Análisis de Elementos Críticos para la Sustentabilidad del Desarrollo del Sector Mini-Hidro (<20 MW) en Chile

Pedro Jesús Arriagada Sanhueza

Guía: Dr. Oscar Link Lazo

Co-Guía: Dra. Evelyn Habit

Diciembre, 2019

Índice

Índice de Figuras

Índice de Tablas

RESUMEN:

En el presente trabajo de Tesis se analizan tres elementos críticos para el desarrollo sustentable del sector hidroeléctrico a través de pequeñas centrales hidroeléctricas (<20MW), relacionados con cada una de las dimensiones de la sustentabilidad: Efectos de la variabilidad y cambio climático sobre la disponibilidad del recurso; Efectos del aprovechamiento del recurso sobre la conservación de especies y; Efectos del aprovechamiento del recurso sobre el medio humano. Debido a la amplitud de la temática, el trabajo presenta un análisis que avanza el estado del conocimiento científico relacionado con estos tres elementos críticos y con ello proporciona una base para delinear propuestas conceptuales a nivel de política para la adecuada planificación del desarrollo del sector mini-hidro en Chile Central.

La escasez y mala calidad de los registros hidrometeorológicos de Chile presentaron uno de los mayores desafíos técnicos para estimar el potencial hidroeléctrico, ya que éste depende directamente del caudal de los ríos en los lugares de aprovechamiento y en la mayor parte de los puntos donde se debió estimar el potencial, no existía estadística de caudales. Por ello, fue necesario desarrollar una aplicación de inteligencia artificial para el relleno de estadística hidrológica de caudales diarios en las cuencas de Chile Central.

El análisis de los efectos del clima sobre la disponibilidad del recurso, mostraron que: (1) existen tendencias decrecientes significativas del potencial hidroeléctrico aprovechable en todas las cuencas analizadas que van desde los -22 a -47 MW/año y que dichas tendencias se mantendrán en el futuro. (2) Las tendencias observadas en el potencial hidroeléctrico aprovechable se encuentran moduladas por la variabilidad climática presentando periodos crecientes y decrecientes alternados. En el caso de estudio, i.e. en Chile Central, el potencial hidroeléctrico está correlacionado significativamente con la oscilación de El Niño en la escala interanual en todas las cuencas estudiadas. En la escala interdecadal se encontraron correlaciones significativas con la oscilación decadal del Pacífico (PDO), oscilación multidecadal del Atlántico (AMO) y el modulo anular del sur (SAM), donde el dominio de cada oscilación presenta diferencias entre cuencas. (3) La disponibilidad del recurso hidroeléctrico, es decir, los valores medios y medianos, se mantendrán hasta el año 2050. Sin embargo, se observaron reducciones en los valores extremos, sobre todo en los potenciales mínimos que pueden reducirse a un 40% en los escenarios más extremos. (4) Existe un riesgo de sobreinversión al no considerar los efectos de la variabilidad climática sobre el recurso hidroeléctrico, por ejemplo, de seguir la tendencia de desarrollo, la capacidad instalada para aprovechar hidroelectricidad en las cuencas del Biobío y Maule podría llegar a superar la disponibilidad del recurso.

El análisis de los efectos del aprovechamiento del recurso sobre la conservación de especies mostró que: (1) Se espera que la fragmentación de los sistemas fluviales andinos aumente severamente en el corto y mediano plazo, afectando la conectividad y función ecológica, así como su resistencia a los factores de stress antropogénicos. (2) El potencial hidroeléctrico puede ser aprovechado disminuyendo los impactos sobre la conectividad fluvial priorizando los afluentes de la cuenca alta de fragmentos por encima de barreras ya existentes.

El análisis de la evaluación de impactos de proyectos mini-hidro sobre el medio humano mostró que: (1) Existe un vacío de información de los efectos del desarrollo hidroeléctrico sobre las comunidades locales, ya que el actual desarrollo de centrales con potencia menor a 20 MW realiza principalmente Declaraciones de Impacto

Ambiental, las cuales no evalúan adecuadamente estos impactos, sino que sólo justifican la no significancia de ellos. (2) Los EIA presentan falencias en la determinación de las áreas de influencia de los proyectos hidroeléctricos y una falta de levantamiento de información primaria en las líneas bases del medio humano. (3) Se omite la detección de impactos sitio-específicos. (4) Hay escasa participación ciudadana en la evaluación de los proyectos hidroeléctricos, y en el caso de existir, no es vinculante lo que genera descontento, frustración, induce la judicialización y provoca el conflicto social. (5) La valoración de los impactos en el medio humano es mayoritariamente de carácter negativo no significativo, observándose principalmente compromisos voluntarios por parte de los desarrolladores de proyectos en vez de medidas de mitigación, compensación y/o reparación.

En base a los resultados y conclusiones obtenidas, se recomienda: Establecer políticas de desarrollo hidroeléctrico que consideren la variabilidad temporal y espacial del clima en la disponibilidad del recurso hidroeléctrico, estableciendo niveles máximos de desarrollo que consideren los potenciales esperados a futuro en cada cuenca; Diseñar e implementar políticas con un enfoque interdisciplinario desde la Ciencia de Ríos que exijan herramientas como las ecohidráulicas en los diseños de los proyectos y planes de seguimiento de impactos ambientales, así como obras de infraestructura que permitan mitigar los efectos en la conectividad longitudinal de las fauna fluvial, como los pasos de peces para especies nativas; Incorporar políticas que fomenten la participación ciudadana vinculante, sobre todo de comunidades locales, en los EIA y que se mejoren los estándares de calidad de las líneas de base, propendiendo a la generación de antecedentes sitio específicos.

ABSTRACT:

The present thesis analyzes three critical elements for the sustainable development of the mini hydropower sector in Central Chile, which are related to each of the dimensions of sustainability: The effects of climate variability and change; The effects of resource exploitation on species conservation; and social impacts of the resource exploitation. Due to the breadth of the subject matter, the present thesis advances the frontier of knowledge in this three critical directions, providing a basis for an improved planning and development of the mini hydropower sector in Central Chile.

The scarcity and bad quality of existing hydro-meteorological data in Central Chile represented the highest technical challenge of this work, as the available potential is directly related to the river discharge, and in the majority of the points of interests no discharge data were available. Therefore an advanced artificial intelligence algorithm for infilling daily streamflow data was developed and applied.

The analysis of the effects of climate on the availability of technically exploitable hydropower showed that: (1) there are significant decreasing trends of the hydropower potential in all the analyzed basins ranging from -22 to -47 MW/year and that trends will be maintained in the future. (2) The trends observed in the hydropower potential are modulated by climatic variability, with alternating increasing and decreasing periods. In the case study, i.e. Central Chile, the hydropower potential is significantly correlated with the oscillation of El Niño in the inter-annual scale in all the basins studied. At inter-decadal scale, significant correlations were found with the Pacific decadal oscillation (PDO), Atlantic multi-decadal oscillation (AMO) and the southern annular mode (SAM), where the domain of each climate oscillation presents differences between basins. (3) The availability of the hydropower resource, i.e. the mean and median values, will be maintained until 2050. However, reductions in extreme values were observed, especially in the minimum potentials that can be reduced up to 40% in the most extreme scenarios. (4) There is a risk of overinvestment by not considering the effects of climate variability on the hydropower resource, for example, if the hydropower development trend is followed, the installed capacity in the Biobío and Maule basins could exceed the availability of the resource.

The analysis of the effects of the hydropower resource exploitation on species conservation showed that: (1) The fragmentation of the Andean fluvial systems is expected to increase severely in the short and medium term, affecting connectivity and ecological functions, as well as their resistance to anthropogenic stress factors. (2) The hydropower potential can be exploited reducing the impacts on fluvial connectivity, if new water intakes and dams are installed preferring the tributaries of the upper basin upstream of existing barriers.

The analysis of the impacts evaluation of mini-hydro projects on the human environment showed that: (1) There are gaps of information on the effects of hydropower development on local communities, since small hydropower plants only declare negligible impacts but don't adequately evaluate impacts. (2) The EIAs present shortcomings in the determination of the influence areas and lack primary information in the baselines of the human environment. (3) Detection of site-specific impacts is omitted. (4) Citizen participation in the evaluation of hydroelectric projects is not binding, which generates discontent, frustration, induces judialization and provokes social conflict. (5) The assessment of impacts on the human environment is mostly negative and non-significant, with voluntary commitments being adopted by project developers instead of mitigation, compensation and/or reparation measures.

On the basis of the results and conclusions obtained, following recommendations are highlighted: To establish hydropower development policies which consider the climate temporal and spatial variability on the availability of the hydropower resource, establishing maximum levels of development that consider the expected future potentials in each basin; To design and implement policies with an interdisciplinary approach from River Science, including an eco-hydraulic perspective in the design of plants and plans for monitoring environmental impacts, as well as effective infrastructure to mitigate the effects on the longitudinal connectivity of river fauna, e.g. fish passes for native species; To incorporate policies that promote binding citizen participation in the EIA, especially of local communities, and that improve the quality standards of the social baselines, tending to the generation of specific site antecedents.

AGRADECIMIENTOS

Quisiera agradecer a todos los que, de alguna u otra forma, hicieron posible la realización de esta tesis. En primer lugar a mi familia que siempre estuvo presente y confiando en mi: A mis padres Amina y David, y a mi hermano Leonardo, por estar siempre apoyándome en este difícil y duro, pero maravilloso camino. Este éxito, claramente, también es de ustedes. También agradezco a Yoselyn, que a pesar que la vida nos hizo tomar caminos separados, su apoyo fue fundamental para conseguir este logro.

Agradecer, también, a mi profesor guía, Oscar Link, por todo lo brindado, por su paciencia y apoyo durante este proceso, por haberme apremiado a terminar esta tesis y por confiar siempre en mí. Espero haber retribuido de alguna forma las muchas cosas que me enseño.

A mis amig@s, por supuesto, por todas las buenas vibras que siempre me desearon y por nunca dudar de mí, incluso cuando yo mismo pensaba que no era capaz. Muchas gracias por estar presentes, no solo en esta tesis, si no que durante todo el camino del doctorado. Quisiera agradecer, de igual forma, a los profesores que contribuyeron a mi formación doctoral, y a todos los trabajadores de la facultad de ciencias ambientales e ingeniería que me apoyaron de alguna forma.

Para finalizar, espero sinceramente que esta investigación sea útil para poder avanzar en el conocimiento científico y de utilidad para mi país.

I. Introducción

El crecimiento sostenido de la población y de las economías mundiales conllevan un aumento de la demanda por energía y especialmente en las últimas décadas por electricidad. La generación eléctrica mundial ha incrementado desde 6.131 TWh hasta 25.606 TWh entre los años 1973 al 2017 (IEA, 2019), y se basa fundamentalmente en la producción mediante combustibles fósiles tales como carbón, petróleo y gas natural. Suplementariamente la producción de electricidad se ha realizado mediante centrales hidroeléctricas de embalse, energía nuclear y energías renovables. Dentro de las energías renovables, la energía hidráulica es las más utilizada, alcanzando en el año 2017 un 15.9% de la generación eléctrica global, superando a otras fuentes renovables (9.0%) e incluso a la energía nuclear (10.3%), gracias a sus notables ventajas como (Paish 2002, Sternberg 2010, Kilama 2013, Akpinar 2013, Killingtveit 2019): Es una energía renovable a la escala humana, el agua utilizada es devuelta a los cauces pudiendo ser utilizada aguas abajo del punto de generación, no presenta dependencia a la volatilidad de precios de los mercados globales, el factor de planta es alto, presenta bajos costos de inversión y operación en comparación a otras fuentes renovables. Estas ventajas y un escenario geo-político y económico favorable provocaron que desde 1920 hasta el año 2000 se construyeran más de 2000 centrales hidroeléctricas en el mundo (Zarfl *et al.* 2015) donde dominó la construcción de presas con grandes embalses. La construcción y operación de las grandes centrales de embalse en el siglo XX, dejó de manifiesto impactos ambientales importantes, tales como (Sternberg 2010, Abassi & Abassi 2011, Ansar *et al.* 2014, Zarfl *et al.* 2014, Kirchherr *et. al* 2016): La alteración del régimen hidrológico de los ríos embalsados, cambios biológicos, físicos y químicos en los ríos intervenidos, fragmentación de hábitats fluviales, conflictos por el uso del agua y efectos socioculturales debido al desplazamiento de las comunidades que habitan las zonas inundadas. Esto provocó que desde fines de la década del '70 la imagen de las grandes centrales de embalse cambiara de una sustentable por una amenazante al medio ambiente, generando conflictos económicos, ambientales y sociales, que complicaron la inversión en hidroelectricidad (Abassi & Abassi 2011).

En particular, aproximadamente el 41.5% de las emisiones de CO_2 a la atmósfera se debe a la producción de energía mediante combustibles fósiles (IEA 2018), lo que ha llevado a intentos por reemplazarlos por energías limpias. Los combustibles fósiles a nivel mundial han disminuido su participación en la generación de electricidad desde un 75,2% a un 64,8% entre 1973 y 2019. Sin embargo, los combustibles fósiles siguen siendo la principal fuente de energía. El explosivo aprovechamiento de estos combustibles ha generado problemas de disponibilidad, elevados precios y contaminación, debido a que sus ciclos de renovación difieren por mucho de la tasa de consumo actual (Akpinar 2013), provocando que el desarrollo tecnológico actual en generación eléctrica se enfoque en utilizar energías desde fuentes renovables como la solar, eólica, hidráulica, marina y geotérmica.

Entre las energías renovables no convencionales ERNC, por lejos la energía hidroeléctrica a través de las denominadas pequeñas centrales hidroeléctricas (PCH) es la que más se ha desarrollado en las últimas décadas. La definición de una PCH es por su potencia instalada, donde el umbral a considerar no es un estándar mundial. Sin embargo, Paish (2002), indica que la variación mundial de este umbral, es entre 2,5 a 25 MW, con una amplia aceptación mundial a considerar como PCH a una central entre 1 a 10 MW. En Chile se considera PCH una central con una potencia de hasta 20 MW. La razón por la cual la hidroelectricidad se ha desarrollado más que otras fuentes renovables no convencionales es que la tecnología es conocida y madura, los costos de inversión y operación son bajos, tiene largas vidas útiles (entre 50 a 100 años) y no sufre de intermitencia (Kilama 2013). Además, existe un importante potencial hidroeléctrico aprovechable, que a nivel mundial se ha estimado en torno a los 16.000 TWh, alcanzando una potencia instalada en el año 2013 de 1.000 GW (Zhou *et al.* 2015). Para el año 2030 se espera que esta potencia se duplique, con un importante crecimiento en Asia, África y Sudamérica (Zhang *et al.* 2018). Desde el año 2000 aproximadamente, se detecta un boom en el desarrollo de centrales hidroeléctricas no convencionales (Zarfl *et al*. 2015), que a su vez ya está mostrando claros indicios de problemas relacionados con el ecosistema y el medio humano.

Entre los impactos más relevantes que producen las PCH al ecosistema se cuentan (Abassi & Abassi 2011, Kilama 2013, Anderson *et al.* 2015, Couto & Olden 2018): La construcción de barreras transversales necesarias para la captación de las aguas y la derivación de las aguas desde el punto de extracción hasta el punto de restitución, lo cual modifica el régimen natural de caudales en el tramo intervenido y fragmenta el hábitat longitudinalmente, impidiendo el libre flujo de la fauna acuática presente en el río, generando alteraciones en la conectividad de las especies, alcanzando incluso caudales bajo el umbral mínimo necesario para mantener los servicios ecosistémicos. Indudablemente, escenarios de desarrollo que contemplan muchas centrales en una misma ecoregión, cuenca y/o río, generan efectos sinérgicos que han sido poco estudiados (Abassi & Abassi 2011, McManamay *et al.* 2014, Link & Habit 2015).

El principal impacto del desarrollo hidroeléctrico sobre el medio humano, es el desplazamiento y relocalización de comunidades, que claramente aplica al caso de grandes áreas de inundación por embalses. Se detecta un vacío de información sobre impactos de las PCH sobre los grupos humanos (Kumar Sharma & Thakur, 2017). En periodos de estiaje y/o sequía surgen especialmente los conflictos entre los diferentes usos del agua en los tramos afectos, por ejemplo: Abastecimiento de agua potable, turismo, agricultura, industria manufacturera, entre otros (Kilama 2013, Kumar Sharma & Thakur, 2017). En la mayoría de los casos, los conflictos terminan en judicialización, pero además generan descontento y una percepción negativa del proyecto en las comunidades locales afectadas (Environmental Justice Atlas, 2019).

Por otro lado, los efectos de la variabilidad climática generan importantes incertidumbres sobre la disponibilidad hidroeléctrica (van Vliet *et al.* 2016), por ejemplo, Ng *et al.* 2017 demostró que la oscilación climática interanual de El Niño (ENSO) puede modificar la producción hidroeléctrica de Sudamérica entre -30% a 30% en sus diferentes fases; Boadi and Owusu (2019) encontraron que la generación hidroeléctrica de Ghana depende en 74% de las diferentes fases de ENSO. Además, los efectos del cambio climático sobre la disponibilidad hidroeléctrica futura es otra fuente relevante de incertidumbre, donde la evaluación de estos efectos a escala global (Zhou *et al.* 2015), continental (Turner *et al.* 2017) y nacional o local (Hamududu & Killingtveit 2016, Wang *et al.* 2019) son una línea actual de investigación.

Evidentemente, el desarrollo hidroeléctrico actual a través de una inmensa cantidad de PCH corresponde a un problema complejo de ingeniería, donde deben considerarse todas las dimensiones de la sustentabilidad para lograr soluciones aceptables. A continuación, se revisa brevemente la evolución que ha tenido el concepto de sustentabilidad desde que fuera promulgado por la Comisión Brundtland en 1987.

I.1 Sustentabilidad

El concepto de sustentabilidad lleva décadas en discusión internacional, donde la necesidad de comprender su significado y establecer estrategias de acción son desafíos de las sociedades actuales (Pelletier *et. al.* 2012). El informe de Brundtland (1987) define el concepto de desarrollo sustentable como "Satisfacer las necesidades del presente sin comprometer las necesidades de las futuras generaciones". Posteriormente Elkington (1994, ver Elkington 2004) propuso el esquema "Triple-Bottom Line" (TBL) donde concibe la sustentabilidad como la intersección entre tres ejes: sociedad, ambiente y economía.

El enfoque Brundtland busca definir la sustentabilidad a una escala global, mientras el esquema TBL reduce el alcance de la sustentabilidad a un enfoque local. Sin embargo, ninguno enfoque logró establecer un consenso para este concepto, potenciando nuevas líneas de pensamiento, la sustentabilidad débil y fuerte (Ekins *et. al* 2003).

"Sustentabilidad Débil": El capital Humano, Social y Tecnológico pueden reemplazar el capital natural y los servicios ecosistémicos proporcionados por la naturaleza, a través del mejoramiento continuo y la incorporación de capitales tecnológicos que no declinen en el tiempo.

