (2007) of trying to influence decision-makers. This may also be recognised in the process of production of the FPP. For instance, in the performance of CONAF which seems to have acted on different occasions as an intermediary between both the INFOR and CORMA coalitions. This is likely due to the fact that within CONAF there are different views on the soil and water issue (Interview 9, January 2019). In this way, all actors that shared similar approaches, could have acted as allies at certain points of the FPP process too. This idea is also consistent with Arnold's (2003) findings, where he reports the presence of professional and academic partners acting as allies between both opposing coalitions.

As for Sabatier's paths to political change, our study demonstrates a combination of external system events, forest hydrology learning, and negotiations as pathways of policy change in the FPP. The combination of external system events and negotiations as mechanisms of change is in concordance with the findings of the review of Pierce et al. (2020), where it is recognized that multiple pathways may be necessary for policy change, and that a combination between negotiations and external system events are often applied for policy change. In this respect, "negotiations are more likely to occur when coalitions recognize the existence of a hurting stalemate" (Pierce et al. 2020, p.67). This is consistent with the case of the FPP, given that both government and forestry company coalitions recognized that public opinion's critical views on plantations, plus the mega-fire effects were a stagnating issue for the forestry sector, and that there was a need to find joint solutions at the FPC working meetings. The foregoing is also corroborated by INFOR and CORMA, which state that the construction of common understandings on the protection buffer-zones was based on scientific articles and technical information (Interview 2, November 2018; Interview 3, December 2018), but also on a negotiation to reach consensus for policy-making in which socio-economic aspects are included as well (Interview 2, November 2018; Interview 6, November 2018). In this way, and despite the scientific-technical differences, both coalitions evaluated the results of the protocol positively. The government coalition was satisfied with raising the standards for the protection of soils and water bodies (Interview 3, December 2018) within the margins set out in decree 82; and the forestry coalition was satisfied given that the FPP was a consensual and viable product that helped validate plantations, as it was based on scientific expertise and all sectors, including the environmental sector, were involved (Interview 2, November 2018). All of the above shows the importance of scientific information in the production of the FPP by providing knowledge to support change within the margins of Decree 82. But, it also demonstrates that the negotiation process was a relevant pathway used for and against policy-change in the FPP.

As for internal subsystem events as a pathway for policy change, the perceptions of the government coalition about the process of producing the Plantation Protocol seem to add another point of view. This may reflect some kind of internal change in the political system that could also have facilitated policy change. For instance, according to the vision of governmental actors, the forests and water issue became a priority for the Ministry of Agriculture in 2014 as their institutions needed to provide a technical solution (Interview 3, December 2018), which year 2014 corresponded with a change of government in the country. In the context of the mega-drought facing the country, and subsequently the issue of fires, the political concern for water issues had grown. This made the Forest Policy Council address the issue of water and soil in its agenda for the construction of protocols and agreements (Interview 3, December 2018).

Finally, regarding the learning pathway for policy change, it was not possible to deduce from the minutes and interviews that the learning process of the participants played a relevant role for the political change. This is consistent with discussions in the ACF literature, insofar as few studies report the existence of political learning, showing that the link between learning and political change may not be as direct as it is claimed in theory (Ma et al. 2020). Rather, as it was evidenced by the final process of discussion on buffer width, the process of policy-change was a negotiation process of which science was part. Yet, the existence of previous constitutional policies and socio-economic criteria also set the margins within which to negotiate. This is evidenced by the fact that none of the final buffer zone outputs went beyond the limits previously established by the stable parameters used in the FPP production (specifically the Decree 82). However, there are some signs of learning from government and industry coalitions. For instance, on the part of forestry companies, considering their specialisation in collaborative work with national academics and international consultants in forest hydrology research over the last years, which may have encouraged them to circulate a forestry hydrology approach, and move forward in the FPP discussions. This learning is evidenced by the fact that forest hydrology discussions held by industry stakeholders have not been reported previously in other forest policy productions (see e.g. Arnold 2003). Another example is that of the government coalition, which through INFOR for the first time evidences a particular scientific approach and does not present itself only as a mediator between environmental and economic coalitions in policy production. This could be explained by the research and specialisation processes, which the institution has carried out alone during the last years (CONAF 2017h), as well as with other academic forest hydrologists with an ecosystem approach, but who were not invited to the SWEC.

7.7. Conclusions

This chapter shows that the inclusion of the ACF concepts as a theoretical tool can enrich political ecology and science studies analysis from a policy-making perspective. Its concepts contribute to addressing and enriching analyses of the application and circulation of scientific knowledge in policy-making, by analysing what kind of knowledge is listened to and applied, on what bases, by whom and how it can change a policy-making (or not) in a governance process.

As for the findings, the investigation demonstrates that in terms of the scientific knowledge listened to in the policy making of the SWEC, this was a combination of ecosystem and forestry hydrogeology scientific approaches. This was demonstrated in the SWEC discussions on forest hydrology, where experts from government, business and academia mobilised various social, environmental and economic arguments. In forest hydrology discussions, both the opposed coalitions of INFOR and CORMA-Academics at the SWEC recognise the effects of plantations on hydrology, but they applied different strategies. CORMA and INFOR differed in their understanding of the relevance of hydrological effects of forests and plantations as well as harvest management (clear-cutting forestry management technique) as measures to be adopted or not. Additionally, some academics, were inconsistent in their statements, and likely as a strategy have used 'knowledge gaps' (or what they called as such) as a way of contestation in the forest hydrology discussions. These strategies of contestation on certain forest hydrology topics, were circulated and applied to advocate 'for avoiding' certain topics in the policy-making process. This was demonstrated through the application of different policy-core beliefs to advocated by the SWEC experts. The governmental coalition and the forestry-academics coalition were in favour and against respectively, of advancing on a unique policy regulation to protect all water and soils in forested watersheds of the country. Moreover, some members of CONAF acted as allies within the CORMA coalition leading to contradictions in the governmental coalition. This was specially demonstrated by the application of the Araucaria-CONAF agreement by industrial actors to avoid major policy-changes. In addition, this study demonstrates that while coalitions may have different policy core beliefs on soil and water issues, focusing the work on common scientific understandings between approaches, allowed to delimit and reduce the differences of both approaches, and therefore, facilitated negotiations to advance policy outcomes. This is relevant in terms of understanding Chilean forestry governance, insofar as working on common understandings may facilitate policy development, but may not in itself ensure a major change in policy making when outputs are compared with previous regulatory standards and margins (e.g. Decree 82).

In terms of how scientific knowledge can contribute to policy-change, the research demonstrates that scientific knowledge played an important but modest role in the policy production of the FPP as a scientific-knowledge basis for the SWEC outcomes' discussions. This is showed, for instance, by the circulation and application of two scientific articles on buffer's width presented by INFOR and one academic from Universidad Austral. However, some academics were also inconsistent with their knowledge stated. Additionally, the role of scientific knowledge in policy-making discussions on water and soil in Chile, was challenged by social and especially economic criteria which are also circulated by the forestry coalition in the forest hydrology discussions, and are applied against advancing in a unique policy regulation and for seeking minor policy changes, without further scientific knowledge/information background. This in particular contributes to turning a scientifically based discussion into a more negotiation-based one, given the various variables and metrics at play, which make it difficult to homologate them. In these ways, the main path of policy change was a combination of external system events, some institutional learning specialisation from both opposed coalitions (INFOR and CORMA), and mainly a process of negotiation between actors. This is demonstrated by the fact that the mega-forest fires (public opinion of the impacts) accelerated the working time of policy outcomes, as well as, that the development of the final outcomes of the buffer zone widths for soil and water protection was a negotiation between the SWEC opposing coalitions. In the same way, this research demonstrates the specialisation and learning in forest hydrology that the various government and forestry industry actors in Chile have developed through various research strategies.

This research also confirms previous ACF findings on how external system events or shocks can destabilize (public opinion, economy, etc.) and shift the balance of negotiation powers within the political sub-system. The forest plantation protocol (FPP) demonstrates, that while external events may constitute a possibility for policy-change, they do not guarantee an absolute change of power in the negotiations between actors. Indeed, the forest plantation protocol case shows, that the effects of the mega fires gave unexpected power to the government coalition to confront the traditionally strong forestry industry actors in the policy negotiations. This was demonstrated through the management of working time in the creation of the FPP. However, the FPP also demonstrates that while external events may constitute a possibility for policy-change, they do not guarantee an absolute change of power between actors in the negotiations. The effects of the mega fires gave modest, but unexpected power to the government coalition to confront the forestry industry actors in a policy production. But the policy-changes applied were only within previous regulatory criteria-margins (e.g. Decree 82) and previously established agreements between dominant forestry stakeholders (CONAF-Araucania agreement). This is demonstrated with the example of the discussion in the SWEC of buffer zone widths for soil and water protection in the country, by the fact that none of the final outputs went beyond the limits previously established in the Decree 82 (relative stable parameters) proposed by CORMA and some CONAF representatives, which consider only margins between 5 and 30 metres. However, within the margins previously established in Decree 82, the minimum widths that were considered did modestly change and advance, thanks to the scientific discussions held at the SWEC, and the existence of two scientific articles published on the forest hydrology effects of buffer zones in forestry plantations in Chile.

Chapter 8

Conclusions

This last chapter discusses the major findings from this research and how they answer the research questions. Section 8.1 present the findings and discuss them theoretically, inspired by the science of forest hydrology and the social theories of the 'field' and 'advocacy coalition framework'. Section 8.2. presents the main empirical contributions of this research and discusses linkages between the three results chapters. Section 8.3 shows and reflects on what this research means today given the context of the dramatic political evolution[25] of the country since 2019. Finally, section 8.4 discusses gaps and possibilities for future research.

8.1. Theoretical contributions

From a theoretical perspective, this research contributes to environmental science research by deepening the understanding of forest hydrology science in three southern hemisphere countries (Australia, Chile and South Africa); and proposes the operationalisation of the 'field' theory and the 'advocacy coalition framework' as theoretical tools to deepen the social understanding of the phases of production, circulation and application of scientific knowledge in a contested forest hydrology policy-making in Chile.

8.1.1. Contributions to forest hydrology

Forest hydrology research on *Eucalyptus* trees reveals, that the effects of these trees on water resources are visible and consistent in the evapotranspiration, runoff, soil and groundwater phases of the hydrological cycle. The research literature on forest hydrology is consistent in demonstrating that *Eucalyptus* has higher water use rates than other land uses such as grasslands, native forests, or other tree species such as *Pinus* or *Acacias*. This is materialised in evapotranspiration, runoff, soil water content, and groundwater, and this as well for

[25] In Spanish referred to as, e.g.: estallido social Chileno; estallido social del 18 de Octubre 2019; primavera de Chile, etc.

Eucalyptus trees growing in native and non-native environmental contexts. The research is also consistent in demonstrating that the effects of *Eucalyptus* on water resources vary according to bio-environmental conditions, as well as forestry management treatments. In terms of bio-environmental factors, this means that *Eucalyptus* trees will vary their water use. For instance, as trees grow, they transpire water through their entry' lives, and this will vary as the tree biologically grows over the years. But their water use will also vary between day and night, as well as through the seasons of the year. This last is essentially due to radiation conditions, water availability (rainfalls, soil water content, groundwater, etc), or soils nutrients (e.g. addition or not of fertilisers, etc). *Eucalyptus* trees also transpire in a direct relationship to water availability, consume fresh water over brackish water, as well as depending on whether the trees are healthy or infected with pests (ill trees will use less water than healthy trees in the same bio-environmental conditions). Regarding to forestry treatments, these will also influence the hydrology of a site. For example, the harvesting of trees will increase water levels. But if new trees are planted, or regrowth of trees occurs, the water level will decrease as the trees grow. This is much more noticeable with young *Eucalyptus* trees, as older Eucalyptus trees (e.g. 50-300 years) decrease their water use noticeably. This has been consistently demonstrated in research in native *Eucalyptus* forests in Australia. Likewise, hydrological effects will be more or less visible depending on whether management treatments are developed in small or large areas/proportions, or scales. Small scales produce hydrological effects more quickly and straightforwardly. Whereas at larger scales the timing of the hydrological effect is more delayed and the multiplicity of factors to be analysed becomes more complex (e.g. areas with different rainfall regimes, land covers, etc.) to follow in a sequence. In this respect, the context of the research and its study design, are relevant aspects to understand, since as explained above, the nuances in the hydrological effects of *Eucalyptus* land uses and changes will depend on the multiple bio-environmental conditions and their forestry treatments. In terms of knowledge gaps in the reviewed forest hydrology literature, in Chile and South Africa in particular, the need for developing forest hydrology research in groundwater and climate change remains. Additionally, the results of this investigation on *Eucalyptus* trees are also consistent with other global reviews on the forest hydrology phenomena (Bonnesoeur et al. 2019; Jones et al. 2017a; Filoso et al. 2017; van Dijk and Keenan 2007b; Farley, Jobbagy, and Jackson 2005; Zhang, Dawes, and Walker 2001; Bosch and Hewlett 1982).

8.1.2. Contributions of the Field Theory

As for the *production and circulation of knowledge*, this research contributes to expanding, both theoretically and geographically the concepts of the field theory (Bourdieu 1988) operationalised by Lave (2012). It does so by analysing the multiplicity of social relations and political-economic practices in the scientific knowledge production and circulation of forest hydrology knowledge in Chile. Research in Chile evidences a diversity of forest institutions and agents, environmental change phenomena and political-economic processes that over time have given rise to and transformed the scientific forest hydrology field. This is consistent with Peet et al. (2011) findings, that scientific production is a product of the environmental transformations and political-economic practices of a place. The historical overview of chapter 4 also contributes to the broad understanding of the context of Chilean forestry science production within the world.

The concept of *habitus* allows us to understand a gradient of research themes, which among other aspects reveals the presence of two research trends within the forest hydrology field: (1) ecosystem and (2) forestry hydrogeology. The ecosystem approach focuses among others on studying the role of plantations and land uses in influencing the phenomenon of water reductions in forest landscapes and plantations. The forestry hydrogeology approach for its part focuses on studying how external factors, such as precipitation/snow, soils, geology or diverse human water consumptions, influence the phenomenon of water reductions in forestry plantations in Chile. Each forest hydrology approach presents research directions regarding 'internal' or 'external' elements of forestry plantations respectively. In this respect, the investigation demonstrates that paying attention to different research objects and concepts shapes the understanding of the problem and may also shape possible solutions that are envisaged. This was evidenced by the fact that some interviewees from the ecosystemic scientific trend envisioned land use and forest management solutions, while others from the forestry hydrogeology approach tend to favour water infrastructural solutions (water transfer, construction of reservoirs) or regulations for rural urbanisation and human water consumption, among others, i.e. solutions essentially external to forestry plantations.