"Sustentabilidad Fuerte": Los servicios ecosistémicos no pueden ser reemplazados en su totalidad, basándose en el principio en que cada actividad económica requiere de energía, materias primas y producirá residuos (Georgescu-Roegen, 1971), por lo que la actividad social y económica es sólo una parte del medio ambiente, ya que utiliza y transforma recursos que provee el medio ambiente. (Ekins *et. al* 2003)

Los distintos enfoques de sustentabilidad se pueden representar de acuerdo a Pelletier *et.al.* (2012) como muestra la Figura 1:

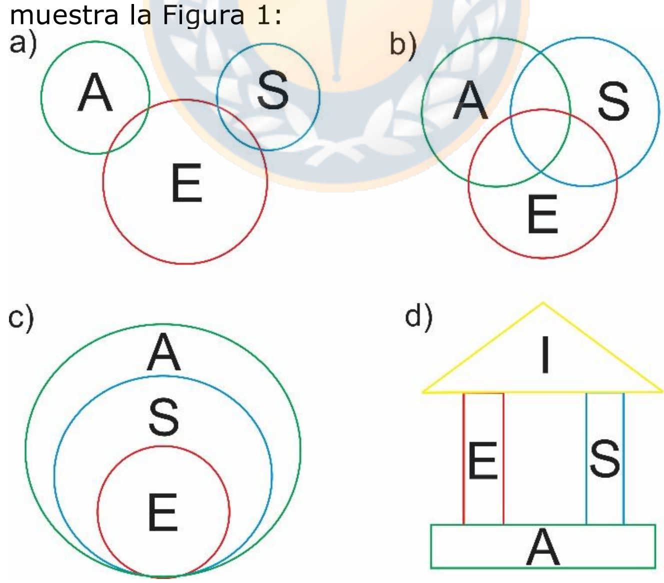

Figura 1. Modelos de sustentabilidad (A: Ambiente, E: Economía, I: Instituciones Públicas, S: Sociedad). Fuente: Pelletier *et al.* 2012

a) Representa el enfoque previo a la aparición del concepto de sustentabilidad, donde el eje económico es el más relevante presentando una pequeña interacción entre el ambiente y la sociedad.

b) Representa el esquema *Triple-Bottom-Line*, donde se define sustentabilidad como la intersección entre los tres ejes, esquema de sustentabilidad débil.

c) Representa el concepto de sustentabilidad fuerte, donde queda establecida la dependencia entre el eje económico y social, ambos contenidos en el eje del medio ambiente.

Finalmente **d)** representa el concepto de sustentabilidad fuerte propuesto por el programa de las naciones unidas para el medio ambiente (CSD, 2007), donde el medio ambiente es la base que permite el desarrollo de los pilares sociedad y economía, los cuales interactúan entre ellos a través de las instituciones públicas.

Estos enfoques conceptuales permiten abordar problemas multidimensionales interrelacionados como la pobreza, el cambio climático, el desarrollo económico y el abastecimiento de energía, agrupando variables en ejes fundamentales y conectándolos a través de su interacción.

I.2 Definición del Problema

En la presente tesis, se abordará el análisis de elementos de sustentabilidad del desarrollo del sector hidroeléctrico a través de pequeñas centrales, siguiendo el marco conceptual de una sustentabilidad fuerte según UNEP (CSD, 2007). La revisión bibliográfica presentada hasta ahora muestra que existen tres elementos críticos que controlan la sustentabilidad del desarrollo mini-hidro. Estos son:

(1) Efectos de la variabilidad y cambio climático sobre la disponibilidad del recurso energético: La potencia aprovechable en un sitio particular depende directamente del caudal del río, que a su vez está relacionado con la precipitación. ¿Cómo cambiará el potencial hidroeléctrico aprovechable en los ríos producto de la variabilidad y cambio climático? ¿Si es que el cambio esperado en el potencial hidroeléctrico es importante, cómo debe considerarse en la planificación del aprovechamiento del recurso?

(2) Efectos del desarrollo hidroeléctrico proyectado sobre la conectividad de los sistemas fluviales: Las captaciones de agua para aprovechamientos hidroeléctricos fragmentan longitudinalmente los hábitats fluviales poniendo en peligro la conservación de especies nativas. ¿Cómo afecta/contribuye el desarrollo hidroeléctrico a la fragmentación de los ríos? ¿Existen formas de aprovechar el recurso energético que disminuyan la fragmentación, ya sea siguiendo un determinado orden espacial en instalación de las centrales hidroeléctricas, o siguiendo una secuencia temporal en particular?

(3) Mecanismos para la identificación de impactos del desarrollo hidroeléctrico sobre el medio humano: Los mecanismos operantes actualmente tales como una participación ciudadana no vinculante, generan descontento, frustración y conflictividad en la sociedad, especialmente en las comunidades locales. ¿Cuáles son los impactos ambientales causados por PCH sobre el medio humano que requieren mayor consideración y cuál es la forma en que deben abordarse las soluciones? ¿De qué manera puede incorporarse una adecuada evaluación de los impactos sobre el medio humano en la política y la planificación del desarrollo hidroeléctrico?

Los tres elementos críticos identificados: efectos del clima sobre la disponibilidad del recurso, efectos del aprovechamiento del recurso sobre la conservación de especies, y efectos del aprovechamiento del recurso sobre el medio humano, correspondientes a los ejes económico, ambiental/ecológico y social, respectivamente, no han sido suficientemente investigados y por lo tanto, se requiere con urgencia ahondar en su estudio a fin de que puedan ser incluidos en la planificación energética, es decir en las instituciones a cargo de la política de desarrollo, para dar sustentabilidad al aprovechamiento del recurso.

Con la intención de contribuir a la contingencia nacional, en esta tesis se toma como área de estudio para analizar los elementos críticos de sustentabilidad del desarrollo hidroeléctrico a la zona de Chile central, la que se describe brevemente a continuación.

I.3 Chile, un caso de estudio para analizar el problema

En el año 2018 la generación eléctrica en Chile alcanzo los 76.175 GWh presentando un 53.5% de dependencia de los combustibles fósiles (CNE 2018), donde prácticamente la totalidad de estos combustibles son importados al país, generando un problema de seguridad energética y una alta sensibilidad a las fluctuaciones de los mercados externos (Ministerio de Energía 2015[a]). Además, la potencia instalada del sistema eléctrico chileno alcanzó los 23.315 MW en el mismo año, dividido en 2 sistemas de transmisión: el sistema eléctrico nacional (SEN) y los sistemas medianos (SSMM) que consideran los sistemas eléctricos de Magallanes, Los Lagos, Aysén e Isla de Pascua (CNE 2018). El SEN concentra el 99,2% de la potencia instalada, donde los principales combustibles utilizados son carbón (21%), gas natural (19%), hidráulica de embalse (14%), diésel (13%), hidráulica de pasada (12%) y solar fotovoltaica (10%).

Frente a la fuerte dependencia de los combustibles fósiles, el estado chileno ha adoptado la política de incorporar a la matriz de generación eléctrica, tecnologías que provengan desde recursos propios y renovables, proponiéndose la meta de que para el 2035, la matriz eléctrica nacional posea al menos un 60% de participación de fuentes renovables no convencionales. Y un 70% para el año 2050, incentivando la generación eléctrica a través de los recursos eólicos, solares e hidráulicos (Ministerio Energía 2015[a]).

La hidroelectricidad ha tenido una importante participación en la generación eléctrica del país, alcanzando un 76% de la generación en el año 1997 (CNE 2016). Sin embargo, en 1998 ocurrió la sequía más extrema registrada en el siglo pasado, la cual provocó racionamiento eléctrico, y por lo tanto que las nuevas inversiones en generación eléctrica se reorientaran hacia una basada en combustibles fósiles, principalmente gas natural (Pollit 2004). Posteriormente en el año 2008 y en acuerdo las directrices internacionales para mitigar los efectos del cambio climático, Chile aprueba la Ley 20.257 que fomenta el desarrollo de energías renovables en el país. Esta ley establece que las compañías eléctricas que realicen retiros desde cualquier sistema interconectado con potencia instalada mayor a 200 MW, deben justificar que el 10% de esos retiros provengan desde fuentes renovables, cuota que fue aumentada a un 20% en el año 2013 por la Ley 20.698. La implementación de estas dos leyes provocó un importante aumento en la inversión de centrales hidroeléctricas no convencionales (CHNC, también llamadas PCH) en el país, construyéndose 27 nuevas CHNC entre el periodo 2008 – 2012 y 38 entre el periodo 2013 – 2016 (Ministerio de Energía, 2019). Actualmente la generación hidroeléctrica en el año 2018 alcanzó el 31% de la generación eléctrica bruta, distribuida en 14% en centrales de embalse y 17% en CHNC (CNE 2018).

I.3.1 Dimensión Económica

La disponibilidad del recurso hidroeléctrico en sitios explotables juega un rol fundamental en la dimensión económica de la sustentabilidad del desarrollo del sector energía. En el año 2015, el Ministerio de Energía estimó que el potencial hidroeléctrico no aprovechado en Chile equivalente a 12 GW, distribuido en 1200 sitios. El potencial hidroeléctrico está íntimamente ligado al caudal de los ríos, por lo que su estimación requiere un certero análisis hidrológico. Para realizar esta estimación se aplicó el modelo "*Variable infiltration capacity*" (VIC, Liang et al. 1994, Bozkurt et al. 2017) y un análisis de los derechos de aprovechamiento de agua no consuntivos (DAANC) registrados en la dirección general de aguas (DGA) hasta el año 2012 (Ministerio de Energía 2014), y posteriormente actualizados hasta el 31 de agosto del 2014 (Ministerio de Energía 2015[b]). La principal limitación de esta metodología es que considera una restricción legal a través de los DAANC y por lo tanto el potencial hidroeléctrico sólo puede ser estimado en cuencas donde se hayan otorgado DAANC, los que no son una característica física del sistema. Esto es especialmente crítico en zonas donde los derechos se encuentran sobreexplotados o son inexistentes, abriendo la pregunta: **¿Cómo estimar el potencial hidroeléctrico sin imponer condiciones de borde legales?**

Por otro lado, la estimación del potencial hidroeléctrico (Ministerio de Energía, 2014) no consideró los efectos de la variabilidad climática sobre la disponibilidad hídrica, la cual presenta correlaciones con oscilaciones climáticas de baja frecuencia como el fenómeno del Niño (ENSO), oscilación decadal del pacífico (PDO), oscilación antártica o también llamada modulo anular del sur (AAO o SAM), entre otras (Valdés-Pineda *et al.* 2014). Tampoco incorporó el efecto de la reducción de la precipitación esperada en Chile central producto del cambio climático, que podría alcanzar hasta un 50% en los escenarios más extremos (Garreaud 2011), abriendo la pregunta: **¿Cuál es el efecto de la variabilidad y cambio climático sobre el potencial hidroeléctrico futuro?**

El caudal es la variable que controla la variabilidad del potencial hidroeléctrico en el periodo de vida útil de los proyectos (Engeland *et al.,* 2017), y para comprender las conexiones entre el potencial y la variabilidad climática se requiere de series temporales de caudal con la mejor resolución y calidad posible. Lamentablemente, la estadística hidrológica de caudales diarios en las cuencas de Chile Central presentan una baja densidad de datos con una mala calidad (Stehr *et al.* 2009, Muñoz *et al.* 2012, Valdés-Pineda *et al.* 2014). Algoritmos de inteligencia artificial para rellenar los vacíos de información como MissForest (Stekhoven & Bühlmann 2012), basado en el método "*Random Forest*" (Breiman, 2001), han demostrado ser una potente herramienta para completar registros temporales de datos complejos de forma automática y sin la necesidad de calibrar un conjunto de parámetros (Muñoz *et al.,* 2018). Missforest ha sido aplicado en diferentes disciplinas, tales como, medicina (Deshmukh *et al.*, 2019, Waljee *et al.* 2013), industria alimenticia (Tao *et al.* 2019) o protección de información (Marino *et al*. 2019), y recientemente en el área de la hidrología, específicamente, en modelos de crecidas repentinas (Muñoz *et al.,* 2018) y series mensuales de caudal (Sidibe *et al.* 2018). Sin embargo, no ha sido aplicado en el relleno de caudales diarios, abriendo la pregunta: **¿Es posible aplicar el algoritmo de inteligencia artificial MissForest para rellenar la estadística diaria de caudales en Chile Central?**

I.3.2 Dimensión Ambiental

Los ríos de la zona centro-sur de Chile presentan la característica natural de drenar sus cuencas en longitudes de entre 200 a 400 km, desde elevaciones del orden de los 3.000 a 6.000 m.s.n.m., lo que genera sectores con fuertes pendientes del orden de 5% a 10% (Link & Habit, 2015), condición favorable para el desarrollo hidroeléctrico. Por otro lado, la zona central de Chile es parte de uno de los 25 *hot spots* de biodiversidad existentes en el mundo (Myers *et al.* 2000). En esta zona habita una fauna íctica con alto valor de conservación, debido a su endemismo y características primitivas (Link & Habit, 2015). Dyer (2000) definió la provincia ictiográfica Chilena, la cual se traslapa con el desarrollo hidroeléctrico proyectado, la Figura 2 muestra la provincia ictiográfica Chilena, centrales hidroeléctricas en operación y proyectadas (Ministerio de Energía, 2019).

En la Figura 2 se puede apreciar cómo la provincia ictiográfica se encuentra bajo la presión del desarrollo hidroeléctrico entre las cuencas del Aconcagua al Maullín. Se detectan escasas investigaciones de los efectos del desarrollo hidroeléctrico sobre las comunidades de peces (Habit *et al.* 2007, García et al. 2011). Por otro lado, autores como Fagan (2002), Cardinale (2011), Carrara *et al.* (2014) y McCluney *et al.* (2014), han descrito la importancia de la conectividad longitudinal para la mantención de los distintos servicios ecosistémicos de los cauces fluviales, que podría verse alterada fuertemente en el caso de los ríos chilenos, si el desarrollo hidroeléctrico proyectado no considera medidas de mitigación que minimicen el efecto sobre la conectividad longitudinal de las especies de peces endémicas de Chile (Laborde *et al.* 2016, Link *et al.* 2017), abriendo las preguntas: **¿Qué efectos tendrá el desarrollo hidroeléctrico sobre los ecosistemas fluviales chilenos? ¿Cómo cuantificar el efecto que tendrá el desarrollo hidroeléctrico sobre la conectividad longitudinal?**

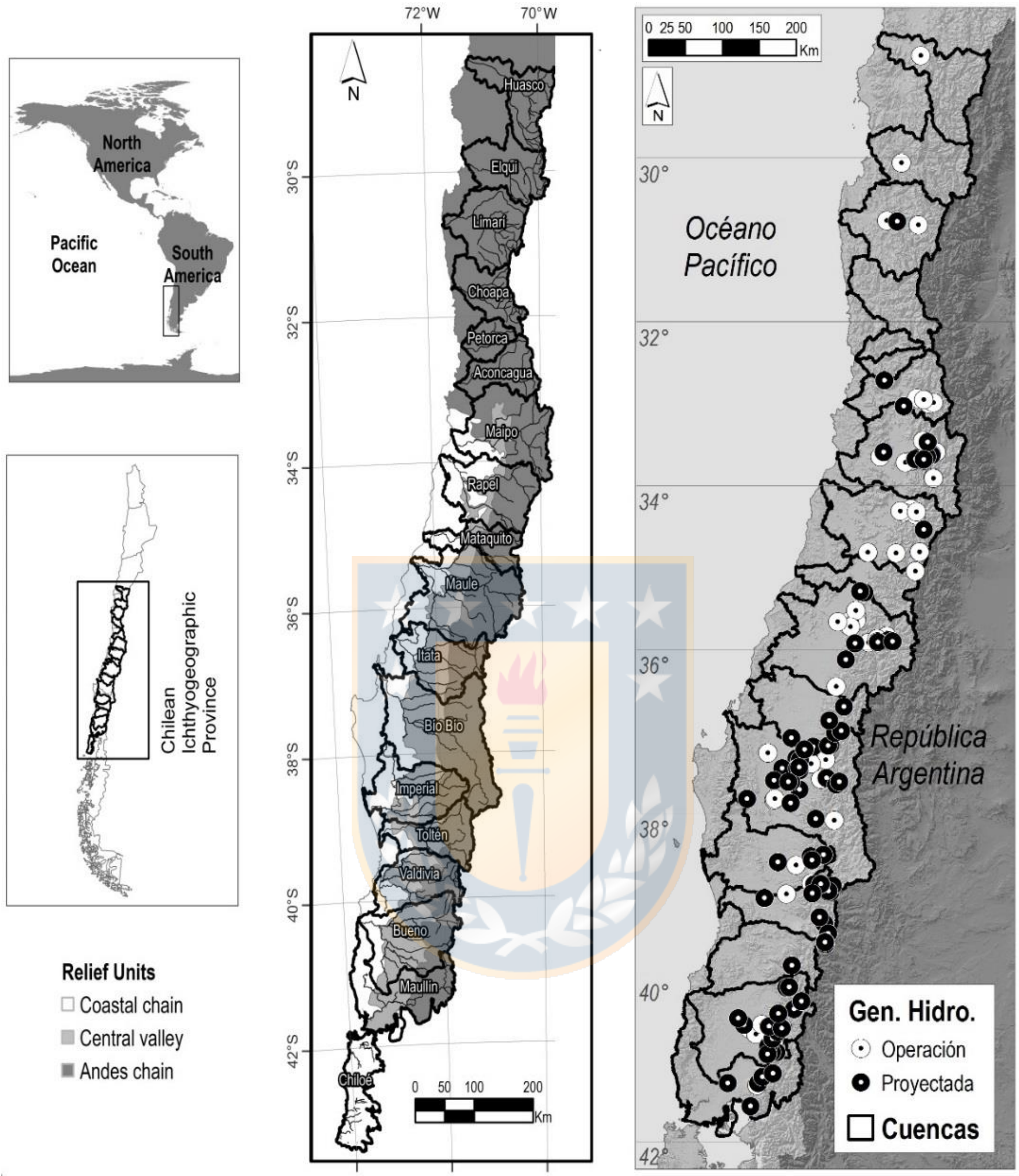

Figura 2. Provincia ictiográfica Chilena y zona de desarrollo hidroeléctrico

I.3.3 Dimensión Social

Los conflictos sociales debidos al desarrollo hidroeléctrico están presentes en Chile. El atlas de la justicia ambiental (Environmental Justice Atlas, 2019) documenta 15 conflictos en el país debido al desarrollo hidroeléctrico, que se resumen en la Tabla 1. Las principales causas de estos conflictos son: distintos usos y distribución del agua, reubicación de poblaciones y diferentes intereses para el uso de suelo de las áreas inundadas.

Tabla 1. Conflictos socio-ambientales en Chile debido a proyectos hidroeléctrico

Nº	Proyecto	Potencia (MW)	Ubicación	Causa conflicto
1	Alto Maipo	530	Cajón del Maipo, RM	Distribución y usos del agua Usos de suelo
2	HidroÑuble	136	San Fabián de Alico, XVI región	Distribución y usos del agua Usos de suelo
3	Embalse la Punilla	94	San Fabián de Alico, XVI región	Distribución y usos del agua Usos de suelo
4	Aguas Calientes	24	Pinto, XVI región	Distribución del agua
5	Angostura	316	Santa Bárbara, VIII región	Distribución y usos del agua Comunidades Indígenas desplazadas
6	Ralco	690	Alto Biobío, VIII región	Distribución y usos del agua Comunidades Indígenas desplazadas
7	Alto Cautín y Doña Alicia	6 y 6,3	Curacautín, IX región	Distribución del agua
8	Puesco y Momolluco	19,8 y 19,9	Villarrica, IX región	Distribución y usos del agua
9	Tranguil	3	Panguipulli, XIV región	Distribución del agua
10	Neltume	490	Panguipulli, XIV región	Distribución y usos del agua Usos de suelo
11	Maqueo	400	Futrono, XIV región	Distribución y usos del agua
12	Mediterráneo	210	Cochamó, X región	Distribución y usos del agua Usos de suelo
13	Yelcho	1.390 (3 CH)	Futaleufu, X región	Distribución y usos del agua Usos de suelo
14	Cuervo	640	Aysén, XI región	Distribución y usos del agua
15	Hidroaysén	2.750 (5 CH)	Cochrane, XI región	Distribución y usos del agua Usos de suelo

Fuente: "Environmental Justice Atlas, 2019"

Por otro lado, las guías de evaluación de impacto ambiental para el medio humano (SEA 2012 y 2014) proporcionan un marco de referencia centrado sólo en la relocalización de las comunidades. Frente al explosivo crecimiento del sector denominado mini-hidro (con potencia menor a 20 MW) observado desde el año 2008 entre las cuencas del río Maipo al río Maullín se plantea la pregunta: **¿Cuáles son las principales brechas y falencias existentes en la evaluación actual de impactos causados por proyectos mini-hidro sobre el medio humano en Chile?**

I.4 Referencias

Abbasi, T., and Abbasi, S. (2011). Small hydro and the environmental implications of its extensive utilization. Renewable and Sustainable Energy Reviews, 15(4), 2134–2143

Akpinar, A. (2013). The contribution of hydropower in meeting electric energy needs: The case of Turkey. *Renewable Energy.* 51, 206–219

Anderson, D., Moggridge, H., Warren, P. and Shucksmith, J. (2015). The impacts of "run-of-river" hydropower on the physical and ecological condition of rivers. *Water and Environment Journal*. 29(2), 268–276

Ansar, A., Flyvberg, B., Budzier, A., and Lunn, D. (2014) Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy,* 69, 43–66

Boadi, S. and Kwadwo, O. (2019). Impact of climate change and variability on hydropower in Ghana. *African geographical review*, 38(1), 19-31

Bozkurt, D., Rojas, M., Boisier J. and Valdivieso, J. (2017). Climate change impacts on hydroclimatic regimes and extremes over Andean basins in central Chile. *Hydrol. Earth Syst. Sci. Discuss.* 1-29

Breiman, L., (2001). Random forests. Mach. Learn. 45, 5–32. https://doi.org/10.1023/A:1010933404324

Brundtland Report. (1987), disponible en: http://www.un-documents.net/wced-ocf.htm

Cardinale, B. (2011) Biodiversity improves water quality through niche partitioning. *Nature*, 472, 86-89

Carrara, F., Rinaldo, A., Giometto, A., and Altermatt, F. (2014) Complex interaction of dendritic connectivity and Hierarchical patch size on biodiversity in river-like landscapes. *The american naturalist*, 183(1), 13-25

Comisión Nacional de Energía (CNE, 2016). Generación bruta SING-SIC, 1996-2016. Disponible en: https://www.cne.cl/estadisticas/electricidad/

Comisión Nacional de Energía (CNE, 2018). Anuario estadístico de energía 2018. Disponible en: https://www.cne.cl/wp-content/uploads/2019/04/Anuario-CNE-2018.pdf

Couto, T. and D'Olden J. (2018). Global proliferation of small hydropower plants-science and policy. *Front. Ecol. Environ*, 16(2): 91-100

CSD. (2007). Indicators of sustainable development: Guidelines and Methodologies. 3rd Edition. United Nations Commission on Sustainable Development. Available online: http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf

Deshmukh, H., Papageorgiou, M., Kilpatrick, E.S., Atkin, S.L. and Sathyapalan, T. (2019). Development of a novel risk prediction and risk stratification score for polycystic ovary syndrome. Clin. Endocrinol. (Oxf). 90, 162–169. https://doi.org/10.1111/cen.13879

Dyer, B. (2000). Systematic review and biogeography of the freshwater fishes of Chile. *Estudios Oceanológicos,* 19**,** 77-98

Elkington, J. (2004). *Enter the Triple Bottom Line: Does it All Add Up?,* London, England, Earthscan

Ekins, P., Simon, S., Deutsch, L., Folke, C., and Groot, R. (2003) A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecological Economics,* 44, 165-185

Engeland, K.; Borga, M.; Creutin, J.-D.; François, B.; Ramos, M.-H.; Vidal, J.-P. (2019) Space-time variability of climate variables and intermittent renewable electricity production – A review. *Renew. Sustain. Energy Rev. 79*, 600–617

Environmental Justicia Atlas (2019), Atlas de la justicia ambiental. Disponible en https://ejatlas.org/

Fagan, W., (2002) Connectivity, fragmentation, and extinction risk in dendritic metapopulations. *Ecology* 83(12), 3243–3249

Georgescu-Roegen N. (1971). *Entropy and the economic process*. Harvard University Press, Cambridge

García, A., Jorde, K., Habit, E., Caamaño, D. and Parra, O. (2011). Downstream environmenal effects of dam operations: Change in hábitat quality for native fish species. *River Res. Applic.,* 27, 312-327

Garreaud, R. (2011). Cambio climático: Bases físicas e impactos en Chile. *Revista Tierra Adentro,* 93, 1-14

Habit, E., Belk, M. and Parra, O. (2007). Response of the riverine fish community to the construction and operation of a diversion hydropower plant in central Chile. *Aquatic Conserv: Mar. Freshw. Ecosust.* 17: 37-49

Hamududu, B.H. and Killingtveit, Ä (2016). Hydropower production in future climate scenarios: The case for Kwanza River, Angola. Energies 9, 363

IEA (2018). CO_2 emissions from fuel combustion, disponible en https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018-highlights

IEA (2019). Key World Energy Statiscs 2019, disponible en https://webstore.iea.org/key-world-energy-statistics-2019

Kilama, O. (2013). Review of small hydropower technology. *Renewable and Sustainable Energy Reviews,* 26, 515-520

Killingtveit, A. (2019). Hydropower. In Managing Global Warmimng; pp. 265–315

Kirchherr, J., Pohlner, H., and Charles, K. (2016). "Cleaning up the big muddy: A meta-synthesis of the research on the social impact of dams". *Environmental Impact Assessment Review*, 60, 115-125

Kumar Sharma, A. and Thakur, N. S. (2017). Assessing the impact of small hydropower projects in Jammu and Kashmir: A study from north-western Himalayan region of India. Renewable and Sustainable Energy Reviews, 80(May), 679–693.

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, M., Habit, E. and Link, O. (2016). Hydropower development, riverine connectivity, and non-sport fish species: Criteria for hydraulic design of fishways. *River res. Applic.* 32, 1949-1957

Liang, X., Lettenmaier, D., Wood, E. and Burges, S. (1997). A simple hydrologically bases model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research,* 99: 14,415 – 14,428

Link, O., and Habit, E. (2015). Requirement and boundary conditions for fish passes of non-sport fish species based on Chilean experiences. *Reviews in Environmental Sciences and Biotechnology,* 14 (1), 9-21

Link, O., Sanhueza, C., Arriagada, P., Brevis, W., Laborde, A., González, A., Wilkes, M. and Habit, E. (2017). The fish Strouhal number as a criterion for hydraulic fishway design. *Ecological Engineering.* 103, 118-126

Marino, S., Zhou, N., Zhao, Y., Wang, L., Wu, Q. and Dinov, I.D. (2019). HDDA: DataSifter: statistical obfuscation of electronic health records and other sensitive datasets. J. Stat. Comput. Simul. 89, 249–271. https://doi.org/10.1080/00949655.2018.1545228

McCluney, K., Poff, N., Palmer, M., Thorp, J., Poole, G., Williams, B., Williams, M., and Baron, J. (2014) Riverine macrosystems ecology: sensitivity, resistance, and resilience of whole river basins with human alterations. *Frontiers in Ecology and the Environmental,* 12(1), 48–58

McManamay, R., Samu, N., Kao, S., Bevelhimer, M., and Hetrick, S. (2014). A Multi-scale Spatial Approach to Address Environmental Effects of Small Hydropower Development. *Environmental Management*, *55*(1), 217–243

Ministerio de Energía (2014). Energías Renovables en Chile. El Potencial Eólico, Solar e Hidroeléctrico de Arica a Chiloé. Disponible en: http://www.minenergia.cl/archivos_bajar/Estudios/Potencial_ER_en_Chile_AC.pdf

Ministerio de Energía (2015[a]). Energía 2050. Disponible en: http://www.energia.gob.cl/sites/default/files/energia_2050_-_politica_energetica_de_chile.pdf

Ministerio de Energía (2015[b]). Potencial hidroeléctrico de Chile. Disponible en: http://walker.dgf.uchile.cl/Explorador/DAANC/

Ministerio de Energía (2019). Módulo cartográfico. Disponible en http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/

Muñoz, E., Arumí, J. and Vargas, J. (2012) A design peak flow estimation method for medium-large and data-scarce watersheds with frontal rainfall. *Journal of the American water resources association.* 48(3), 439-448

Muñoz, P., Orellana-Alvear, J., Willems, P. and Célleri, R. (2018). Flash-flood forecasting in an andean mountain catchment-development of a step-wise methodology based on the random forest algorithm. Water (Switzerland) 10. https://doi.org/10.3390/w10111519

Myers, N., Fonseca, G., Mittermeier, R., Fonseca, G., and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–8.

Ng, J.Y.; Turner, S.W.D. and Galelli, S (2017). Influence of El Niño Southern Oscillation on global hydropower production. *Environ. Res. Lett. 12*

Paish, O. (2002). Small hydro power: Technology and current status. *Renewable and Sustainable Energy Reviews*, *6*(6), 537–556

Pelletier N., Maas R., Malgorzata G., and Wolf, M. (2012). Towards a Life-Cycle Based European Sustainability Footprint Framework. *JRC Scientific and Policy Reports.* Luxemburgo 2012

Pollitt, M.G. (2004) Electricity reform in Chile: Lessons for developing countries. *J. Netw. Ind.*, *5*, 221–262

SEA (2012). Guía para la evaluación de impacto ambiental de centrales de generación de energía hidroeléctrica de potencia menor a 20 MW. Disponible en: https://www.sea.gob.cl/sites/default/files/migration_files/20121109_hidro_terminada.pdf

SEA (2014). Guía de evaluación de impacto ambiental. Reasentamiento de comunidades humanas. Servicio de evaluación ambiental, segunda edición. ISBN: 978-956-9076-20-6

Stehr, A., Debels, P., Arumi, J., Romero, F. and Alcayaga, H. (2009) Comibining the soil and water assessment tool (SWAT) and MODIS imagery to estimate monthly flows in a data-scarce Chilean Andean basin. *Hydrological Sciences Journal*, 54 (6), 1053-1067

Sternberg, R. (2010). Hydropower's future, the environment, and global electricity systems. *Renewable and Sustainable Energy Reviews,* 14: 713-723

Stekhoven, D.J. and Bühlmann, P. (2012). Missforest-Non-parametric missing value imputation for mixed-type data. Bioinformatics 28, 112–118. https://doi.org/10.1093/bioinformatics/btr597

Sidibe, M., Dieppois, B., Mahé, G., Paturel, J.E., Amoussou, E., Anifowose, B. and Lawler, D. (2018). Trend and variability in a new, reconstructed streamflow dataset for West and Central Africa, and climatic interactions, 1950–2005. J. Hydrol. 561, 478–493. https://doi.org/10.1016/j.jhydrol.2018.04.024

Tao, N., Chen, Y., Wu, Y., Wang, X., Li, L. and Zhu, A. (2019). The terpene limonene induced the green mold of citrus fruit through regulation of reactive oxygen species (ROS) homeostasis in Penicillium digitatum spores. Food Chem. 277, 414–422. https://doi.org/10.1016/j.foodchem.2018.10.142

Valdés-Pineda, R.; Pizarro, R.; García-Chevesich, P.; Valdés, J.B.; Olivares, C.; Vera, M.; Balocchi, F.; Pérez, F.; Vallejos, C.; Fuentes, R., Abarza, A. and Helwing, B. (2014). Water governance in Chile: Availability, management and climate change. *J. Hydrol. 519*, 2538–2567

van Vliet, M.T.H.; Wiberg, D.; Leduc, S. and Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Chang. 6*, 375–380

Waljee, A.K., Mukherjee, A., Singal, A.G., Zhang, Y., Warren, J., Balis, U., Marrero, J., Zhu, J. and Higgins, P.D.R. (2013). Comparison of imputation methods for missing laboratory data in medicine. BMJ Open 3, 1–8. https://doi.org/10.1136/bmjopen-2013-002847

Wang, H., Xiao, W., Wang, Y., Zhao, Y., Lu, F., Yang, M., Hou, B. and Yang, H. (2019). Assessment of the impact of climate change on hydropower potential in the Nanliujiand River basin of China. *Energy,* 167: 950-959

Zarfl, C.; Lumsdon, A.E. and Tockner, K. (2015) A global boom in hydropower dam construction. *Aquat. Sci. 77*, 161–170

Zhou, Y., Hejazi, M., Smith, Edmonds S., J., Li, H., Clarke, L., Calvin, K. and Thomson, A. (2015) A comprehensive view of global potential for hydrogenerated electricity. *Energy Environ. Sci.*, 2622–2633

II. Hipótesis

La sustentabilidad del desarrollo del sector mini-hidro (centrales con potencia <20MW) en la zona de Chile central depende de la adecuada consideración de tres elementos críticos en la institucionalidad y la política energética, siendo los tres elementos críticos: en la dimensión económica, los efectos de la variabilidad y cambio climático sobre la disponibilidad del recurso; en la dimensión ambiental, la fragmentación de los sistemas fluviales mediante las obras de captación de las centrales hidroeléctricas y; en la dimensión social, la adecuada valoración, mitigación, reparación y compensación de impactos sobre el medio humano.

III. Objetivo General

Evaluar elementos críticos para la sustentabilidad del desarrollo del sector mini-Hidro (<20 MW) en Chile Central.

III.1 Objetivos Específicos

- Analizar los efectos de la variabilidad y cambio climático sobre la disponibilidad del potencial hidroeléctrico en Chile Central.
- Analizar la fragmentación de los sistemas fluviales de Chile Central causada por el desarrollo hidroeléctrico actual y proyectado.
- Analizar brechas y falencias existentes en la evaluación de impactos causados por proyectos mini-hidro sobre el medio humano.

IV. Resultados

IV.1 Efectos de la variabilidad y cambio climático sobre la disponibilidad del potencial hidroeléctrico en Chile Central

IV.1.1 Relleno de estadística fluviométrica diaria de caudales utilizando de inteligencia artificial.

AUTOMATIC GAP-FILLING OF DAILY STREAMFLOW TIME SERIES IN DATA-SCARCE REGIONS USING A MACHINE LEARNING ALGORITHM

Pedro Arriagada[a,b,*] , Bruno Karelovic[c] & Oscar Link[d]

[a] School of Engineering, University of Concepción, Chile
[b] Environmental Engineering Department, School of Environmental Sciences, University of Concepción, Chile
[c] Computer Science Department, University of Concepción, Chile
[d] Civil Engineering Department, University of Concepción, Chile

Enviado a Journal Advances in Water Resources

Abstract

Complete hydrological time series are crucial for water and energy resources management and modelling in a changing climate. The reliability of the non-parametric stochastic machine learning algorithm MissForest was assessed for gap-filling of daily streamflow time series in a data-scarce region with 11 different climates. A total of 1,586 reconstructions of streamflows for 1970-2016 were analyzed. Reconstructed daily streamflow time series of rivers with natural flow regimes were simulated with good performance, which slightly decreased for discharge magnitude alterations by runoff inputs from urbanized areas and water diversion for irrigation. In cases of severe alterations of the flow regime, such as by hydropeaking, MissForest failed at filling daily streamflow series gaps. Overall, MissForest performed satisfactorily to well, allowing a precise and reliable simulation of the missing data quickly and automatically. Reconstructed hydrographs allow analysis of streamflow change and variability and their interactions with key climatic variables.

Keywords: MissForest, Data Gaps, Imputation, Discharge Records.

***Corresponding author. Email address: parriagada@udec.cl, Phone: +56 41 2204065**

1 Introduction

Complete hydrological time series are crucial for management and modeling of water, energy and other natural resources in a changing climate (Arriagada et al., 2019; Tencaliec et al., 2015). Data gaps cause difficulties in data interpretation, ineffective model calibration, unreliable timing of peak flows and biased statistics (Dembélé et al., 2019; Starrett et al., 2010), but are inherent to daily streamflow series for a number of reasons related to limited economic resources and political conflicts, such as sporadic operation of gauge stations, blackouts of the measuring devices, effects of extreme weather events, limited access to download data from loggers located in remote areas, scarcity of observers and human errors (Dembélé et al., 2019; Elshorbagy et al., 2000; Harvey et al., 2012). Incomplete streamflow series are more frequent and gaps are generally longer in developing countries (Amisigo and van de Giesen, 2005; Dembélé et al., 2019; Gyau-Boakye and Schultz, 1994; Sidibe et al., 2018), where so-called data-scarce regions, i.e., areas with a gauge density below World Meteorological Organization standards (WMO, 2008), also occur. At the same time, these regions are under the greatest pressure to develop water use infrastructure (Vörösmarty et al., 2010).

Daily streamflow time series of rivers and streams with natural flow regimes (Poff et al., 1997) are more suitable for successful application of gap-filling methods (e.g., Dembélé et al., 2019; Sidibe et al., 2018; Vega-Garcia et al., 2019), as the flow regime is characterized by the magnitude, frequency, duration, timing and rate of change, which respond to global and regional climate drivers such as modes of climate variability, jet streams, storm tracks and atmospheric rivers, as well as to river basin characteristics such as land uses, geology, vegetation and topography (McGregor, 2019). By contrast, in regulated rivers, alteration of one or more attributes of the flow regime due to human activities such as energy production, flood protection, irrigation, industrial and recreational activities and urbanization can introduce heavy artificial influences and significantly complicate (e.g., Mackay et al., 2014) automatic computation of the missing streamflow values from neighboring gauge stations (Harvey et al., 2010, 2012). In analysis of streamflow gauge series on a large spatial scale, both classes of streamflow data are mixed, coming from rivers with natural and regulated flow regimes, challenging gap-filling methods.