The application of the concept of *capital* in Chile allows us to understand the symbolic dimension of the varying understandings of scientific legitimacy and contestations of authority in the forest hydrology field. The research demonstrates that the central State delegitimises its scientific authority and legitimacy, as well as the authority and legitimacy of (most) academic research previously done on forest hydrology in the country. Senior State representatives do so, by stating that the academic research done in Chile 'is irrelevant research'. The central State representatives have done so, likely to protect the economic development of the forestry sector, which is at stake for them. Some participants from academia, forest industry and regional governments, for their part, struggle to keep or move the borders of scientific legitimacy and authority. To do so, each participant highlights elements on which they are stronger than other knowledge producers, in order to maintain or challenge the legitimacy and academic authority of the forest hydrology field in Chile. This was demonstrated by the fact that academic knowledge producers understand legitimacy, among others, as a peer-reviewed process and the sharing of information through published research in forest hydrology, public/open data, participation in conferences, national and international academic collaborations, professorship, etc. – as usually current scientific regimes do – while new forestry industry producers understand legitimacy as a long-term and expensive forest hydrology work, with the use of some new technologies, in collaboration with some national academics and international consultants. For some central State forestry representatives, it has been shown that scientific legitimacy lies in the fact that the research can offer economic solutions to the forestry sector in Chile. This perception of legitimacy of the central State distorts and challenges the multiple elements that generally constitute the scientific legitimacy – and autonomy – in the forest hydrology field.

The research demonstrates that the relative *autonomy* of the production and circulation of forest hydrology knowledge has been strongly influenced by Chile's neoliberal transformations. This finding is consistent with previous Sciences Studies and political ecology research conducted in Chile, which have demonstrated the multiple ways in which neoliberalism, and its politico-economic practices, have influenced the role of scientific knowledge in environmental assessment (Barandiaran 2018; 2015), or in the assessment of water resources in Chile (Budds 2009; 2012; 2013; 2020; Prieto 2015). In this sense, this research contributes to the advancement of these discussions to the analysis of the field of forest hydrology in Chile. Through extensive privatisation practices and the reduction of public resources for research, neoliberalism in Chile has promoted – in some cases – the orientation of forest hydrology research towards industrial needs (the heteronomous pole of the field). This is demonstrated through practices of production and circulation of forest hydrology knowledge, which very likely has promoted the origin of the forestry hydrogeology trend. For instance, for researchers to gain access (or not) to forestry plantations to carry out forest hydrology in forestry industrial lands, research questions must be of interest to the forestry industry, who can give access or deny it selectively to some scholars. Other facts are demonstrated by practices of circulation and publication of forest hydrology knowledge, both in public (central State) and private (industrial) research spheres. Such practices might – in certain cases – promote the development of knowledge gaps in Chile, through the control of topics or timing of publications for academics involved in public or private spheres of forest hydrology production thought scientific collaborations. In some cases, internal institutional hierarchies might also play a part in this challenge to autonomy. It is therefore concluded that the autonomy of academic production and circulation in the forest hydrology field has, in some industrial and governmental cases, been influenced by political-economic relations, and putting its academic relative autonomy at stake in Chile. These findings are relevant according to Beck et al. (2017, p.1067) given that "*who gets to participate in defining which knowledge matters, through what processes, and at what times. These choices shape how knowledge is generated and subsequently adopted into policy*".

8.1.3. Contributions of the Advocacy Coalition Framework (ACF)

As for the *application and circulation of forest hydrology knowledge in policy-making*, this investigation demonstrates that the inclusion of ACF enriches political ecology analyses from a policy-making analysis perspective and governance lenses, which have not been a traditional focus or strength of political ecology and STS analyses. To address this, the research proposes the operationalisation of the concepts of the 'advocacy coalition framework' (ACF) (Sabatier 1988) as theoretical tools to reveal what kind of knowledge is circulated, by whom – government, market, academic and social actors – on what scientific basis, and how it is applied in policy-making and policy-change in Chile. At the same time, this research also contributes to geographically expanding ACF theoretical analyses, given the small number of ACF studies done in South America in comparison with Europe and the US (Pierce et al. 2017; Weible et al. 2009; Ma et al. 2020).

The ACF investigation in Chile demonstrates that the forest hydrology approaches listened to (circulated) in the Soil and Water Expert Commission (SWEC) of the FPP policy-making process corresponded to the scientific approaches within the forest hydrology field of (1) the forestry hydrogeology approach advocated by some academics, and forestry industry experts, and (2) the ecosystem services approach advocated by regional State expert representatives, also identified in the broader analysis of the Chilean forest hydrology field in chapter 6. However, some experts of CONAF acted as allies of the forestry hydrogeology approach creating contradiction within the SWEC coalition of State experts. Additionally, there is also a subgroup of academics with scientific inconsistencies in their forest hydrology arguments. Thus, inconsistencies are used as contestation strategies in the forest hydrology discussions of policy-making. This is demonstrated by the forest hydrology discussions hold in the SWEC (e.g. on the point of forestry plantations aiding aquifer recharge, which constitutes a research gap in Chile). While generally, both approaches recognise the reduction effects of forestry plantations on water resources, some researchers differ in their understanding of the 'relevance' of the objects involved in water reductions as a broader environmental phenomenon. In particular, the ecosystem approach demonstrates that forestry plantations and their management affect hydrological dynamics (regulation), which put at stake the supply of water for human consumption. The forestry hydrogeology approach on the other hand, stresses factors external to forestry plantations such as climate change, snow and rainfall reductions, geology-soils, increasing agricultural and human water consumption, among others, to diminish the relevance of forestry plantations in water reductions. Although through these forest hydrology discussions some experts circulated scientific support (publications and various documents) to demonstrate their statements, there were also forestry industry experts who did not provide any written scientific basis or publications, etc. to back up their statements. And socio-economic factors (e.g. searching for a balance between timber and water production in watersheds) were also circulated and applied into the SWEC forest hydrology discussions and policy-outputs. As for the policy core beliefs at stake, the ecosystem approach advocated for advancing in a common forest hydrology policy regulation in all forestry watersheds of the country, while the forestry hydrogeology approach advocated against the advancement of a common forest hydrology policy regulation in all forestry watersheds of the country. In addition, this study demonstrates that while coalitions may have different policy-core beliefs on soil and water issues (e.g. advance or not in a unified policy-making), focusing the work on common understandings between approaches allowed to delimit and reduce the differences of both approaches, and therefore, facilitated negotiations of policy outcomes. This is relevant in terms of understanding Chilean forestry governance, insofar as working on common understandings may facilitate policy negotiations, but may not in itself ensure major changes in policy making, such as about the water and soil protection buffer-zones (WSPBZ).

As for the influence of 'relative stable parameters' (RSP) in the policy-governance, the process of decision-making demonstrated that in order to produce the 'water and soil protection buffer-zones' (WSPBZ), the RSP play a key role in defining the margins of policy negotiation. This is demonstrated by the example of the discussion on the buffer-zone widths for soil and water protection in forestry plantations, in particular by the fact that none of the final outputs (widths) went beyond the limits previously established in Decree 82 and the previous CONAF-Araucania agreement (relative stable parameters). Nevertheless, within the margins previously established in Decree 82, the minimum widths that were considered did change and move on, thanks to the scientific discussions held at the SWEC, and the existence of two scientific articles regarding buffer zones in forestry plantations in Chile. The inclusion of previous agreements (CONAF-Araucania) was circulated and applied, in order to try to maintain the margins of previous buffer-zone standards agreed between certain actors in a particular region. These facts demonstrate that the scientific knowledge on forest hydrology played an important role in policy-change (e.g. scientific articles), but they also evidence that a process of negotiation (e.g. forestry economic criteria) was involved in it too.

ACF stands that 'external system events' (ESE) can be a powerful force modifying the policy system (Sabatier & Weible 2007). In this respect, the Chilean case demonstrates that while external events, such as the forest fires in Chile (2016-2017), are able to modify the governance system – exemplified by the change of the name and structure of the initial commission, and the acceleration (time) of the working process – they had but relative power, as they could not modify the traditional forces of the Chilean forestry sector. This is illustrated by the policy-outputs of the soil and water protection buffer-zone. In this sense, the Chilean case of the FPP is consistent with the ACF theory, but also differs in demonstrating a gradient to be considered in such analyses, as the influence of ESE may not necessarily be far-reaching enough to influence policy-outputs.

So, regarding the application of forest hydrology knowledge in/and the *pathways for policy-change*, the investigation in Chile demonstrates that the process of policy change was a combination of some learning processes (specialisation) of the actors and a negotiation process, which was also influenced by the 'external system events' of the forest 'mega' fires in Chile in 2016-2017. These findings on the specialitation process were corroborated by comparing the ACF study of Arnold (2003) and the current FPP (2017) analysis. By analysing the production of the law 20.283 on native forest in Chile (1992-2008), Arnold (2003) found the existence of a 'neoliberal economic approach' and an 'ecosystemic approach' as core beliefs of the CORMA and environmental organisations opposing coalitions, respectively. In the case of the Forest Plantations Protocol (FPP) in 2017, the analysis of the SWEC core beliefs demonstrated the existence of forest hydrology approaches corresponding to: (1) the forestry hydrogeology approach, and (2) the ecosystem approach. In addition, it revealed the presence of economic core beliefs (e.g. balance between timber production and water production in watersheds), but there is also evidence of a knowledge specialisation in forest hydrology from the part of industrial actors. The above is evidence of an evolution in the arguments of the CORMA coalition, who after their learning process following the development of their own research projects in forest hydrology in collaboration with some national academics over the last few years, are developing a forestry hydrogeology approach to address and challenge the issues of water reductions in forestry plantations. The older report of an 'ecosystemic approach' in Arnold's (2003) study, might reflect that the ecosystemic approach is long-standing in Chile. In the case of FFP, and especially SWEC, it contributes to advancing the ACF studies by demonstrating that actors in both the opposing coalitions of the forestry industry (CORMA and allies) and the government coalition (INFOR and allies) have sought scientific specialization in forest hydrology issues but have applied different strategies and evidence to support them. This is consistent with Arnold's (2003) findings that both opposing coalitions had the support of/or searched for diverse academics and professionals' advice. On the other hand, the case of the FPP disagrees with Arnold (2003)'s findings, insofar as it demonstrates inconsistencies within the government coalition, with CONAF in particular acting as an ally in both, but specially in the CORMA (forestry industry) coalition. This was demonstrated by the application of the CONAF-CORMA Araucania agreement, influencing the outputs of the SWEC width-buffer discussion. The incorporation of the CONAF-Araucania agreement was relevant in the process of producing a water protection buffer-zones policy-output, since it was through this that the negotiation process was promoted in the discussion of buffer widths. This was evidenced mainly outside the SWEC, in the discussion of the CTPPF, and plenary session of the Forestry Council, where different actors in favour of one or the other coalition, mobilised different arguments (e.g. FSC, costs involved for small forestry producers) to advance or maintain the water protection buffer standards established in the current Decree 82 on soil, water and wetlands. But the science of forest hydrology played a modest role in the outputs of the SWEC. Forest hydrology knowledge was not able to move the buffer margins already defined by decree 82, and socio-economic criteria were also included in the evaluation. Yet, two scientific papers, coming from the forestry hydrogeology and ecosystem approach, were able to demonstrate that a 5 meters buffer is not enough to protect water quantity and quality, and the buffer widths were indeed advanced, within the margins previously established by the decree 82.

8.2. Empirical contributions

One of the central questions of this research is how the production, circulation and application of forest hydrology knowledge can influence the interrelations between environmental science and policy-making in Chile. In other words, how has the environmental science of forest hydrology been produced, circulated and applied to decision-making (or not) by actors (who and how) in Chile? To address this, a deep understanding of the state of the art in the science of forest hydrology was crucial. This question was inspired by the existence of forest hydrology knowledge contestations or controversy in Chile, about the hydrological effect of forestry plantations on water resources and especially about water reductions. In this respect, this section synthetizes and discusses empirical findings and contributions of this research.

Conclusions are organised as follows. Section 8.3.1 presents the situation of forest hydrology knowledge contestations or controversy in Chile. Section 8.3.2 summarises the main actors and their interrelationships in the phases of production, circulation and application of forest hydrology knowledge in Chile. And, section 8.3.3 discusses interrelation between forestry, forest hydrology science, and policy-making in Chile, from a historical perspective.

8.2.1. Forest hydrology knowledge contestations or controversy in Chile

Research in chapter five on *forest hydrology science* contributed to demonstrating that the forest hydrology contributions are vast and largely consistent in their results. They indeed demonstrate that forest plantations of *Pinus*, and especially of *Eucalyptus* trees do contribute to water reductions in various territories. These results are consistent under the diverse conditions of land use, land use changes, forestry management and bio-environmental conditions analysed in detail in chapter 5. Considering these findings, the forest hydrology debates in Chile analysed in chapters 6 and 7, suggest that contestations or controversy over forest hydrology knowledge on forestry plantations effects on water reductions are mainly promoted by argumentative misconceptions. Some of these misconceptions are based on (bordering) denialism or out of ignorance, and/or stated inconsistencies among others, produced, circulated and applied by some participants and producers of the forest hydrology field in Chile. These discursive strategies consciously or unconsciously seem to play on a thin edge of what is known or not (yet) and by whom, on existing knowledge and its knowledge gaps, and the constant possibility and need to continue developing future research on a topic.

In this research, different strategies or elements have been shown, and it is suggested here that these might contribute to contestations or generate controversy in the forest hydrology field and its knowledge in Chile. These strategies seem to be used in parallel, in a changing manner, and by different actors. Some examples include: a) doubting, ignoring or denying the existence of scientific studies and their knowledge on the hydrological effects of forestry plantations; b) delegitimising previous forest hydrology studies from academia by categorizing them as 'irrelevant studies'; c) denying the existence of water scarcity in the south of the country; d) diverting attention away from forestry plantations (*Eucalyptus*) to other external factors (such as climate change, agriculture or human consumption of water, etc.) as certain factors contributing to water scarcity, but doubting about the effects of forestry plantations on water reductions; e) stating forest hydrology phrases with inconsistencies, not demonstrated facts or wrong; f) using certain words or concepts that may contribute to misunderstandings or confusion about the forest hydrology phenomenology of certain objects in question, among others found and exemplified in this research (chapters 6 and 7). Senior state forestry officials (including former directors of CORMA) and certain academics were found to be conscious or unconscious practitioners of such strategies.