Techniques for infilling missing flow data vary from simple interpolation to models and complex statistical analysis (Gyau-Boakye and Schultz, 1994). A classification of existing methods for infilling gaps in streamflow time series according to their mathematical complexity was provided by Harvey et al. (2012), who distinguished six classes of methods, namely manual inference, serial interpolation techniques, scaling factors, equipercentile techniques, linear regression and hydrological modelling. Further, a number of machine learning methods have been applied to infill missing flow data, including artificial neuronal networks (e.g., Ben Aissia et al., 2017; Kim et al., 2015; Mwale et al., 2012; Vega-Garcia et al., 2019), random forest models (Petty and Dhingra, 2018; Sidibe et al., 2018) and stochastic non-parametric methods such as direct sampling (Dembélé et al., 2019).

In particular, random forest by Breiman (2001) is a non-parametric machine learning algorithm for data simulation based on a combination of tree predictions. It was extended by Stekhoven and Bühlmann (2012) to the MissForest algorithm for missing value imputation in mixed-type data series. Potential advantages of MissForest models over other alternatives for infilling daily streamflow data in large regions are that they can quickly handle large amounts of data and the missing data imputation is unsupervised and automatic, avoiding the determination of predictor stations (Sidibe et al., 2018); they can handle multiple data gaps in the series (Tang and Ishwaran, 2017); they are easy to implement in computational languages such as R, as they don't require initial setting and calibration of parameters (Muñoz et al., 2018); and they achieve competitive predictive performance and are computationally efficient, making them suitable for real-world prediction tasks (Sidibe et al., 2018).

Random forest has been applied in different scientific contexts such as medicine (Deshmukh et al., 2019; Stekhoven and Bühlmann, 2012; Waljee et al., 2013), sensitive information protection (Marino et al., 2019) and food chemistry (Tao et al., 2019). In water resources (see Tyralis et al., 2019), random forests have recently been tested for reconstruction of monthly streamflows in regions with different climates (Sidibe et al., 2018) and for flash-flood forecasting (Muñoz et al., 2018). The infilling of gaps in daily streamflow series in regions with different climates is more challenging because temporal and spatial variability is higher and relatively short periods of time without data, i.e., months, require that a large amount of data be filled in. Clearly, the gap-filled data are more accurate when examining trends at the annual scale, followed by the monthly scale and, finally, the daily scale, at which the results are the least satisfactory (Zhang and Post, 2018).

The aim of the present work is to assess the reliability of the machine learning algorithm MissForest for automatic gap-filling of daily streamflow time series in a data-scarce region with a variety of different climates, including regulated and unregulated rivers and streams.

2 Materials and Methods

2.1 Study Area

The study area of 152,351 km^2 includes 10 watersheds located in central Chile, between latitudes 32°55' and 41°17' S, and longitudes 69°48' and 73°43' W. The population of about 12,316,144 inhabitants (71% of the country, INE 2018) is concentrated in a few big cities located in the Central Valley or coastal plain. Table 2 shows the important properties of the watersheds in the study area.

Tabla 2 Location, geomorphological and climate data for each basin in the study area.

Basin	Latitude (° ')	Longitude (° ')	Area (km^2)	Maximum altitude (m)	Predominant Climate	Flow regime*	PP_{MA} (mm)**	Q_{MA} (m^3/s)
Maipo	32°55'-34°18' S	69°48'-71°38' W	15,273	6,546	Csa-Csb	Snowmelt	650	134
Rapel	33°54'-35°00' S	70°01'-71°51' W	13,766	5,138	Csa-Csb	Snowmelt-rain	882	169
Mataquito	34°48'-35°38' S	70°24'-72°11' W	6,332	4,058	Csb	Snowmelt-rain	1373	113
Maule	35°06'-36°35' S	70°21'-72°27' W	21,052	3,931	Csb	Snowmelt-rain	1400	495
Itata	36°12'-37°20' S	71°02'-72°52' W	11,326	3,178	Csb	Snowmelt-rain	1764	331
Bío Bío	36°52'-38°54' S	70°50'-73°12' W	24,369	3,487	Csb	Rain	1873	971
Imperial	37°49'-38°58' S	71°27'-73°30' W	12,668	3,066	Csb-Cfb	Rain	2056	264
Toltén	38°36'-39°38' S	71°24'-73°14' W	8,448	3,710	Cfb	Rain	2062	540
Valdivia	39°18'-40°12' S	71°36'-73°24' W	10,244	2,824	Cfb	Rain	2592	546
Bueno	39°54'-41°17' S	71°40'-73°43' W	15,366	2,410	Cfb	Rain	2861	394

* from Valdés-Pineda et al. (2014)
** estimated from Atlas del Agua (DGA, 2016)

In the northern part of the study area, from Maipo to Bío Bío, the climate is dominated by the Pacific anticyclone (Garreaud et al., 2009; Valdés-Pineda et al., 2018). According to the Köppen classification (Beck et al., 2018), the predominant climate is a temperate dry and warm summer climate (Csb). In the southern part of the study area, from Imperial to Bueno, the climate is dominated by the southern westerlies (Garreaud et al., 2009; Valdés-Pineda et al., 2018). According to the Köppen classification (Beck et al., 2018) the predominant climate is temperate without a dry season and a warm summer (Cfb). The Biobío and Imperial watersheds are located in a climatic transition area with mixed influence of the southeast Pacific anticyclone and the westerlies (Falvey and Garreaud, 2009; Valdés-Pineda et al., 2018). The climate variability is influenced by oscillations, with different periods such as the El Niño-Southern Oscillation (Escobar and Aceituno, 1998), the Pacific Decadal Oscillation (Mantua and Hare, 2009; Montecinos and Aceituno, 2003), and the Antarctic Oscillation (Urrutia et al., 2011; Valdés-Pineda et al., 2018). About 30% of the winter storms are warm winter rainstorms caused by atmospheric rivers (Garreaud, 2013).

According to the Soil Taxonomy classification system, most of the study area is covered by six orders, namely Alfisols, Entisols, Inceptisols, Mollisols, Ultisols, and Vertisols, as well as Andisol and Histosol series (Bonilla and Johnson, 2012). Land surface slope values range from close to zero in the Central Valley – a geological depression with an approximately 70-km-wide plain formed between the Andes and the coastal range, extending south from Valparaíso for about 1000 km to the Araucanía Region – to 0.65 (m/m) in the Andes (Carretier et al., 2018). The study area includes most of the cultivated and productive land in the country, with the majority of farms (72%) and national forest area (54%) (Bonilla and Johnson, 2012). The rainfall regime, soil properties, high slopes and land uses make the study area particularly vulnerable to erosion processes (Bonilla and Vidal, 2011; Ellies, 2000). At the same time, the study area includes 91 of the 148 existing hydropower plants in Chile, with a total power of 5.05 GW, i.e., 76% of the national installed hydropower; in addition to these existing projects, 30 new hydropower plants with a total of 0.65 GW are under environmental evaluation or construction. Moreover, the exploitable hydropower of the study region has been estimated at about 12 GW, spread among 1200 sites, most which are located in the Andes or the piedmont region (Arriagada et al., 2019). There is clearly a conflict between water uses for agriculture and hydropower, with both activities severely affecting river discharges and the conservation of native freshwater fauna (Habit et al., 2019; Laborde et al., 2016).

2.2 Streamflow data

In the study area streamflow is monitored at 320 gauges administrated by the National Water Agency (Dirección General de Aguas, DGA). Figure 3 shows the location of the study area, climates and locations of streamflow gauges (SFG), including the data availability for the 1970-2016 period.

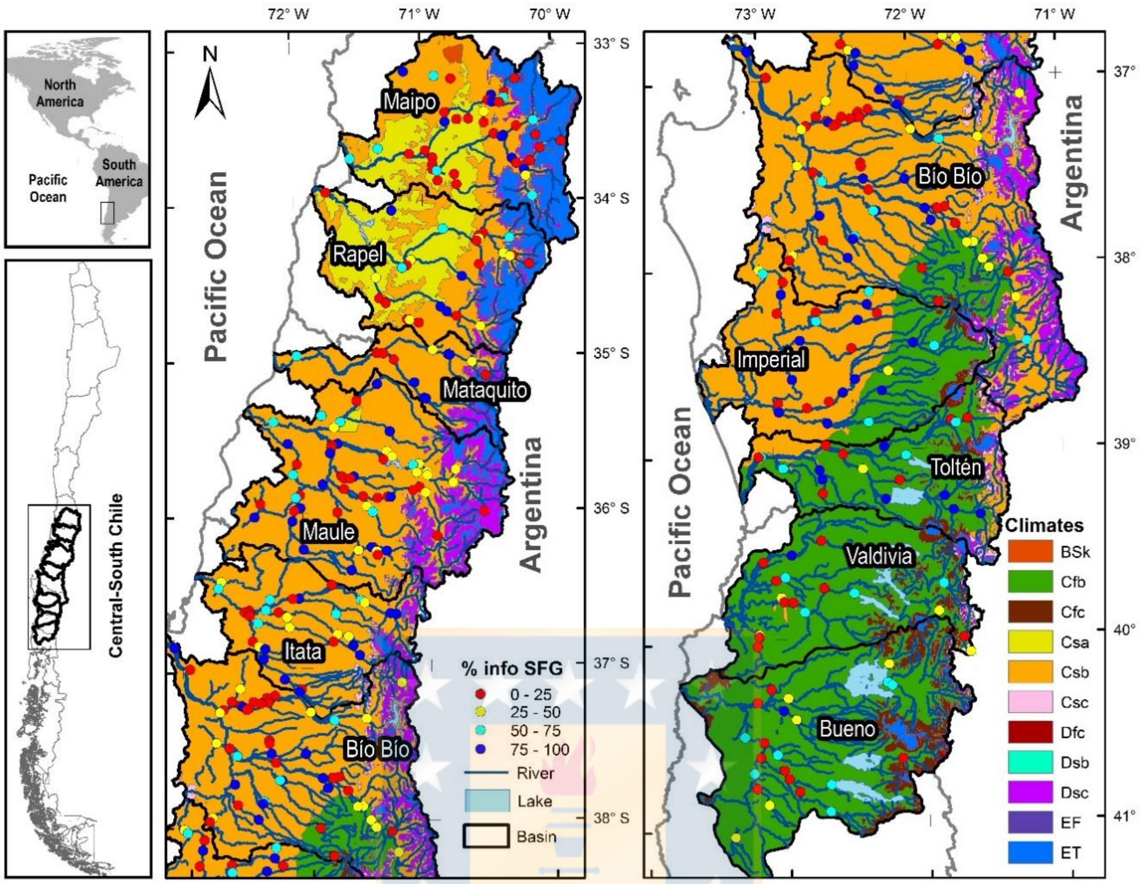

Figura 3. Location of the study area, climates and locations of streamflow gauges, including the data availability for the 1970-2016 period.

Figure 4 shows the available and missing data at the 122 streamflow gauges with data records that are at least 50% complete in the study period.

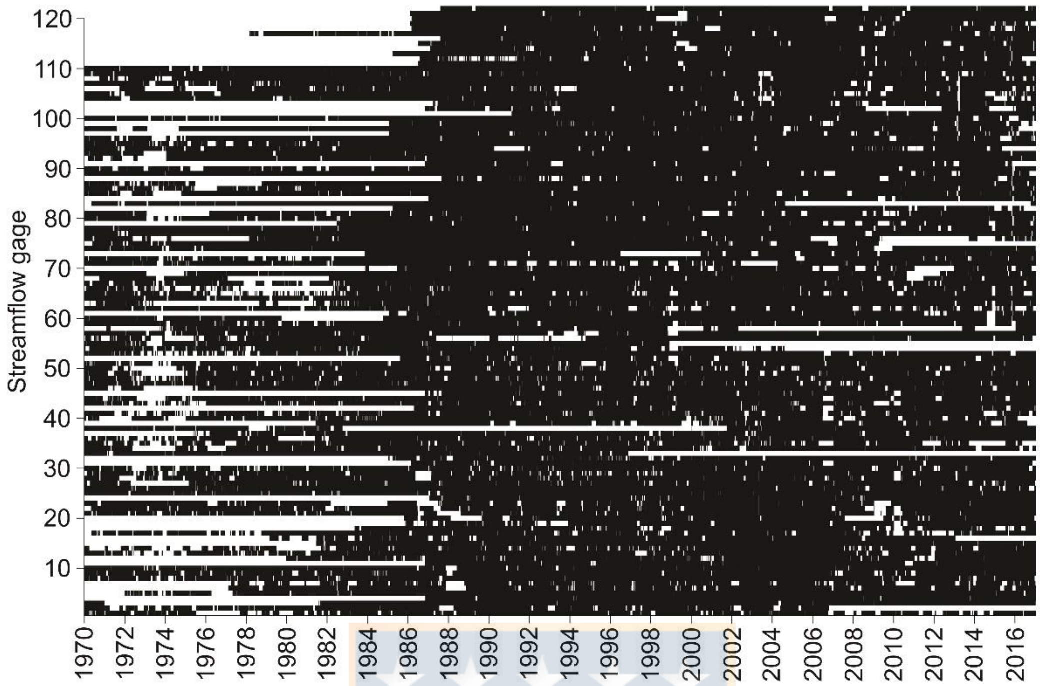

Figura 4. Available and missing data at the 122 streamflow gauges data records >50% complete in the study period (1970-2016).

Even though the overall streamflow gauge density in the study area, 456 km^2 per gauge station, is in compliance with WMO standards (WMO, 2008), there are 171 decommissioned gauges and only 122 gauges present data over 50% of the time between 1970 and 2016. Consequently, considering only the 122 usable gauges, the gauge density is 1,238 km^2 per gauge, which is below WMO standards, and thus the study region is data scarce. Table 3 shows the number of streamflow gauges in the study area, distinguishing between decommissioned gauges and those having records over 50% complete during the study period, and the gauge density.

Tabla 3. Streamflow gauges in the study area.

Basin	Number of SFG	Number of decommissioned SFG	Number of SFG having over 50% of data in the study period	SFG density (km^2 per gauge) *
Maipo	46	17	16	332 (955)
Rapel	30	16	7	459 (1,967)
Mataquito	14	7	6	452 (1,055)
Maule	57	30	22	369 (957)
Itata	33	17	16	343 (708)
Bío Bío	55	30	15	443 (1,625)
Imperial	26	13	16	487 (792)
Toltén	19	13	11	445 (768)
Valdivia	18	9	5	569 (2,049)
Bueno	22	19	8	698 (1,921)

* Numbers in parentheses shows the SFG density based only on gauges with information that is at least 50% complete.

2.3 The MissForest algorithm

Random forests (RF; Breiman, 2001) grow many decision trees and average their results. Each decision tree applies the bootstrap aggregation technique; i.e., given the training set they select m times a random sample with replacement of the training set and fit a decision tree to these samples. Thus, the correlation between the trees is reduced and better results are achieved. Stekhoven and Bühlmann (2012) extended the RF to the MissForest algorithm (MF) for missing value imputation in mixed-type data. MF consists of training a random forest iteratively on observed variables for prediction of the missing values. Defining $X = (X_{1,}...,X_p)$ as a data set of $n \times p$ dimensions, corresponding to p streamflow gauges with n recorded daily streamflows. For a given station X_s, let $i_{miss}(s)$ be the set of days where station s presents missing values. Then, the dataset is separated into four parts:

$Y_{obs}^{(s)}$: The observed streamflow values at station X_s

$Y_{mis}^{(s)}$: The missing values at station X_s

$X_{obs}^{(s)}$: The observed streamflow at another gauge in days $\{1,...,n\} \setminus i_{miss}(s)$

$X_{mis}^{(s)}$: The missing streamflow at another gauge in days $i_{miss}(s)$

Note that $X_{obs}^{(s)}$ can have missing values and $X_{mis}^{(s)}$ can contain observed streamflows.

Our goal is to fill the missing values $Y_{mis}^{(s)}$. To do so, the main idea is to train a random forest to predict $Y_{obs}^{(s)}$ from $X_{obs}^{(s)}$ and then to use this trained random forest to predict our missing values at station X_s ($Y_{mis}^{(s)}$) from $X_{mis}^{(s)}$. Nevertheless, there could be some missing values in $X_{mis}^{(s)}$ and $X_{obs}^{(s)}$, in which case we should fill these values as a first step as follows: the average recorded daily streamflows at each gauge station X_t during the study period are imputed to each missing value of gauge station t.

Now, gauges are sorted by first placing those with less missing data. For each value X_s, the missing values are imputed by fitting a random forest with input $X_{obs}^{(s)}$ and output $X = (X_{1,}...,X_p)$. Next, missing values $Y_{mis}^{(s)}$ are predicted by the trained random forest with input $X_{mis}^{(s)}$. The imputation procedure is repeated until the difference in step k between the newly imputed data and the previous one increases for the first time.

More precisely, let X_k^{imp} be the previouly imputed data in the k-th interation and X_{k+1}^{imp} be the updated imput in the (k+1)-th iteration. The difference (Δ) is calculated as follows:

$$\Delta_k = \frac{\sum i \in X\left(X_{k+1}^{imp} - X_k^{imp}\right)^2}{\sum i \in X\left(X_{k+1}^{imp}\right)} \quad (3)$$

The stop criterion is met as soon as Δ_{k+1} is larger than Δ_k. One thousand regression trees were used in all computations based on previous experiences by Arriagada et al. (2019), and the maximum number of iterations was set to hundred, i.e., a sufficiently large number to ensure fulfilment of the convergence criterion in Eq. (3). The algorithms were implemented using R (https://www.R-project.org/). Figure 5 shows a flow diagram for automatic gap-filling of daily streamflow data using MissForest.

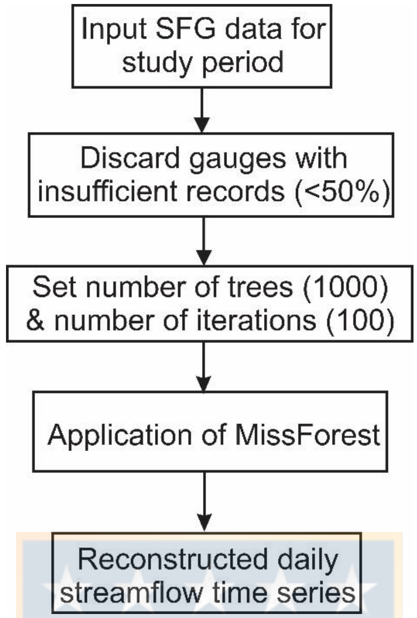

Figura 5. Flow diagram for automatic gap-filling of daily streamflow data using MissForest.