As a concrete example in Chile, the influence of forestry plantations on groundwater recharge in certain occasions (e.g. when plantation trees are mature and permanent) cannot be rejected a priori, but, as some forest hydrology producers assert, cannot be confirmed neither, as 'forestry plantations help to produce water'. Yet, the assertion 'forestry plantations help to produce water' – at least where it concerns *Eucalyptus* and *Pinus* tree species analysed in chapter five – contradict forest hydrology groundwater results that have been widely reported and applied in countries such as Australia, from where *Eucalyptus* trees originate and where they are widely planted. In this regard, the statement that 'plantations help to produce water' is an inconsistency which need further clarification. Additionally, the aforementioned statements seem to use the 'groundwater' knowledge gap (a need to know) in Chile as a strategy to state as facts, hypotheses which are not yet proven or rejected in Chile. This in turn, might contribute to creating confusion or controversy by some academics about certain knowledge of the forest hydrology phenomenology.

As another example, a forest hydrologist working in academia who participated in the policy debates of the soil and water experts commission (SWEC) on the Forestry Plantation Protocol, stated 'the need to know' about hydrological differences between *Eucylaptus* and *Pinus* tree species and claimed it as a research gap that should be studied. However, the same author had written and presented at the SWEC a forest hydrology report, where he and others forest hydrology experts reported that *Eucalyptus* trees consume more water as a function of time than native forests or *Pinus* tree species. In doing so, this academic(s) has been inconsistent between what he declares and writes – and likely as a strategy – has presented as a research gap (a need to know) a fact of his/their own forest hydrology knowledge which he presented in a document from 2017 as a backup of the forest hydrology discussions held in the SWEC in 2017. Additionally, these strategies of contestation on certain forest hydrology topics, very likely were circulated and applied to advocate 'for avoiding' the inclusion of certain topics in the policy-making advancing of the FPP. Such punctual contradictions and inconsistences between oral and written statements from some academics, arguably have contributed to building controversy by some academics over forest hydrology knowledge in a policy-making context in Chile.

As a further example, the research highlights senior State forestry institutions who by denialism or out of ignorance, state that there are no studies or that they are not aware about the existence of forest hydrology knowledge and information in the country related to forestry plantations and water reductions. Other senior forestry government officials challenge also the legitimacy and authority of most Chilean research on forest hydrology; stating that those are irrelevant studies since they do not provide management solutions to 'reach the magic hectare' that allows forestry industry to continue to increase forestry production with less land and more water use efficiency. The insufficiency and delegitimization (irrelevance) of forest hydrology studies in Chile, alleged by forestry agents of the central State − some of them former forestry industry representatives, - is in contradiction with internal institutional reports. It also contradicts statements from some international forestry organisations that classify the development of forestry hydrology in Chile as advanced in comparison with most countries in the world which do not have research centres in their governments (e.g. opinion of an expert of the FAO's forest and water section in Rome, on INFOR's work in Chile). It is also contradictory with the fact that the same government institutions, such as CONAF and INFOR in diffe'ent periods have developed research on forest hydrology together with national and international academics. But many of these State research results have not been publicly circulated or applied by the Chilean State, thus hiding or blocking, arguably for strategical considerations, the circulation of certain scientific forest hydrology knowledge. This in order not to have to consider the current scientific research existing in Chile on forest hydrology in their decision-making. Such contradictions between statements and facts about the existence or not of forest hydrology studies, has very likely contributed to the construction of controversy – or the creation of doubt and uncertainty – about what research exists, and thus about what is or not (yet) known in the country about the scientific knowledge of forest hydrology, especially for the wider audiences in the country.

All the aforementioned concrete actions, conceivably have contributed to construct controversy over the forest hydrology knowledge in Chile. This very likely has also contributed to prolonging – or gaining time for – the forest hydrology policy-making and actions in the country. In this way, it is shown that part of the production mechanisms of this 'controversy' about the effects of forestry plantations on hydrology, has a high component of statements with inconsistencies, or are based on bordering denialism or ignorance. Those are practiced on the part of some participants in the forest hydrology field in Chile who in one way or another, are generally linked to the forestry industrial sector.

8.2.2. Actors in the production, circulation and application of forest hydrology knowledge

As to the forest hydrology production, its circulation and knowledge application in Chile, there is a wide diversity of actors and topics investigated. Regarding actors producing forest hydrology knowledge, in broad terms, there have been identified two forest hydrology trends: (1) the ecosystem science approach, and (2) the forestry hydrogeology science approach. Both these forest hydrology scientific trends are mostly consistent in their findings related to forestry plantation on water resources. On the one hand, the ecosystem approach studies the effects of forestry lands on hydrology compared to other land uses in different environmental and management contexts. The forestry hydrogeology approach, on the other hand, is carrying out studies to develop a new 'theory or forest hydrology trend', which addresses how also soil, geology, precipitation, human or agricultural water consumption influence the hydrology of a forestry site. In this way, the research moves in different directions or trends within the field. However, some forestry hydrogeology trend participants and producers challenge the legitimacy, or sometimes mobilise inconsistent statements, among others, about forest hydrology research and information in Chile. Additionally, both forest hydrology trends are characterised by producing forest hydrology research in different collaboration and publication schemes, as demonstrated in chapters 6 and 7 of this investigation. In this sense, the investigation demonstrates that some academics working with industrial and government forest hydrology actors experience certain influences on their relative autonomy in the production or circulation of forest hydrology knowledge. Specifically, this has been demonstrated in Chile through strategies for selectively allowing access to forestry lands for developing research in forest hydrology, as well as through selection of questions to research in forest hydrology, or through agreements on timeframes/deadlines of publication results, among others. These strategies mainly block or postpone the production and circulation of certain knowledge and information in forest hydrology. Finally, regarding scientific legitimacy and authority, this research demonstrates that scientific legitimacy and authority in recent years and at present is in the hands of academia. The aforementioned with certain exceptions as some academics were found to produce and circulate some inconsistent statements. Academic authority is backed up by their research trajectories, conferences, publications, peer recognition, and the consistency of their forest hydrology research. For its part, the forestry industry in Chile is working hard to build its scientific legitimacy and authority in the field of forest hydrology. The Chilean State for its part also has research that could provide it with authority and scientific legitimacy, but it works against it that currently the neoliberal Chilean State at its central level is self-diminishing its legitimacy and scientific authority on issues of forest hydrology. In addition, it works against academic authority that central State forestry representatives have delegitimised most of the scientific forest hydrology research previously produced by the academia in Chile. Senior State representatives have done so very likely to protect the economic development of forestry at stake for them in the country. As for legitimacy contestations in general terms, this research suggests they need to always be explored in more detail at their fundaments. Because this research demonstrates that some legitimacy contestations might be strategically made (e.g. by senior State forestry representatives) to challenge proven scientific research and to promote as legitimate or relevant only forest hydrology research that provide economic solutions to the forestry sector (e.g. contribute to find the 'magic hectare'). Legitimacy contestations – of any kind – should be understood as struggles to usually challenge (or maintain) the legitimacy and authority of scientific fields, and/or as a way to divert attention from research results.