2.4 Synthetic missing data scenarios and method performance

Missing daily streamflows in the study area were assumed completely at random. Two types of artificial gaps were generated, namely a) Removed single data points: observed values (30, 60, 90, 120, 180 and 365 days) were randomly removed from the entire record (1970-2016) at each of the gauges; b) Removed contiguous segments: entire segments of observed data (having lengths of 7, 14, 21, 30, 60, 180, and 365 days) were randomly removed from the entire record (1970-2016) at each of the gauges. In total, 13 reconstructions of the 1970-2016 period at each of the 122 streamflow gauges were developed, i.e., 1.586 simulations.

The performance of MissForest at infilling daily streamflow data was tested by comparing the filled series with the observed data using goodness-of-fit indicators: coefficient of determination (*R^2*), the percent bias (*PBIAS*), and the Kling-Gupta efficiency (*KGE*) (Kling et al., 2012):

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \mu_o)(S_i - \mu_s)}{\sqrt{\sum_{i=1}^{n}(O_i - \mu_o)^2}\ \sqrt{\sum_{i=1}^{n}(O_s - \mu_s)^2}}\right] \tag{4}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n} O_i - S_i}{\sum_{i=1}^{n} O_i}\right] \tag{5}$$

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \tag{6}$$

$$\beta = \frac{\mu_s}{\mu_o} \tag{7}$$

$$\gamma = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o} \tag{8}$$

where *O* and *S* are the observed and simulated data, μ is the mean, σ is the standard deviation, *r* is the correlation coefficient between simulated and observed data, β is the bias ratio and, finally, γ is the variability ratio. The optimal value of R^2 and *KGE* is one, while the optimal value of PBIAS is zero. The threshold values for satisfactory, good and very good performance are: $0.60 < R^2 \leq 0.75$, $0.75 < R^2 \leq 0.85$, $R^2 > 0.85$ and ±15 > PBIAS ≥ ±10, ±10 > PBIAS ≥ ±5, and PBIAS < ±5 (Moriasi et al., 2015). Knoben et al. (2019) distinguished two classes of performance according to KGE, namely good for KGE > -0.41 and bad for KGE < -0.41.

2.5 Effects of altered flows on MissForest performance

The effects of altered flows on MissForest performance were investigated by creating a 365-day-long gap in a year missing less than 20% of data at selected gauges where human alterations – such as water diversion to an irrigation channel, surface runoff inputs from urbanized areas, and upstream hydropower operation – affect river flows. Again, MissForest performance was tested by comparing filled and observed series by means of goodness-of-fit indicators R^2, *PBIAS*, and *KGE.*

2.6 Reconstruction of streamflow records

As an application case, MissForest was used for the reconstruction of streamflow records at the 122 gauges located in the study area for the 1970-2016 period.

3 Results

MissForest was applied to the subset of streamflow gauges with less than 50% missing data, i.e., 122 streamflow gauges here. In all presented computations ten or fewer iterations were needed to satisfy the convergence criterion in Eq. (3).

3.1 MissForest performance at gap-filing of daily streamflow time series

Figure 6 shows observed and simulated hydrographs in streamflow gauges located in different climates and geographic units for the scenario of a continuous gap with a duration of 365 days randomly placed in the data series.

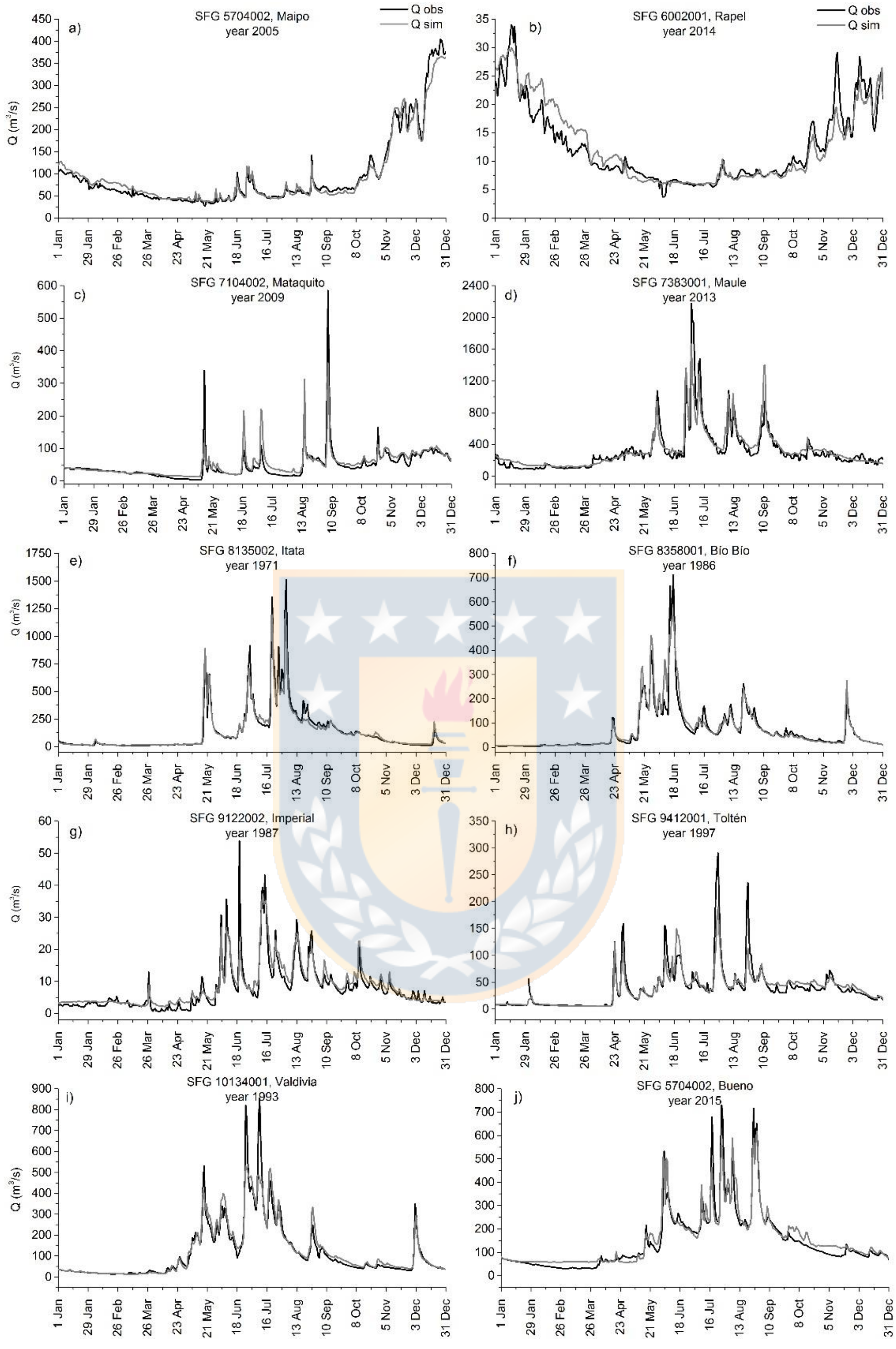

Figura 6. Observed and simulated hydrographs in streamflow gauges located in the a) Maipo River in the Andes, with a Csb climate; b) Rapel River in the Andes, with a Csb climate; c) Mataquito River in the Andes, with a Csa climate; d) Maule River in the coastal plain, with a Csb climate; e) Itata River in the Central Valley, with a Csb climate; f) Bío Bío River in the coastal plain, with a Csb climate; g) Imperial River in the Andes with a Cfb climate;, h) Toltén River in the Andes, with a Cfb climate; i) Valdivia River in the Central Valley, with a Cfb climate; and j) Bueno River in the Andes, with a Cfb climate.

Overall, the shape of the observed hydrograph is well reproduced, with good timing and representation of the annual seasonality in all cases, suggesting that climate diversity and the geographic units in which the different gauges are located are not important controls for MissForest performance. The simulated hydrographs match observed low flows in rainfall-dominated flow regimes (dry season corresponds to summer from December 21 to March 21) as well as high flows in watersheds with rain, snow and/or glacial melting. Figure 7 shows a) R^2, b) PBIAS and c) KGE of the simulated daily streamflow for the study region, for all simulated scenarios.

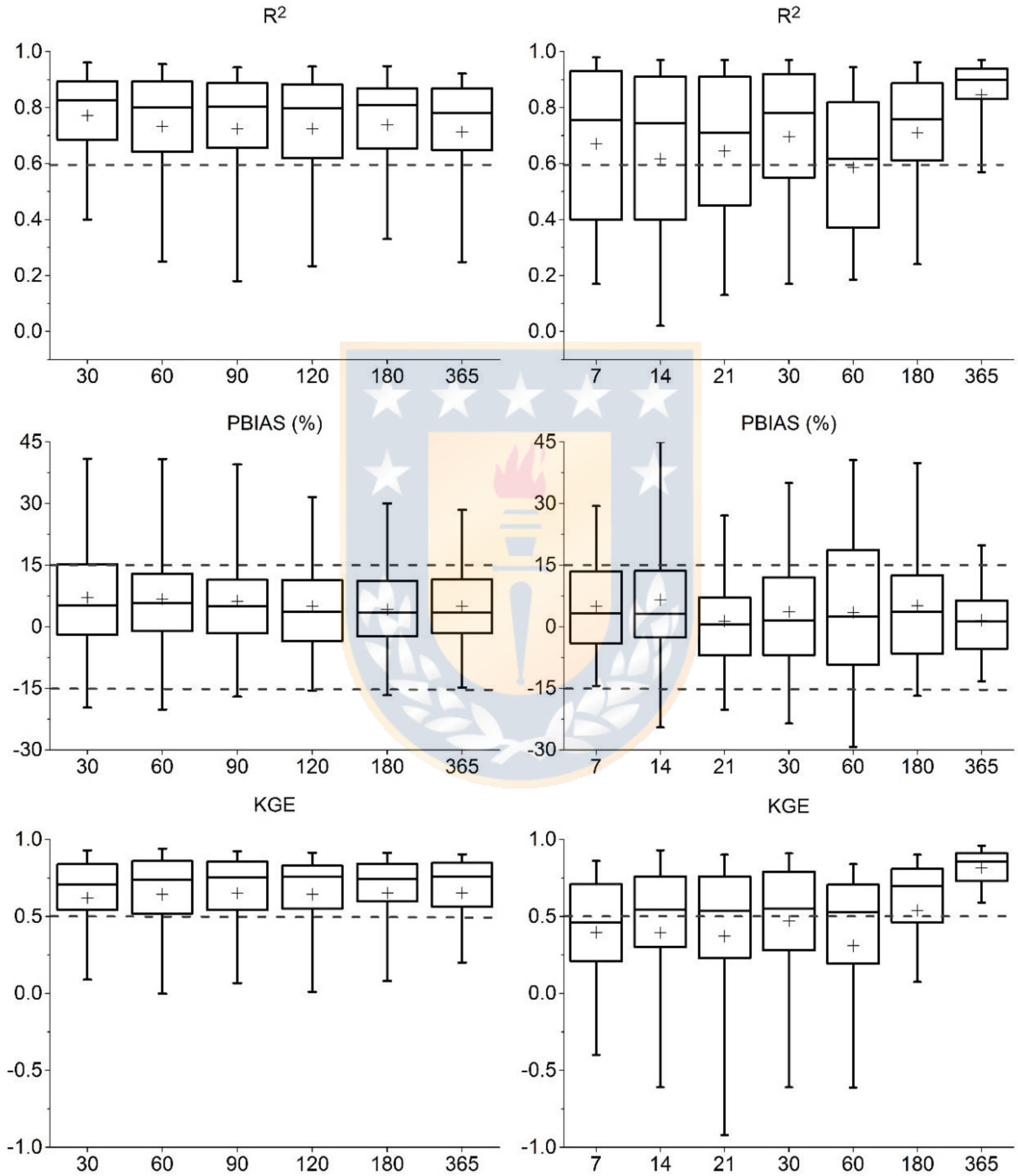

Figura 7. Validation of the RF method of filling the gaps in daily flow series, as determined through R^2, PBIAS and KGE. The left column shows the results for the removed single data points and the right column shows the results for the removed contiguous segments. The crosses indicate the mean value, the whiskers show the 5th and 95th percentiles and the dashed lines represent the recommend value.

MissForest performed well at infilling single data points and contiguous segments (average values of $R^2 > 0.6$, $PBIAS < \pm15\%$ and $KGE > 0.5$ in both cases). Mean values of R^2, *PBIAS,* and *KGE* were different in both cases (Mann-Whitney U Test, U = 6.0, p = 0.038), and slightly higher for the infilling of single data points, illustrating that for MissForest temporal correlations are important. Mean values of R^2, *PBIAS,* and *KGE* did not change significantly with the number of removed single data points (Mann-Whitney U Test by R^2, U > 7456, p > 0.224; PBIAS, U > 7239, p > 0.539; and KGE U > 7068, p > 0.497), nor with the length of removed continuous segments for lengths up to 60 days (Mann-Whitney U Test by R^2, U > 6774, p > 0.162; PBIAS, U > 7366, p > 0.386; and KGE U > 6729, p > 0.196). However, R^2 and *KGE* presented a significant increase for removed continuous segments longer than 60 days (Mann-Whitney U Test by R^2, U > 4276, p < 0.0007; and KGE U > 3480, p < 0.0008). These results suggest that MissForest performance is not highly sensitive to the amount of missing data. Dispersion of R^2, *PBIAS,* and *KGE* was important in all cases and higher when infilling contiguous segments. These high dispersion values represent important differences in the quality of reconstructed hydrographs at the different gauges, suggesting that external factors such as altered flow regimes play an important role in MissForest performance for infilling daily streamflow time series; thus, such cases are analyzed in further detail below.

3.2 Effects of altered flows on MissForest performance

3.2.1 Water diversion for irrigation

The study area includes most of the cultivated and productive land in the country, including most of its farms, and thus it presents several water intakes placed in rivers and streams to divert water for irrigation. The Laja River presents significant water diversions for agriculture (Mardones and Vargas, 2005). The irrigation period is usually from October 15 to March 31, altering the natural flow regime downstream of the water intakes. Figure 8 shows measured and simulated hydrographs at a gauge upstream of a water intake that diverts water for irrigation during the irrigation period (October-March).

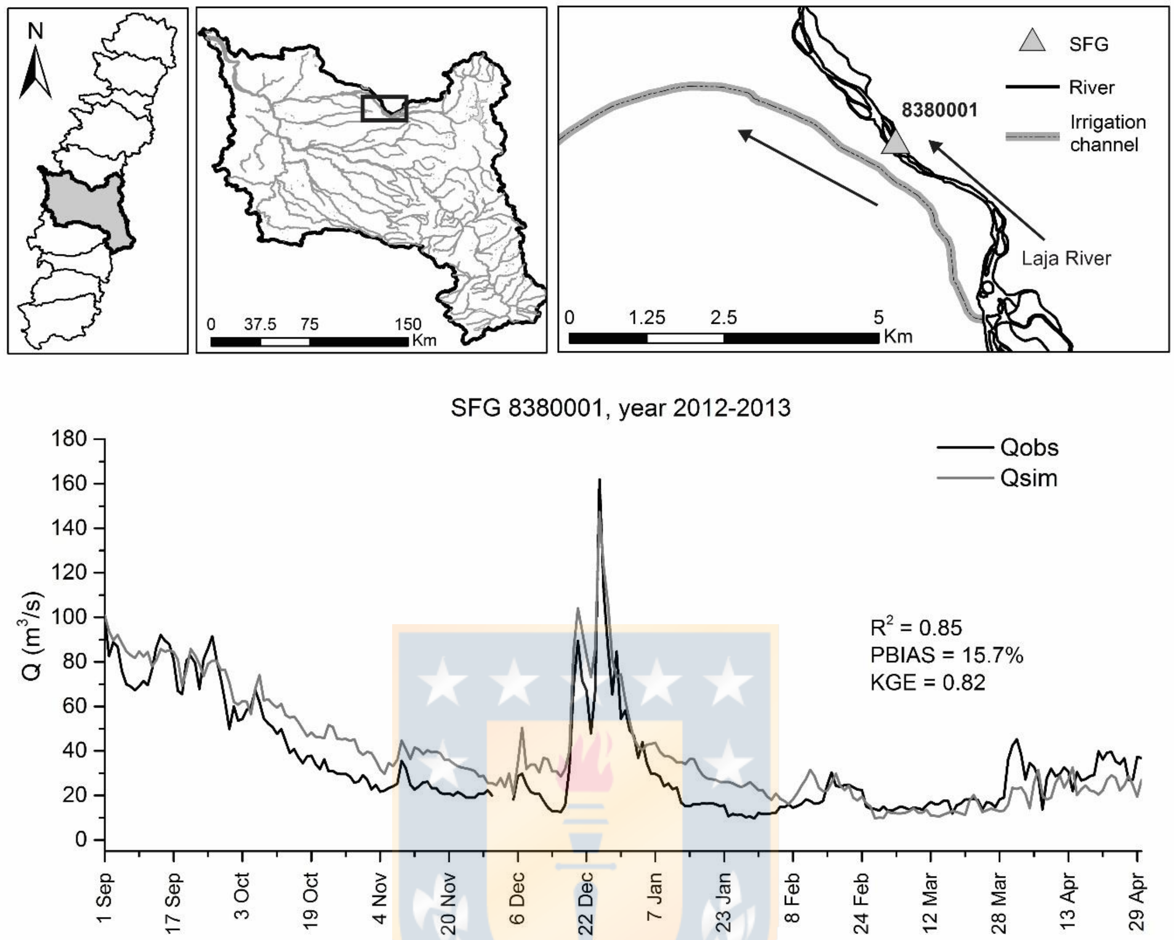

Figura 8. Observed and simulated hydrographs at a gauge located downstream of a water diversion for irrigation.

Clearly, the water diversion for irrigation altered the natural flow regime, diminishing the discharges during the irrigation period. In this case, the simulated flows are higher than the observed flows. However, MissForest performance is satisfactory to good (R^2=0.85, PBIAS = 15.70%, KGE = 0.82), showing that systematic alterations of discharge can still be followed by MissForest, at least in terms of trends. Remarkably, a small flood that occurred around Christmas forced the water intakes to close, and the streamflow imputation was correct in this period.

3.2.2 Runoff inputs from urbanized areas

Areas that are impervious due to urbanization increase surface runoff and thus water contribution from these areas increases peak discharges of rivers during storms. Figure 9 shows measured and simulated hydrographs at a gauge located downstream of rainwater inputs form the city of Talca, near the Claro River.

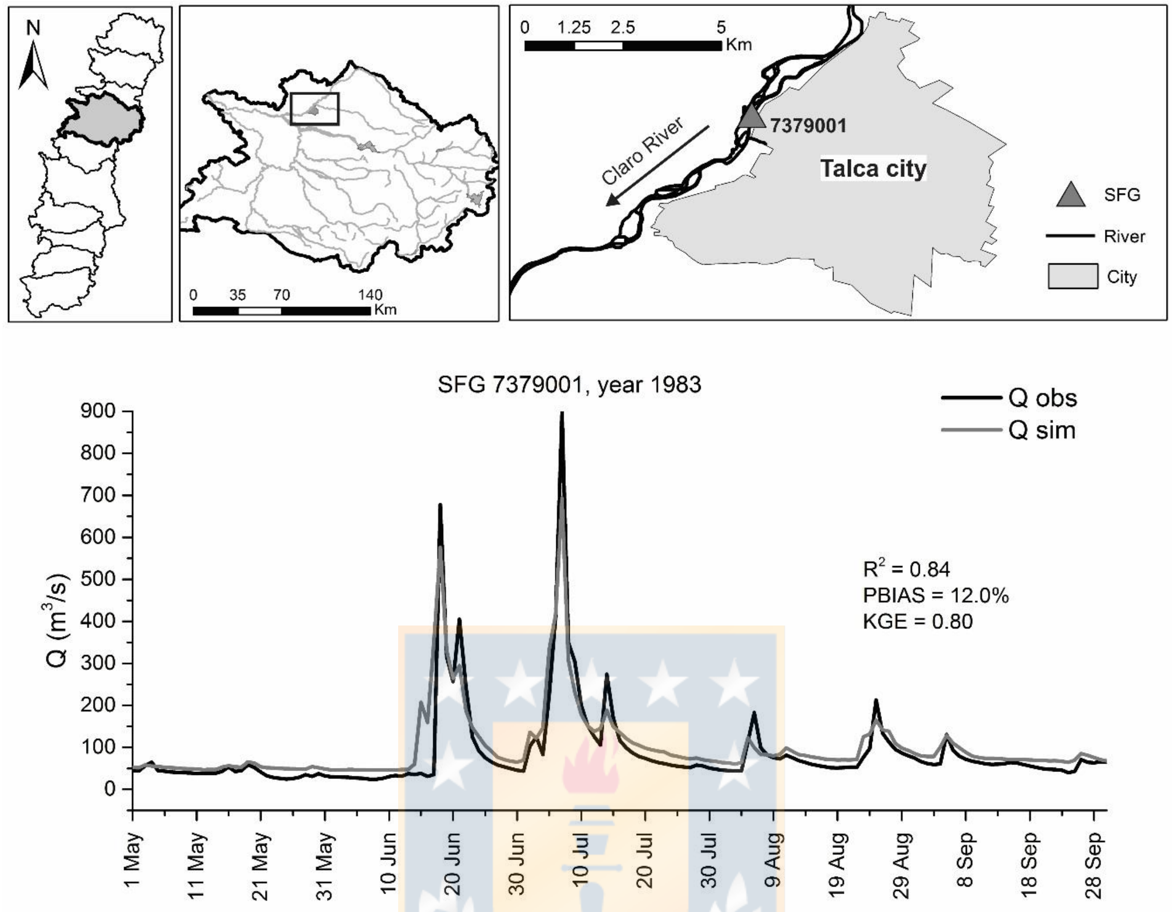

Figura 9. Observed and simulated hydrographs at a gauge downstream of urbanized areas.

Simulated peak discharges are clearly lower than observed discharges during the storms, and consequently during the recession limb of floods the simulated discharges are higher than the observed discharges, evidencing the effects of urbanization on river discharges. In such cases, MissForest performance decreased to satisfactory (R^2 = 0.84, PBIAS = 12.0%, KGE = 0.80).

3.2.3 Discharge regulation for hydropower

Hydropower dams can alter their discharge several times a day to meet peak electricity demand, resulting in the alteration of downstream flow, including changes in magnitude, duration, timing, rate of change (upramping and downramping rate) and frequency. Figure 10 shows measured and simulated hydrographs at two gauges in the Maule River, located up- and downstream of the Colbún dam (400 MW), i.e., with natural and altered flow regimes, respectively, in 2013.

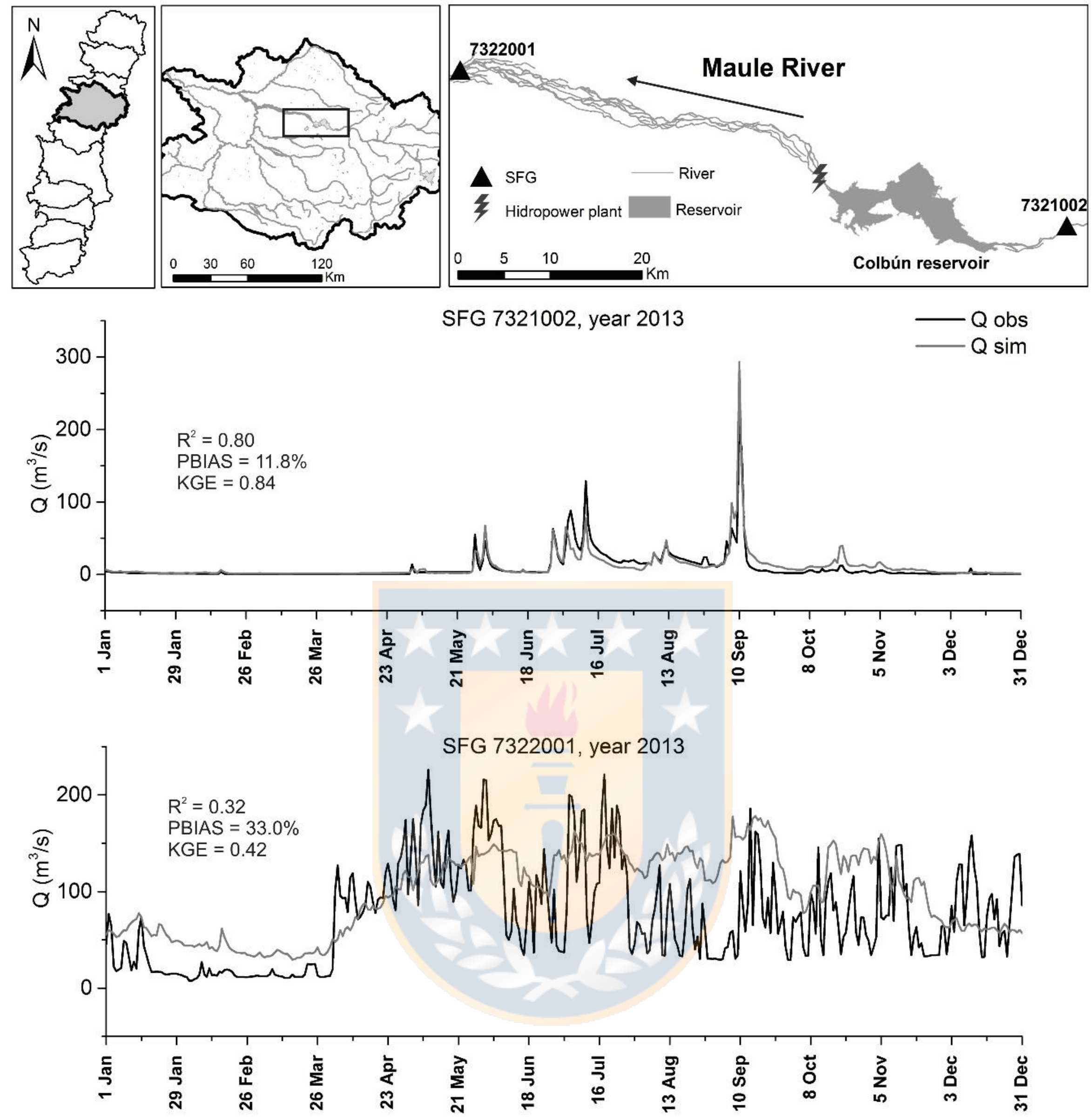

Figura 10. Observed and simulated hydrographs at two gauges located up- and downstream of the Colbún dam (400 MW), respectively.

Upstream of the dam, the flow regime is natural, and the performance of MissForest was clearly good (R^2=0.8, PBIAS=11.8%, KGE=0.84). However, downstream of the dam, streamflows change according to energy production to satisfy variable demand with a high stochastic component, and MissForest performance declined (R^2 = 0.32, PBIAS = 33%, KGE = 0.42), evidencing difficulties in the imputation of values in these cases.

3.3 Reconstruction of streamflow records

Complete daily streamflow time series are crucial for water, energy and natural resources management. As overall MissForest presented satisfactory to good performance at gap-filling of daily streamflow time series, existing records at the 122 gauges located in the study area were reconstructed. Figure 11 shows the observed and reconstructed hydrographs over the 1970-2016 study period at the nearest gauges to the mouth of the ten studied watersheds: a) Maipo, b) Rapel, c) Mataquito, d) Maule, e) Itata, f) Bío Bío, g) Imperial, h) Toltén, i) Valdivia and j) Bueno.

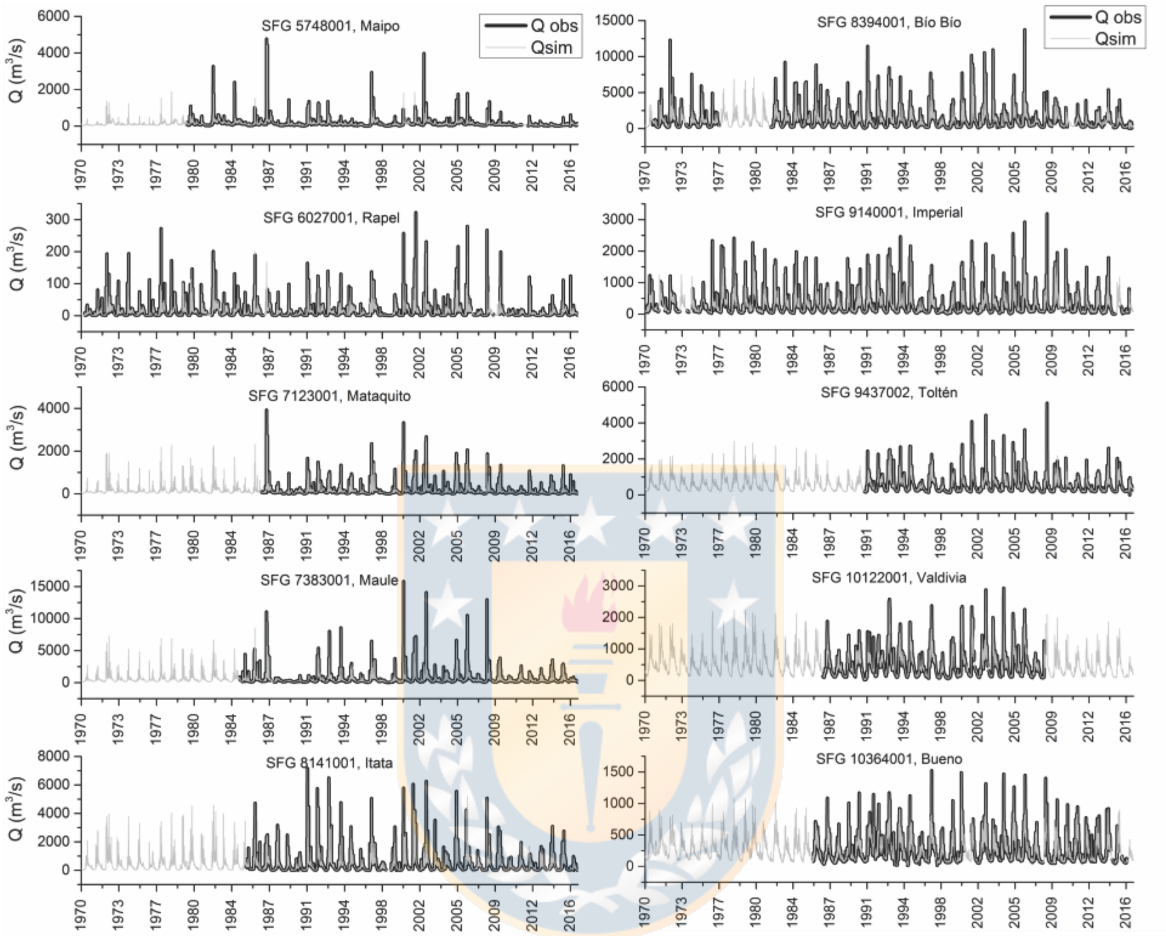

Figura 11. Observed and reconstructed hydrographs over the 1970-2016 study period at the mouths of the ten studied watersheds: Maipo, Rapel, Mataquito, Maule, Itata, Bío Bío, Imperial, Toltén, Valdivia and Bueno.

The predicted hydrographs allow the analysis of streamflow change and variability and their interactions with key climatic variables such as precipitation, temperature and potential evapotranspiration in central Chile between 1970 and 2016.

4 Discussion

Researchers often set a threshold for the acceptable percentage of missing data to consider a gauge station usable. For instance, thresholds of 1% (Petrone et al., 2010), 5% (Ukkola et al., 2016), 10% (Déry et al., 2009), 15% (Liu and Zhang, 2017), and 20% (Lopes et al., 2016) have been adopted in previous studies. In the presented study, we adopted a threshold of 50%, which allowed us to work with 122 out of 324 (38%) existing gauge stations. Under such conditions, we showed that the study area is a data-scarce region with poor availability of daily streamflow records, well below the desired standards recommended by the World Meteorological Organization (WMO, 2008). The very low gauge density and data availability present a challenging scenario for gap-filling methods.

The problem of gaps in data series may be solved theoretically by completing daily flow records from existing data at nearby gauging stations, either upstream or downstream of the same watercourse, although in most existing methods the choice of predictor station may be a critical factor affecting the results (Harvey et al., 2010). Data-driven models such as MissForest are purely empirical and do not consider the complex physical laws in the real world, but as they depend only on the information content in the hydrological data, they are usually easier to develop (Vega-Garcia et al., 2019) and integrate into hydrological information systems, which, combined with a suite of numerical models – physical, statistical or socio-economic – comprise a decision support system for water, energy and natural resources management such as SHEM (Petty and Dhingra, 2018).

According to the goodness-of-fit indicators coefficient of determination (R^2), percent bias (PBIAS) and the Kling-Gupta efficiency (KGE), MissForest achieved satisfactory to good performance, similar to the results of Sidibe et al. (2018) for monthly streamflows in West and Central Africa and Dembélé et al. (2019) for daily streamflows in West Africa using the Direct Sampling method. Remarkably, the performance achieved by MissForest at gap-filling daily streamflows in a data scarce region – central Chile in this case – was comparable to that achieved with alternative methods in data-rich regions such as Mediterranean Europe. For instance, Vega-Garcia et al. (2019) selected 5 out of 240 gauges in the Ebro watershed that presented unimpaired, natural flow regimes with a reliable data range of 30 years of daily weather and flow records and no more than three gaps, achieving R = 0.7 - 0.8 with an advanced ANN model.

The presented results showed that MissForest performance declined for altered flow regimes such as reduced streamflows due to water diversion for irrigation during the dry season and increased streamflows due to surface runoff inputs from urban areas. In such cases, i.e., when the natural flow regime is changed mostly in terms of magnitude, but maintains other properties like frequency, timing and rate of change, MissForest performance is still satisfactory. Severe alterations to the flow regime such as hydropeaking impeded acceptable performance of MissForest for missing-value imputation. The alteration of the natural flow regimes of the studied rivers and streams partly explains the high dispersion observed in MissForest performance. In a heavily modified environment, the hydrological effects of human activity can exceed those caused by climate variability (Somorowska and Łaszewski, 2019); consequently, our future work will concentrate on the automatic reconstruction of altered daily streamflow series.

5 Conclusion

MissForest, a non-parametric stochastic machine learning algorithm, was applied to infill gaps in daily streamflow time series and its performance was assessed. A total of 1,586 reconstructions of streamflows for the 1970-2016 period were developed using data records from 122 gauge stations located in different regulated and unregulated rivers and streams in 11 climatic regions throughout central Chile.

Reconstructed daily streamflow time series of rivers with natural flow regimes were simulated with good performance, with quality similar to that attained in reconstruction of monthly streamflow time series or by applying alternative methods in data-rich regions. Reconstruction of altered flows was more challenging for gap-filling methods. In these cases, MissForest performance slightly decreased for discharge magnitude alterations such as those caused by runoff inputs from urbanized areas and water diversion at water intakes for irrigation. In cases of severe flow regime alterations such as hydropeaking, MissForest failed at filling the gaps in daily streamflow series.

Overall, MissForest presented satisfactory to good performance (R^2>0.6, *PBIAS* ±15%, *KGE* >0.5), allowing a precise, reliable simulation of the missing data quickly and automatically, making it suitable for applications in large data-scarce regions with different climates.

The reconstructed hydrographs for 1970-2016 allow the analysis of streamflow change and variability and their interactions with key climatic variables such as precipitation, temperature and potential evapotranspiration in central Chile.

Acknowledgments: The authors thank the Energy Doctorate Program of the Universidad de Concepción for providing the institutional support to conduct this research.

6 References

Amisigo, B.A., van de Giesen, N.C., 2005. Using a spatio-temporal dynamic state-space model with the EM algorithm to patch gaps in daily riverflow series, with examples from the Volta Basin, West Africa. Hydrol. Earth Syst. Sci. Discuss. 2, 449–481. https://doi.org/10.5194/hessd-2-449-2005

Arriagada, P., Dieppois, B., Sidibe, M., Link, O., 2019. Impacts of Climate Change and Climate Variability on Hydropower Potential in Data-Scarce Regions Subjected to Multi-Decadal Variability. Energies 12, 2747. https://doi.org/10.3390/en12142747

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future köppen-geiger climate classification maps at 1-km resolution. Sci. Data 5, 1–12. https://doi.org/10.1038/sdata.2018.214

Ben Aissia, M.A., Chebana, F., Ouarda, T.B.M.J., 2017. Multivariate missing data in hydrology – Review and applications. Adv. Water Resour. 110, 299–309. https://doi.org/10.1016/j.advwatres.2017.10.002

Bonilla, C., Johnson, O., 2012. Soil erodibility mapping and its correlation with soil properties in Central Chile. Geoderma 189–190, 116–123.

Bonilla, C., Vidal, K., 2011. Rainfall erosivity in Central Chile. J. Hydrol. 410, 126–133.

Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32. https://doi.org/10.1023/A:1010933404324

Carretier, S., Tolorza, V., Regard, V., Aguilar, G., Bermúdez, M.A., Martinod, J., Guyot, J.L., Hérail, G., Riquelme, R., 2018. Review of erosion dynamics along the major N-S climatic gradient in Chile and perspectives. Geomorphology 300, 45–68. https://doi.org/10.1016/j.geomorph.2017.10.016

Dembélé, M., Oriani, F., Tumbulto, J., Mariéthoz, G., Schaefli, B., 2019. Gap-filling of daily streamflow time series using Direct Sampling in various hydroclimatic settings. J. Hydrol. 569, 573–586. https://doi.org/10.1016/j.jhydrol.2018.11.076

Déry, S.J., Stahl, K., Moore, R.D., Whitfield, P.H., Menounos, B., Burford, J.E., 2009. Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. Water Resour. Res. 45, 1–11. https://doi.org/10.1029/2008WR006975

Deshmukh, H., Papageorgiou, M., Kilpatrick, E.S., Atkin, S.L., Sathyapalan, T., 2019. Development of a novel risk prediction and risk stratification score for polycystic ovary syndrome. Clin. Endocrinol. (Oxf). 90, 162–169. https://doi.org/10.1111/cen.13879

Direccion General de Aguas (DGA), 2016. Atlas del agua Chile. Available in http://bibliotecadigital.ciren.cl/handle/123456789/26705

Ellies, A., 2000. Soil erosion and its control in Chile - An overview. Acta Geol. Hisp. 35, 279–284.