As for actors circulating forest hydrology knowledge, stakeholder groups are also distinguished by their publication practices. As evidenced in chapter seven, both the 'ecosystem' and 'forestry hydrogeology' trends publish in peer-reviewed scientific journals, but additionally, the 'forestry hydrogeology' trend has also been noted to develop forest hydrology reports. Regarding this 'forestry hydrogeology' trend, it is also important to highlight that a sub-group of these participants mainly publish in reports (not in journals, or other peer-reviewed documents). In terms of what type of forest hydrology knowledge is circulated for decision-making in environmental governance, the presence of both ecosystemic and forestry hydrogeology trends is noted, but there are distinctive elements. In terms of what kind of academic expertise is listened to in the state-led policy process, the SWEC case notably demonstrates that the academic experts that are listened to correspond to those actors who mostly carry out or have carried out forest hydrology work with or mandated by the forestry industry and some State forestry institutions. The above also has implications for the knowledge that is applied in forest hydrology decision-making, policy-production and in forest hydrology governance in Chile.

As for the application of forest hydrology knowledge for policy-making, the SWEC case demonstrates contradictions when it comes to forest hydrology expert legitimacy, authority and their knowledge bases to back up statements and advocate for their application. For instance, while some actors presented diverse documents to back up their statements on forest hydrology (e.g. articles or reports), other expert groups did not present evidence, or other kind of documents to back up their arguments. This may contribute to producing miscommunications in the circulation and application of knowledge in decision-making and policy-outputs. Under these mechanisms of policy production, scientific knowledge is limited in its application, and the way is opened for negotiation processes that do not need to demonstrate a scientific or knowledge basis to be applied.

8.2.3. Historical reflections on forestry, science and policy

The science of forestry has a long history, as has the research field of forest hydrology. In Chile, studies in forestry and forest hydrology started later than, for example, countries like South Africa and Australia. Despite this, Chile has international recognition for the science of forest hydrology, being an exception compared to most countries that do not develop research on this. This is confirmed by interview statements and literature review.

In Chile, *Eucalyptus* species were introduced more than a century ago by mistake and promoted by increasing movements of people, materials and technology (e.g. colonisation of southern Chile by Germans, Swiss, etc.). As in the South African case (section 4.1.2), in Chile the large-scale development of forestry plantations – at the beginning of the twentieth century – was driven by the need for fast wood supply for mining development; especially at the city of Lota and its surroundings in the central-south of the country, which as such played a major role in Chilean forestry development history.

In this sense, the forestry sector in Chile has taken more than a century to develop, and has undergone multiple economic transformations. It has gone from a model of development to one of import substitution under a neoliberal economy particularly strong in Chile. These economic transformations have not only been reflected in scientific and forestry institutions and policy, but have also profoundly transformed the forestry landscape of the country. This environmental change also transformed scientific production. Following the introduction and expansion of fast-growing *Pinus* and *Eucalyptus* trees on a large scale, this led to the first forest hydrology studies in Chile in the early 1970s, focusing on understanding the influence of land use and its treatments on water flows, as South Africa and Australia did so too years earlier after the arrival and expansion of exotic *Eucalyptus* and *Pinus* tree plantations that changed the environmental landscapes in each country. In this way, the investigation is also able to demonstrate how scientific production is intimately linked to its historical landscape and environmental change context. As such, its evolution in the phases of production, circulation and application of knowledge must be understood as a product of its political, economic, social and, above all, environmental and landscapes dimensions.

8.3. What this research today means given the context of the dramatic political evolution of Chile since 2019.

This section reflects on what this thesis could mean today, given the socio-political changes in the country. The section is organised as follows. It first presents the context of the Chilean social movement that started in 2019. It then presents current developments (or not) of the country's Forest Plantations Protocol (FPP) concerning the issues of plantations, water reductions and fires, as well as new forest hydrology studies published in the country. Finally, the relevance of this thesis in these current contexts is presented.

As a general context in Chile, since Friday 18 October 2019 the discontent of a large majority of Chilean citizens became visible, through several demonstrations in the country (Wikipedia 2022). The social movement has been labelled as 'Estallido Social', 'Primavera de Chile', etc. Among the reasons for this social movement were the rising cost of living and the low quality of life, visible in transport, pensions, health, education, environment, etc., as well as aspects of gender and ethnic group inequalities, among others. These were quickly channelled into the citizens' demand for a new constitution for Chile (Wikipedia 2022). The current Chilean constitution of 1980 – written and put into effect by the military dictatorship of Chile (1973-1990) – has been identified as the cause of such multiple inequalities. On October 25, 2020, with 79% of the vote, Chile approved the creation of a new constitution through a governance system called the 'Convention' composed of members 100% elected by citizen vote (Convención 2021). Subsequently, a first draft of the new constitution was rejected in a plebiscite with 62% of the citizen vote (BCN Biblioteca del Congreso Nacional de Chile 2022). Currently, the Chilean Congress has proposed a change in the governance system previously approved by popular vote, to continue with the constituent process of drafting a new constitution for Chile. In particular, the Congress of Chile proposes a 'Constitutional council' composed of 50 members elected by a popular vote and – as something new – a 'Committee of experts' composed by 24 experts to be "elected in equal parts by each branch of the National Congress" (Senado de Chile 2022, p.1). This proposal by Congress contradicts the will expressed by popular vote by the citizens on 25 October 2020, who voted for representatives 100% elected by popular vote, and not in a mixed formula with popular representatives and experts elected by Congress (which was the rejected option in that plebiscite). Possibly, this citizen vote of 25 October 2020 in favour of 100% elected members, reflects a feeling of distrust towards both the Congress and 'Committees of experts' or 'scientists' as agents free from third party influences (see for example the case of Barandiaran (2018) presented in detail in this thesis).

As for the discussions of the Forest Plantations Protocol (FPP) in Chile, the discussions of the social movement in Chile do not seem to have meaningfully affected it. The FPP continues to be a voluntary policy that forestry companies implement in the country. As of 3 January 2023, despite the declared intentions to advance and continue with research and post-monitoring linked to the FPP development (CONAF 2017a), nothing can be found on the public website of CONAF – as it was possible before – regarding the FPP materials. In addition, after consulting with a senior State official, no news was obtained on the applicability and post-monitoring progress of the FPP in the country either. Further inquiry on the FPP works could reveal the progress of buffer works implemented (or not) in the territories. By January 3rd, only the FPP document appears in digital format, as the only evidence on internet of the existence of this FPP process and discussions. In parallel, based on a general internet search, water scarcity in Chile continues to be present with at least 47.5% of the population suffering from it (DGA 2022). In addition, this also shows that new forestry fires continue to burn further south in the country with 45.200 hectares already burned in the summer season of beginning January 2023 (CONAF 2023). By the 6th of February, at the time of submission of this thesis, the forest fires in Chile had again become a national emergency. Thousands of hectares of forest have been destroyed. These are concentrated in the Bio Bio region, in the heart of the Chilean forestry plantations region (CONAF 2023). So far at least 24 people died, 1.800 people have been affected, 977 have been injured, and 800 houses have been destroyed by the forest fires (BBC 2023). The news on TV talk about the early arrival of the 'Ten Tanker' (water-tanker airplane) to extinguish the fires in the Concepcion area and about help from Mexico. In comparison, in 2017 forest fires in the same area of the country left 11 dead, 1.500 houses destroyed and affected 467.000 hectares of forest, and the news talked about the 'Super Tanker' (water-tanker airplane) (BBC 2023). Today, the loss of human lives is greater than in the forest fires of 2017 that led to the creation of the first national Forest Plantations Protocol (FPP) analysed in this thesis. This leaves the question: how effective is the applicability of a voluntary regulation-policy (such as the FPP) in the 'umpire State' of Chile?

Complementary, since the end of 2020, several forest hydrology experts in Chile have published new scientific papers. In particular, the forestry companies Mininco (CMPC) and Arauco (through its subsidiary Bioforest), have at least 10 articles published on forest hydrology in peer-reviewed international and national journals between 2020 and 2023 – i.e. after the development of chapter 5 – in an attempt to build their scientific legitimacy and authority over the country's forest hydrology field. These articles report for the first time the results from their monitoring sites and have been published in collaboration with 2 scientific consultants from Western Australia, and some national and international academics. Those collaboration patterns and actors are consistent with the forest hydrology trends identified in chapter 6 and 7 of this thesis. Among these 10 articles, one just published in 2023 stands out for being a first of its kind in the history of the Chilean forestry industry – as this article has been written together with a wider group of academics and government officials in Chile. This may be an attempt by the industry to build consensus with broader fractions of the Chilean academia and State experts, as well as an attempt to build scientific legitimacy and to promote future actions in the field of forest hydrology and the forestry sector at national and international level (as they themselves express in their articles). Preliminarily, the study of Balocchi et al. (2023) seem to be mostly consistent with the findings of this research in Chapter 5. For example, by recognising that Chilean native forests use much less water than *Eucalyptus* or *Pinus* trees, which is a remarkable milestone of new and public recognition in this respect. It also seems consistent with the existence of knowledge gaps around groundwater in Chile, among others. At first sight only one aspect stands out as striking and distinctive from Balocchi et al. (2023)'s study in relation to previous knowledge on forest hydrology studies found in chapter 5 (see for instance. Huber et al. 2010; Scott and Lesch 1997; Scott and Prinsloo 2008; Farley et al., 2005, who found that the water use of *Eucalyptus* trees is significantly higher than that of *Pinus* trees). This consists in the statement that the difference in water use (evapotranspiration) between *Eucalyptus* and *Pinus* trees is not significant or is the same (cited in Balocchi et al. 2023 but the original source is White et al. 2021). The unique study found in chapter 5 that seems to be consistent with White et al. (2021)'s findings, is the Australian study of Benyon and Doody (2015). Yet, it is suggested in chapter 5 that the variation in result of Benyon and Doody (2015) study is due to its study design.

In this sense, chapter 5 which reviews water and *Eucalyptus* forests, offers a wide literature review and contribution to understand the general forest hydrology behaviour of *Eucalyptus* trees in relation to different land uses, land use changes, forestry management (harvesting, fires, etc.) and diverse bio-environmental conditions. It does so by reviewing the literature of tree relevant countries in the history and development of the forest hydrology field. This review includes information about *Eucalyptus* forestry plantations but also research about native Australian *Eucalyptus* forests, which provide an enormous depth of knowledge to understand their hydrological effects in these countries or elsewhere. It not only provides information on the results of evapotranspiration studies, but also on streamflow, soil and groundwater studies in those countries. To our knowledge this extensive systematic review on *Eucalyptus* trees is relevant in Chile and internationally as this has not been done before.

Forest hydrology, through more than a century of studies in different geographies around the world (see chapter 4) has been demonstrating some general water behavioural patterns of land use, land use changes, land management and according to the different bio-environmental factors in which trees and vegetation communities are located elsewhere (see for instance, Bosch and Hewlett 1982; Zhang et al. 2001; Farley et al., 2005; Bren and Hopmans 2007; Bren 2015, among others). And this research found consistency with those general forest hydrology patterns and their possible nuanced effects and some of their causes. Where there is different forest hydrology behaviour or exceptions, it is important to understand why. Because these cases might correspond to nuances of the phenomenology or reflect the multiple factors involved in the study design. But on closer inspection of the study design the results may also be consistent with previous general results, as showed and suggested in chapter 5. Both today's and in the future, in Chile and other countries, chapter 5 of this research can also help to initially understand why some forest hydrology results may – at times – appear at first sight – or indeed be – different.

Chapter 4 of this research, can mean for today's Chile a deeper understanding of the history of the forestry sector and the forest hydrology field globally. Chapter 4 also offers a contribution to today's Chile by looking at the various ways in which South Africa and Australia have taken the production, circulation and especially the application of scientific knowledge in forest hydrology policy-making to develop forestry and at the same time diminish its adverse hydrological effects in these countries. Chapters 4, 6, and 7 help to provide context and an international historical perspective on Chile's own historical past, evolution, present and the possible futures of the forest hydrology field in science and policy-making. These chapters contribute from a historical and geographical perspective to understand the scientific, social, economic, political and environmental contexts that have given rise to, transformed and re-transformed the forestry science and forest hydrology field, both internationally and in Chile.

Chapters 6 and 7 in particular, offer today's Chile the first social study that investigates the production and circulation of scientific knowledge in the forest hydrology field, and its application (or not) of forest hydrology scientific knowledge in decision and policy-making (by whom) in the FPP in Chile. These chapters also highlight current trends in the production of forest hydrology, its challenges to the autonomy of scientific production, and the contestations of scientific legitimacy; as well as shows how diverse actors in the FPP have shared actions, forest hydrology approaches and policy core beliefs to advocated for or against the advancement of a unified national forest hydrology policy in all watersheds of Chile. Tangentially, this research also confirms the lack of participation in decision and policy-making on the FPP by social rural communities' organisations affected by water scarcity in forestry territories. In this sense, the case of the FPP analysed in this thesis, could be exemplary of a broader governance trend of the central political power of the Chilean State. A trend in which the National Congress seems to prefer the participation of 'experts' delegated by the Congressmen in the ongoing decision and policy-making on a new constitution, rather than more direct participation of the common citizenship. In this context, the non-democratic or non-transparent election of experts could aggravate the crisis of legitimacy of the Chilean political class, and could further affect the legitimacy of State institutions, and of 'expertise' in Chile.

8.4. Gaps and opportunities for future research

In terms of knowledge gaps and possibilities for future research, this last section envisions three opportunities to further built on the findings of this research and deepen its knowledge- and/or of others - in future investigations.

First, further Chilean forest hydrology can help to develop knowledge on the interactions of various *Eucalyptus*, *Pinus* tree plantations and other land uses with groundwater and their long-term effects on hydrology. Australian and South African forest hydrology studies on groundwater and soils can serve here as examples, and contribute with their knowledge to understand what is happening with *Eucalyptus* and groundwater in Chile. The information from research carried out in previous years on different *Eucalyptus* species at the University of Concepcion, and others, could also be very useful in improving this understanding in Chile.