Elshorbagy, A.A., Panu, U.S., Simonovic, S.P., 2000. Group-based estimation of missing hydrological data: I. Approach and general methodology. Hydrol. Sci. J. 45, 849–866. https://doi.org/10.1080/02626660009492388

Escobar, F., Aceituno, P., 1998. Influencia del fenómeno ENSO sobre la precipitación nival en el sector andino de Chile Central, durante el invierno austral. Bull. Inst. Fr. Etudes Andin. 27, 753–759.

Falvey, M., Garreaud, R.D., 2009. Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979-2006). J. Geophys. Res. Atmos. 114, 1–16. https://doi.org/10.1029/2008JD010519

Garreaud, R., 2013. Warm winter storms in central chile. J. Hydrometeorol. 14, 1515–1534. https://doi.org/10.1175/JHM-D-12-0135.1

Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 180–195. https://doi.org/10.1016/j.palaeo.2007.10.032

Gyau-Boakye, P., Schultz, G.A., 1994. Filling gaps in runoff time series in west africa. Hydrol. Sci. J. 39, 621–636. https://doi.org/10.1080/02626669409492784

Habit, E., García, A., Díaz, G., Arriagada, P., Link, O., Parra, O., Thoms, M., 2019. River science and management issues in Chile: Hydropower development and native fish communities. River Res. Appl. 35, 489–499. https://doi.org/10.1002/rra.3374

Harvey, C., Dixon, H., Hannaford, J., 2010. Developing best practice for infilling daily river flow data, in: BHS Third International Symposium, Managing Consequences of a Changing Global Environment. pp. 1–8. https://doi.org/10.7558/bhs.2010.ic119

Harvey, C.L., Dixon, H., Hannaford, J., 2012. An appraisal of the performance of data-infilling methods for application to daily mean river flow records in the UK. Hydrol. Res. 43, 618–636. https://doi.org/10.2166/nh.2012.110

Instituto nacional de Estadística (INE), 2018. Síntesis de resultados censo 2017. Available in https://www.censo2017.cl/descargas/home/sintesis-de-resultados-censo2017.pdf.

Kim, M., Baek, S., Ligaray, M., Pyo, J., Park, M., Cho, K.H., 2015. Comparative studies of different imputation methods for recovering streamflow observation. Water (Switzerland) 7, 6847–6860. https://doi.org/10.3390/w7126663

Kling, H., Fuchs, M., Paulin, M., 2012. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. J. Hydrol. 424–425, 264–277. https://doi.org/10.1016/j.jhydrol.2012.01.011

Knoben, W.J.M., Freer, J.E., Woods, R.A., 2019. Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. Hydrol. Earth Syst. Sci. Discuss. 1–7. https://doi.org/10.5194/hess-2019-327

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, M., Habit, E., Link, O., 2016. Hydropower Development, Riverine Connectivity, and Non-sport Fish Species: criteria for Hydraulic Design of Fishways. River Res. Appl. 32, 1949–1957. https://doi.org/10.1002/rra.3040

Liu, J., Zhang, Y., 2017. Multi-temporal clustering of continental floods and associated atmospheric circulations. J. Hydrol. 555, 744–759.

Lopes, A., Chiang, J., Thompson, S., Dracup, J., 2016. Geophysical Research Letters. Geophys. Res. Lett. 43, 1–8. https://doi.org/10.1002/2016GL067738

Mackay, S.J., Arthington, A.H., James, C.S., 2014. Classification and comparison of natural and altered flow regimes to support an Australian trial of the Ecological Limits of Hydrologic Alteration framework. Ecohydrology 7, 1485–1507. https://doi.org/10.1002/eco.1473

Mantua, N.J., Hare, S.R., 2009. The Pacific Decadal Oscillation. J. Oceanogr. 58, 35–44.

Mardones, M., Vargas, J., 2005. Efectos hidrológicos de los usos eléctrico y agrícola en la cuenca del río Laja (Chile centro-sur). Rev. Geogr. Norte Gd. 33, 89–102.

Marino, S., Zhou, N., Zhao, Y., Wang, L., Wu, Q., Dinov, I.D., 2019. HDDA: DataSifter: statistical obfuscation of electronic health records and other sensitive datasets. J. Stat. Comput. Simul. 89, 249–271. https://doi.org/10.1080/00949655.2018.1545228

McGregor, G.R., 2019. Climate and rivers. River Res. Appl. 1–22. https://doi.org/10.1002/rra.3508

Montecinos, A., Aceituno, P., 2003. Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies. J. Clim. 16, 281–296. https://doi.org/10.1175/1520-0442(2003)016<0281:SOTERR>2.0.CO;2

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. Trans. ASABE 58, 1763–1785. https://doi.org/10.13031/trans.58.10715

Muñoz, P., Orellana-Alvear, J., Willems, P., Célleri, R., 2018. Flash-flood forecasting in an andean mountain catchment-development of a step-wise methodology based on the random forest algorithm. Water (Switzerland) 10. https://doi.org/10.3390/w10111519

Mwale, F.D., Adeloye, A.J., Rustum, R., 2012. Infilling of missing rainfall and streamflow data in the Shire River basin, Malawi - A self organizing map approach. Phys. Chem. Earth 50–52, 34–43. https://doi.org/10.1016/j.pce.2012.09.006

Petrone, K.C., Hughes, J.D., Van Niel, T.G., Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950-2008. Geophys. Res. Lett. 37, 1–7. https://doi.org/10.1029/2010GL043102

Petty, T.R., Dhingra, P., 2018. Streamflow Hydrology Estimate Using Machine Learning (SHEM). J. Am. Water Resour. Assoc. 54, 55–68. https://doi.org/10.1111/1752-1688.12555

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784. https://doi.org/10.2307/1313099

Sidibe, M., Dieppois, B., Mahé, G., Paturel, J.E., Amoussou, E., Anifowose, B., Lawler, D., 2018. Trend and variability in a new, reconstructed streamflow dataset for West and Central Africa, and climatic interactions, 1950–2005. J. Hydrol. 561, 478–493. https://doi.org/10.1016/j.jhydrol.2018.04.024

Somorowska, U., Łaszewski, M., 2019. Quantifying streamflow response to climate variability, wastewater inflow, and sprawling urbanization in a heavily modified river basin. Sci. Total Environ. 656, 458–467. https://doi.org/10.1016/j.scitotenv.2018.11.331

Starrett, S.K., Heier, T., Su, Y., Bandurraga, M., Tuan, D., Starrett, S., 2010. An example of the impact that filled-in peakflow data can have on flood frequency analysis, in: World Environmental and Water Resources Congress 2010: Challenges of Change - Proceedings of the World Environmental and Water Resources Congress 2010. pp. 2451–2455. https://doi.org/10.1061/41114(371)252

Stekhoven, D.J., Bühlmann, P., 2012. Missforest-Non-parametric missing value imputation for mixed-type data. Bioinformatics 28, 112–118. https://doi.org/10.1093/bioinformatics/btr597

Tang, F., Ishwaran, H., 2017. Random forest missing data algorithms. Stat. Anal. Data Min. 10, 363–377. https://doi.org/10.1002/sam.11348

Tao, N., Chen, Y., Wu, Y., Wang, X., Li, L., Zhu, A., 2019. The terpene limonene induced the green mold of citrus fruit through regulation of reactive oxygen species (ROS) homeostasis in Penicillium digitatum spores. Food Chem. 277, 414–422. https://doi.org/10.1016/j.foodchem.2018.10.142

Tencaliec, P., Favre, A., Prieur, C., Tencaliec, P., Favre, A., Prieur, C., Mathevet, T., 2015. Reconstruction of missing daily streamflow data using dynamic regression models. Water Resour. Res. 51, 9447–9463. https://doi.org/10.1002/2015WR017399.Received

Tyralis, H., Papacharalampous, G., Langousis, A., 2019. A brief review of random forests for water scientists and practitioners and their recent history inwater resources. Water (Switzerland) 11. https://doi.org/10.3390/w11050910

Ukkola, A.M., Keenan, T.F., Kelley, D.I., Prentice, I.C., 2016. Vegetation plays an important role in mediating future water resources. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/9/094022

Urrutia, R.B., Lara, A., Villalba, R., Christie, D.A., Le Quesne, C., Cuq, A., 2011. Multicentury tree ring reconstruction of annual streamflow for the Maule River watershed in south central Chile. Water Resour. Res. 47, 1–15. https://doi.org/10.1029/2010WR009562

Valdés-Pineda, R., Cañón, J., Valdés, J.B., 2018. Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. J. Hydrol. 556, 1153–1170. https://doi.org/10.1016/j.jhydrol.2017.01.031

Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J.B., Olivares, C., Vera, M., Balocchi, F., Pérez, F., Vallejos, C., Fuentes, R., Abarza, A., Helwig, B., 2014. Water governance in Chile: Availability, management and climate change. J. Hydrol. 519, 2538–2567. https://doi.org/10.1016/j.jhydrol.2014.04.016

Vega-Garcia, C., Decuyper, M., Alcázar, J., 2019. Applying Cascade-Correlation Neural Networks to In-Fill Gaps in Mediterranean Daily Flow Data Series. Water 11, 1691. https://doi.org/10.3390/w11081691

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. https://doi.org/10.1038/nature09440

Waljee, A.K., Mukherjee, A., Singal, A.G., Zhang, Y., Warren, J., Balis, U., Marrero, J., Zhu, J., Higgins, P.D.R., 2013. Comparison of imputation methods for missing laboratory data in medicine. BMJ Open 3, 1–8. https://doi.org/10.1136/bmjopen-2013-002847

WMO, 2008. Guide to Hydrological Practices. Volume I: Hydrology–From Measurement to Hydrological Information, Journal of the Nepal Medical Association. https://doi.org/10.1080/02626667.2011.546602

Zhang, Y., Post, D., 2018. How good are hydrological models for gap-filling streamflow data? Hydrol. Earth Syst. Sci. 22, 4593–4604. https://doi.org/10.5194/hess-22-4593-2018

IV.1.2 Variabilidad y cambio climático sobre el potencial hidroeléctrico nacional

IMPACTS OF CLIMATE CHANGE AND CLIMATE VARIABILITY ON HYDROPOWER POTENTIAL IN DATA-SCARCE REGIONS SUBJECTED TO MULTI-DECADAL VARIABILITY

Pedro Arriagada[1,*], Bastien Dieppois[2], Moussa Sidibe[3] and Oscar Link[4]

[1] Environmental Engineering Department, Universidad de Concepción, Chile; parriagada@udec.cl
[2] Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Coventry, UK; Department of Oceanography, University of Cape Town, South Africa; School of Geography, Earth and Environmental Sciences, University of Birmingham, UK; bastien.dieppois@coventry.ac.uk
[3] Centre for Agroecology, Water and Resilience (CAWR), Coventry University, Coventry, UK; sidibem@uni.coventry.ac.uk
[4] Civil Engineering Department, Faculty of Engineering, Universidad de Concepción, Chile; olink@udec.cl
* Correspondence: parriagada@udec.cl; Tel.: +56-41-2204065

Publicado en: Energies

Abstract: To achieve sustainable development of hydroelectric resources, it is necessary to understand their availability, variability and the expected impacts of climate change. Current research has focused mainly on estimating hydropower potential or determining the optimal locations for hydropower projects without considering the variability and historical trends of the resources. Herein, hydropower potential variability from reconstructed streamflow series estimated with a non-parametric gap-filling method and GIS techniques are analyzed. The relationships between hydropower and large-scale climate variability, expressed by sea surface temperature are explored. Finally, we project hydropower potential through 2050 using 15 global circulation models with RCP 4.5. We used four watersheds in central Chile as a case study. The results show significant interannual and inter-basin hydropower potential variability, with decreasing trends over time modulated by alternating positive and negative decadal trends; these modulations exhibit greater intensities than the general trends and are attributable to climatic oscillations such as El Niño. Future scenarios indicate high hydropower availability and a possible over-investment in hydroelectric plants in two of the four studied watersheds. Results show the need to improve the current policies that promote hydropower development including hydropower resource variability in order to achieve optimal, sustainable hydropower development worldwide.

Keywords: Hydropower Potential Variability, Future Hydropower Scenarios, Climate Variability, Climate Oscillations.

1. Introduction

The world is facing increasing energy demands as a direct consequence of population growth, urbanization, and industrialization. According to the International Energy Agency [1], world gross electricity production reached 25,082 TWh in 2016. In addition, two thirds of electricity generation is based on fossil fuels, with corresponding CO_2 emissions of about 32 million tons, accounting for about 25% of the total global emissions contributing to global warming. To mitigate the effects of climate change, local governments worldwide have been promoting the development of renewable energies through subsidiary policies such as clean development mechanisms and carbon credits [2]. As a result, renewable energies, especially hydropower [3], are undergoing a boom due to their simple engineering, greater efficiency, low energy production cost considering long effective lifetimes and low operating and maintenance costs [4]. Worldwide hydropower potential is estimated at ca. 16,000 TWh [5], and hydropower reached the milestone of 1,000 GW of installed power in 2013. In recent years, the growth of the sector has ranged between 3 and 4%. At this rate, hydropower capacity will double by the late 2030s, with substantial growth expected in Asia, Africa and South America [6]. Effects of climate variability and climate change on water resources, and thus on hydropower potential, introduce important uncertainties that need to be estimated through a proper modelling framework [7]. Naturally, even marginal improvements in the estimation of the installed capacities of hydropower plants could lead to substantial economic and environmental benefits.

Estimation of hydropower, i.e., the product of the specific weight of water, streamflow, and net water head, must include spatio-temporal streamflow and water head patterns. Streamflow is controlled by atmospheric variables such as precipitation and temperature, as well as watershed properties (e.g., topography, soil types and land covers), which together determine surface runoff production. The link between variables controlling hydropower with climate is not trivial. Precipitation, which depends on atmospheric circulation dynamics and orographic effects, is the main driver of streamflow variability [8]. Fabry [9] analyzed the temporal variability of precipitation, proposing that at low-frequency scales, i.e., interannual to centennial, precipitation is controlled by climatic variability, i.e., climatic oscillations. Multiple later works have explored the connections between climatic oscillations and precipitation; e.g., precipitation variability in South America is primarily driven by El Niño South Oscillation (ENSO) at the interannual time-scale and by the Pacific Decadal Oscillation (PDO), Atlantic Multi-Decadal Oscillation (AMO) and the Southern Annular Mode (SAM) at the decadal time-scale [10]. In addition, the temporal variability of water head, which is smaller than that of streamflow, can exhibit long-term dynamics due to gradual geological processes such as tectonics, erosion and sediment transport or due to singular catastrophic events such as volcanism and mega-earthquakes [8].

The effect of climate oscillations on hydropower is a recent line of research; e.g., Ng et al. [11] showed that El Niño (ENSO) climate oscillation strongly influences global hydropower production and causes hydropower production anomalies in South America ranging from -30% to +30% between the different phases. Moreover, the effects of future climate change on hydropower resources introduce another major source of uncertainty for the development of the sector; for instance, van Vliet et al. [7] and Zhang et al. [6] suggest an increase in hydropower potential in the high latitudes of the Northern Hemisphere (North of 55º latitude) and tropical Africa and a decrease in the US, southern Africa, Europe and southern Latin America. Carvajal et al. [12] estimated uncertainty in annual hydropower generation in Ecuador due to climate change at between −55 and +39% with respect to the average historical production. Turner et al. [13] showed that there is no clarity regarding the impacts of climate on hydropower in Latin America, which increases or decreases depending on the specific basin. This absence of consensus highlights a clear need to generate future hydropower scenarios considering the effects of climate variability and change at a reduced scale of analysis, e.g., basin level, to generate sustainable hydropower development policies [5].

In current practice, hydropower potential is estimated by combining geographic information systems (GIS) and hydrology techniques with different levels of complexity at the planetary [5], continental [14], national and local [15,16] scales. Streamflow is determined using surface-runoff hydrological models, from simplified empirical lumped models to watershed-specific distributed hydrological models. The main difficulties of these techniques are: i) the accurate representation of the hydrological processes in runoff generation using simplified models and ii) the availability of the required data for physically- based distributed or semi-distributed modelling, especially for large and data-scarce regions with complex configurations (e.g., orographic effects) [17]. Alternatively, streamflow variability can be obtained by interpolation of existing stream gauge data over the river networks [18]. However, relatively long data series are required to properly represent the different time scales of variability (e.g., intraseasonal to decadal). Gap-filling techniques are thus a good alternative for reconstructing streamflow, especially in data-scarce regions. Suitable methods such as those presented in Breiman [19] and Stekhoven and Bülmann [20] enable uncertainty in hydropower potential estimation to be reduced.

The impacts of climate change on hydropower potential have been evaluated through streamflow projections, which are obtained from hydrological models that use the downscaling projections for precipitation and atmospheric temperature from global circulation models (GCMs) [21]. However, there are errors and uncertainties associated with the precipitation-runoff modelling in hydropower estimations and projections, especially in a data-scarce region [17]. An alternative method to explore and project hydropower resources in these regions is necessary for their sustainable management. In this paper, we hypothesize that the variability of hydropower potential over the lifetime of a hydropower project, i.e., a couple of decades, and in a local area, i.e., basin scale, can be explained by streamflow variability, which in turn is controlled by climate variability, i.e., climate oscillations and trends. If this is the case, future hydropower scenarios can be determined from correlations between observed hydropower potential and sea-surface temperature (SST), and SST projections, obtained from GCM outputs, which will allow us to evaluate the impacts of climate change on hydropower potential in a specific basin. In particular, we evaluate the impacts of climate variability and change on hydropower potential in four major basins of central Chile (in which 76% of the country's hydropower development is concentrated). The observed hydropower potential was estimated from 1970 to 2016, using geographic information system (GIS) techniques and reconstructed daily flow series. The interannual variability of hydroelectric resources was correlated with four climate indices and global-scale gridded SST data. The future hydropower scenarios through 2050 were developed for each basin using the SST projections from 15 GCMs forced with representative concentration pathway (RCP) 4.5, based on the correlations found between SST and observed hydropower potential for each basin. In Section 2, a brief review of hydropower development in Chile and an overview of the study area are presented. Methods are presented in Section 3, including a non-parametric infilling method for stream gauge records and the proposed method for generation of future hydropower scenarios. Section 4 presents the obtained results, highlighting the effects of climate change on hydropower potential. Finally, in Section 5, the implications of the results for hydropower resource management are discussed.