Second, inspiration for further research can be found in the findings on the Chilean forest hydrology field regarding certain challenges found about the relative autonomy of the scientific production and circulation of knowledge in the forest hydrology field. These findings show that these challenges are mainly found on transdisciplinary collaboration schemes between academics-State and academics-industry, and that they are especially about publication dynamics and possible gaps of knowledge created in the field. In this respect, it is pertinent to systematically investigate and deepen our understanding on autonomy in diverse transdisciplinary scientific collaborations schemes that are produced in diverse scientific fields, nationally and internationally. Furthermore, future research should analyse the capitals of such field collaborations, their symbolic capital of legitimacy or authority, but also the economic and material capitals, expressed in formal or informal contracts established between individuals and/or between institutions. Also, how is the data and information produced, circulated, applied and governed in transdisciplinary collaboration schemes of scientific production ? In what times and spatiality? How are these collaborations made transparent and legitimised, and how are the researcher and his/her autonomy safeguarded in the phases of production, circulation and application of scientific knowledge? Especially in the face of sensitive/contested/multi-interest but highly relevant topics to be investigated in present and future research. From a governance perspective of analysis, future research could also look at these collaboration schemes their structures, processes, agencies and asymmetries of such transdisciplinary collaborations.

Third, inspired by the findings of this research, future research should socially investigate and delve into the study design, language and framing of concepts, meanings, methodologies, techniques, models, or statistics, etc. of various scientific dissemination documents, especially on highly contested topics. This in the field of forest hydrology, but also in various other contested scientific fields of research.

In this respect, analyses from both social-historical and physical perspectives seem relevant to be considered. On the one hand, various historical studies of science, science studies, among others, have been demonstrating the relevance of frame, language, rhetoric, etc.

when analysing contestations or controversy about scientific knowledge (e.g., challenge existing knowledge on anthropogenic climate change, its causes and consequences, etc.) (Stocking and Holstein 2009; Ceccarelli 2011; 2013; Harker 2017; Supran and Oreskes 2021a). This seems relevant, as these studies have been showing that often such contestations of scientific knowledge have come from diverse interest groups active on those subjects (Ceccarelli 2011; 2013; Supran and Oreskes 2021). In this respect, the study of Supran and Oreskes (2021) could help to make progress on discursive analyses. For instance, in forest hydrology science, the work of Bennett and Kruger (2015) based on Gush's (2001) study has warned about the conceptual and hydrological differences between transpiration, evapotranspiration and water use efficiency that measure different aspects of forest hydrology phenomena and which could lead to misunderstanding among broader publics. Possible questions could deepen on how and why, different factors included, concepts, methodologies, techniques, or models influence the variability/nuances of analysed hydrological effects? What are the real implications of uncertainty in forest hydrology knowledge? Can uncertainty contradict, cast doubt on or even reject what has been discovered to date by the science of forest hydrology? How and why? Who says it?

On the other hand, from physical geography, environmental sciences and statistical-modelling perspectives, authors such as Linde (2014) have been demonstrating and warning about how various methods or modelling techniques - of groundwater for instance - can also be highly inaccurate, lead to errors that sub-estimate or overestimate, and/or omit relevant aspects for a more representative understanding of the phenomenology under analysis. The attention to be paid to the hydrological underestimation that certain forest hydrology modelling can have, was an aspect that was also found during the interviews of this research with the forest hydrologist Prof. David Scott related to the ACRU model design process and its possible hydrological sub-estimations in South Africa. Possible questions are, what are the magnitude/significancy differences between a hydrological modelling that considers 3 meters depth of *Eucalyptus* roots, vs. a modelling that considers 12-, 20- or 30-meters depth of *Eucalyptu*s roots? Why does 3-, 12- or 30-meters matter? How and why does this vary during tree growth and rotations (time)? And among different conceptual forest hydrology models? The work of Linde (2014), David Scott’s experience, and others can help to deepen aspects of the study design and the different potentials and limitations of each method, technique or model and help to prevent under(over)estimates. Also, to what extent, how and why, can the different factors that are considered, concepts, methodologies, techniques, or models influence the variability and magnitude of the hydrological effects?

Clarifying all of the above can contribute to bringing or reinforcing transparency and autonomy to the process of scientific production and its circulation; reinforce understandings in scientific fields; facilitate understanding between diverse actors with the production of common scientific-methodological protocols in scientific disciplines; reinforce the legitimacy of the scientific knowledge produced; and above all, safeguard considerable environmental-territorial-landscape effects by avoiding that potential under(over)estimations are applied in certain public or private policy solutions.

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Annex

Annex 1. Minimum widths and categories of the water protection buffer zones for waterbodies in general

Categorías	Temporalidad		Pendiente		
	Permanente	Temporales	<30%	30-45%	>45%
Manantiales, cuerpos de agua y cursos de agua *(sección de cauce > 0,5 m^2)*	X		10 m	20 m	30 m
Cursos de agua permanentes *(sección de cauce ≤ 0,5 m2)*	X		10 m	10 m	10 m
Quebrada con cauce *(sección de cauce ≤ 0,5 m2)*	X		5 m	10 m	10 m
		X	5 m	5 m	5 m
Humedales	X	X	10 m	10 m	10 m

Source: (CONAF 2017o). The second draft report of the forest plantation protocol, July 2017.

Annex 2. Minimum widths and categories of the water protection buffer zones for waterbodies supplying water for human consumption

Categorías	Pendiente		
	<30%	30-45%	>45%
Manantiales, cuerpos de agua y cursos de agua *(sección de cauce > 0,5 m^2)*	10 m	20 m	30 m
Cursos permanentes *(sección de cauce ≤ 0,5 m^2)*, cuerpos de agua, quebradas y humedales	10 m	10 m	10 m

Source: (CONAF 2017o). The second draft report of the forest plantation protocol, July 2017.

Annex 3. Minimum widths and categories of the water protection buffer zones for waterbodies in general

ANCHO MÍNIMO DE LA ZONA DE PROTECCIÓN			
Categoría	Ancho zona de protección general (m), según pendiente		
	< 30%	30 - 45%	> 45%
Humedales	10	20	30
Manantiales	10	20	30
Cuerpos de agua	10	20	30
Ríos y esteros permanente y temporal *(sección de cauce > 0,5 m^2)*	10	20	30
Estero permanente y temporal *(sección de cauce < 0,5 m^2)*	10	10	10
Quebrada permanente *(sección de cauce < 0,5 m^2)*	5	10	10
Quebrada no permanente *(sección de cauce < 0,5 m^2)*	5	5	5

Source: (CONAF 2017a). The final report of the forest plantation protocol, 24th August 2017.

Annex 4. Minimum widths and categories of the water protection buffer zones for waterbodies supplying water for human consumption

ANCHO MÍNIMO DE LA ZONA DE PROTECCIÓN EN LAS MICROCUENCAS HIDROGRÁFICAS ABASTECEDORAS DE AGUA			
Categoría	Ancho zona de microcuencas abastecedoras de agua (m), según pendiente		
	< 30%	30 - 45%	> 45%
Humedales	10	20	30
Manantiales	10	20	30
Cuerpos de agua	10	20	30
Ríos y esteros permanente y temporal *(sección de cauce > 0,5 m^2)*	10	20	30
Estero permanente y temporal *(sección de cauce < 0,5 m^2)*	10	10	20
Quebrada permanente *(sección de cauce < 0,5 m^2)*	10	10	20
Quebrada no permanente *(sección de cauce < 0,5 m^2)*	10	10	20

Source: (CONAF 2017a). The final report of the forest plantation, 24th August 2017.