2. Study Area

2.1. Hydropower development in Chile

Due to population and economic growth in Chile, gross electricity generation exhibited a sustained increase from 22.4 TWh in 1996 to 75.5 TWh in 2018, with an expected annual growth rate of 2.5% through 2035 [22]. In 1997, 76% of the country's electricity was generated by hydropower. A severe drought in 1998 caused electric rationing and motivated the generation of electricity using fossil fuels, principally imported natural gas [23]. From that time, the use of hydropower decreased to 27% in 2016 [22]. In line with international concerns about climate change, Chile started to promote renewable energies (according to the Chilean regulatory framework, renewable energy sources include hydropower plants with installed power of up to 20 MW) with laws 20,257 in 2008, and 20,698 in 2013, which are also known as non-conventional renewable energy laws (NCRE). The first forced electricity companies with more than 200 MW of installed power that make energy withdrawals from the interconnected system to prove that 10% of the withdrawals are from renewable sources. The second increased this fraction from 10 to 20%. The implementation of these two laws caused an explosion of small hydropower plant (SHP) development in the country (Figure 12), as 27 new SHP were built between 2008 and 2012, with 60% of these plants located in four basins of central Chile (Maipo, Maule, Bío Bío and Bueno rivers). In addition, 38 new SHP were built between 2012 and 2016, almost exclusively in these four basins. Furthermore, hydropower development in the country is expected to be concentrated in the Bío Bío and Bueno basins [24].

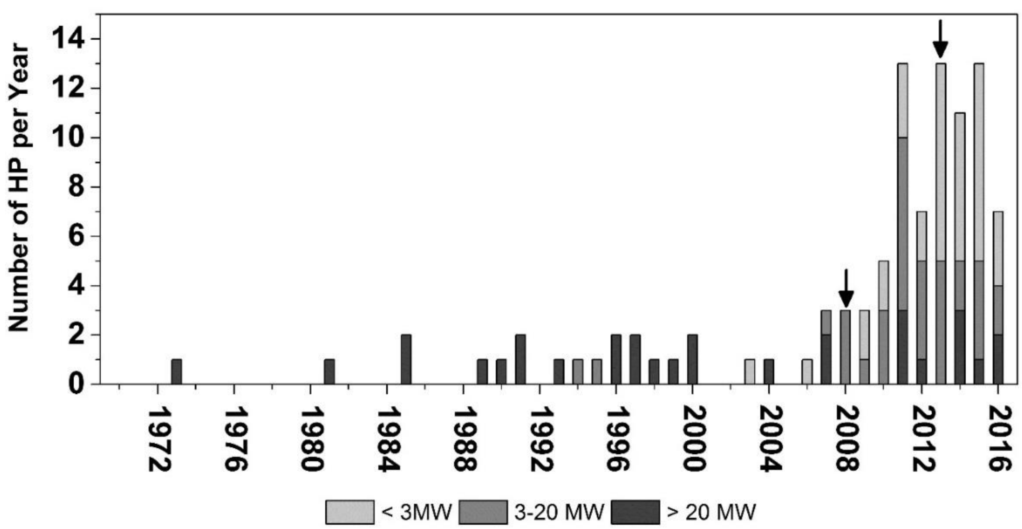

Figura 12. Installed hydropower plants (HP) in Chile between 1970 and 2016. Arrows indicate years of NCRE policy implementation.

In 2015, the Chilean Ministry of Energy estimated the exploitable hydropower of the country at 12 GW, spread among 1200 sites [25]. For this estimation, the flow was estimated with the variable infiltration capacity (VIC) hydrological model [26], and water head was computed as the altitude difference between the water intake and restitution of each site. Only sites with exploitable hydropower were considered in the analysis, i.e., sites which have already been assigned water rights for hydropower production [27], but without considering hydropower potential variability and trends. Currently, Chile aims to satisfy at least 70% of its electricity demand with renewable energies by 2050 [28].

2.2 Study basins

The study area is composed of four major basins in Chile located between 32.55 and 41.17°S, with a surface area of about 15,000 km^2 [29] and maximum altitudes ranging between 2,410 and 6,546 m, from the Pacific Ocean to the Andes. These basins include 91 of the 148 existing hydropower plants in Chile, with a total power of 5.05 GW, i.e., 76% of the national installed hydropower [24]. In addition to these existing projects, 30 new hydropower plants with 0.65 GW are under environmental evaluation or construction. Figure 13 shows the location of the study area, existing hydropower plants and hydropower plants under evaluation.

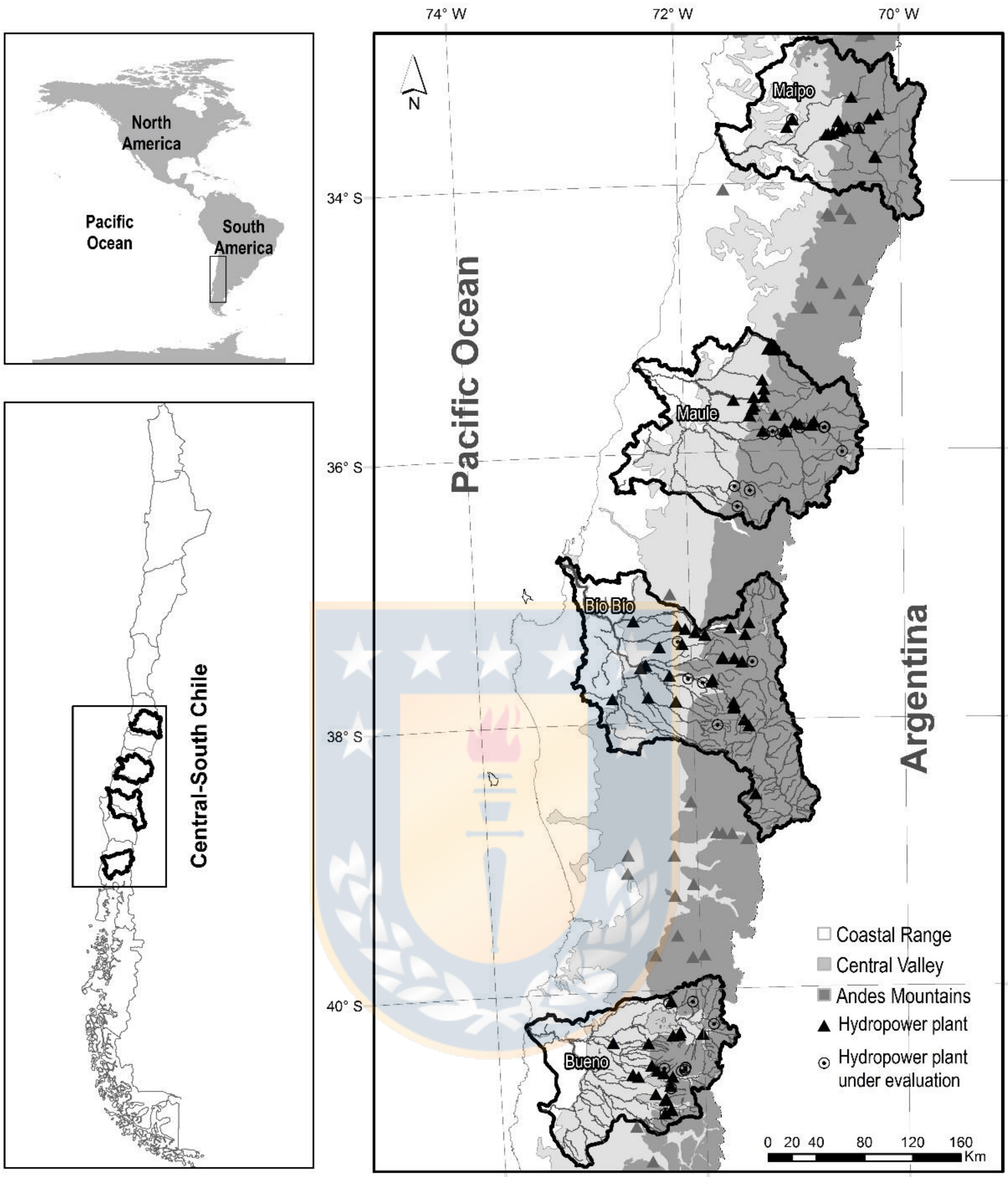

Figura 13. Location of the study area and installed and planned hydropower plants.

According to Köppen's classification, the region is primarily characterized by warm temperature with winter rainfall (Csb) between 30° and 38°S and by warm temperature with rainfall and Mediterranean influence (Cfsb) between 38° and 42°S [30]. Precipitation increases with latitude and altitude between 30° and 40°S. The rivers in the area are steeply graded and show great potential for hydroelectric energy production with mean annual discharges at their mouths ranging between 134 and 971 m^3/s [31]. Table 4 shows the main hydro-climate parameters of the four basins. In addition, climate variability in the area is dominated by ENSO at the interannual scale and the interdecadal oscillations of the PDO, AMO and SAM [32].

Tabla 4. Location, geomorphological and climate data for each basin in the study area.

Basin	Latitude (° ')	Longitude (° ')	Area (km²)	Andean Area (km²)	Maximum height (m)	Dominant Climate	Q_{MA} (m³/s)
Maipo	32°55'-34°18' S	69°48'-71°38' W	15,273	7,781	6,546	Csb	134
Maule	35°06'-36°35' S	70°21'-72°27' W	21,052	10,163	3,931	Csb	495
Bío Bío	36°52'-38°54' S	70°50'-73°12' W	24,369	12,235	3,487	Csb-Cfsb	971
Bueno	39°54'-41°17' S	71°40'-73°43' W	15,366	4,165	2,410	Cfsb	394

2.2.1 Streamflow data

Streamflow in the study area is monitored at 232 streamflow gauges (SFG); however, the records present important information gaps in some cases. In this work, only gauges with more than 10 years of records were considered, i.e., 100 SFG. Figure 14 (A to D) shows the average missing streamflow data per year between 1970 and 2016 for these 100 gauges. Additionally, Figure 14 (E) shows the gap lengths. Note that there are three groups, short gaps lasting from 1 to 2 days (37% of gaps), medium gaps lasting between 14 and 60 days (38% of gaps), and long gaps lasting at least 365 days (4% of gaps).

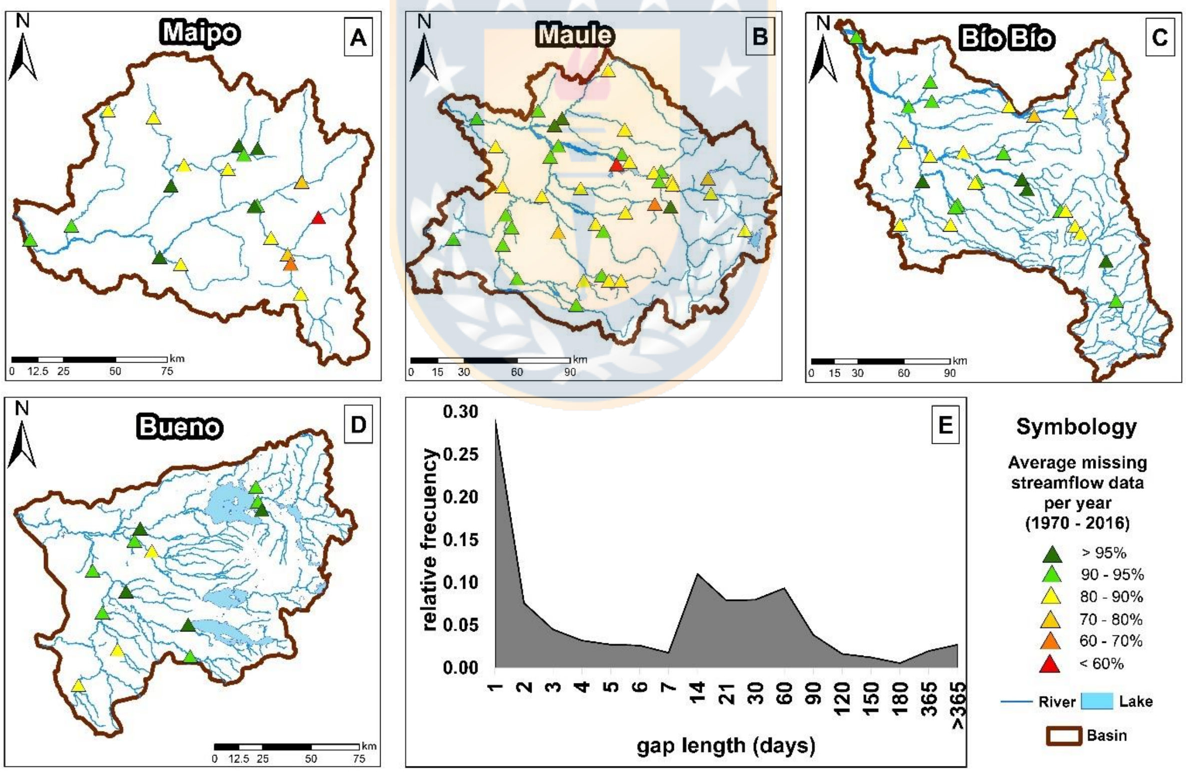

Figura 14. Available streamflow data between 1970 and 2016.

3. Methods

3.1 Gap filling method

As proposed in Sidibe et al. [33], streamflow data were reconstructed using the non-parametric random forest (RF) method [19] to produce a complete data set with no missing values. The method consists of predicting missing values using the RF trained on observed values. This method is particularly effective at accounting for complex interactions in non-linear datasets [20] such as streamflow data. For a given gauge X_i in the streamflow dataset, four different groups were generated: the observed values of the variable X_i (Y_i *obs*), the missing records of the variable X_i (Y_i *miss*), the other variables with observed values coinciding with observation data of X_i (X_i *obs*) and the other variables with observations coinciding with missing data of X_i (X_i *miss*). The initial step consists of a mean imputation of missing values. Each variable is then sorted according to the amount of missing data and ranked in increasing order. For each variable X_i, an RF is trained with response Y_i *obs* and predictors X_i *obs*. The relationship is then applied to Y_i *miss* to predict missing values. The process is iterated until the difference (*Δ*) between the newly imputed dataset and the previous one increases. Then, for *N* variables *Δ* was estimated by:

$$\Delta = \frac{\sum i \in N\left(X_{new}^{imp} - X_{old}^{imp}\right)^2}{\sum i \in N\left(X_{new}^{imp}\right)} \quad (1)$$

Following Sidibe et al. [33], we used 1000 trees and a maximum number of iterations set to 100. RF daily streamflow data filling performance was tested by creating artificial gaps at a random gauge. First, we randomly deleted a different number of observed daily flows (30, 60, 90, 120, 180 and 365) to assess the accuracy of the algorithm at filling the short gaps (1-2 days). Second, we randomly deleted a different number of continuous observed daily flows (7, 14, 21, 30, 60, 180 and 365) at each gauge to assess the accuracy of the algorithm at filling the medium and long gaps. In both cases, we repeated the process 400 times (100 for each basin) and compared the RF-filled series with the observed data using the goodness of fit indicators (GoF), coefficient of determination (R^2) and the percent bias (*PBIAS*), as recommended by Moriasi *et al*. [34]. We also used the modified Kling-Gupta efficiency (*KGE*) [35] instead of the Nash Sutcliffe efficiency (*NSE*), as the KGE criterion ensures that the temporal dynamics (measured by the correlation coefficient), as well as the distribution of flow (measured by the bias and variability ratio), are well represented [35]. The optimal values of R^2 and *KGE* are one and zero in the case of *PBIAS*, the recommend values for a satisfactory performance of simulated data are R^2>0.6 and *PBIAS* ±15% [34], and *KGE* >0.5 [33].

3.2 Historical hydropower potential

Hydropower potential in the 1970-2016 period was computed at every 1 km-long river reach in the study basins. Figure 15 shows the flowchart for estimating the hydropower potential. A 30x30-m-resolution digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission [36]. A virtual streamflow network (VN) similar to the actual river networks obtained from the General Water Directorate of Chile [29] was created in each study basin. The VN was split into 1-km-long river reaches. At each reach, we calculated the water head as the difference in the upstream and downstream elevation from the DEM.

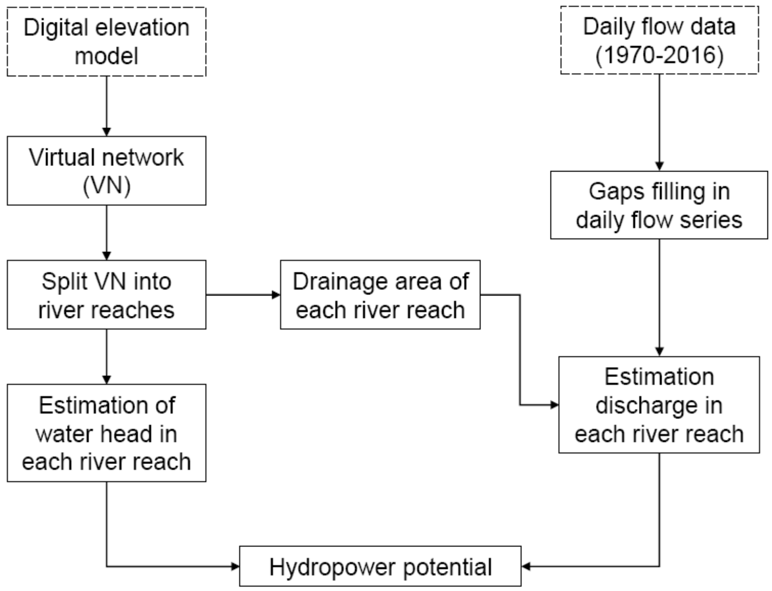

Figura 15. Flowchart for estimation of hydropower potential. Dashed lines represent the input data.

For each reach the hydropower *P* was estimated as:

$$P_{i,y} = \gamma Q_{30_{i,y}} H_i \tag{2}$$

Where γ is the specific weight of water equal to 9,810 N/m^3; $Q_{30i,y}$ is the discharge with 30% exceedance probability in the reach *i* in the year *y*; H_i is the water head of the reach *i*. For each basin, the hydropower potential for the year *y* was then computed as follows:

$$P_{basin,y} = \sum_{i=1}^{n} P_{i,y} \tag{3}$$

Where $P_{basin,y}$ is the hydropower potential in the basin for the year *y*, while *n* is the number of reaches in each basin. Reaches presenting less than 100 kW were deemed to be without exploitable energy.

3.2.1 Estimation of discharge in each river reach

Discharges with a 30% exceedance probability were calculated for each year at each SFG using the filled daily flow series and were then interpolated for every 1-km reach of the VN, transposing those of the nearest SFG by contributing area [18]:

$$Q_{30_{i,y}} = Q_{30_{SFG_{n,y}}} \frac{A_i}{A_{SFG_n}} \tag{4}$$

Where $Q_{30SFGn,y}$ is the Q_{30} in the SFG *n* for the year *y*, A_i is the drainage area of the reach *i*, A_{SFGn} is the drainage area of the SFG *n* and $Q_{30i,y}$ is the discharge at reach *i* for the year *y*.

3.3 Trends in hydropower potential

Trends in hydropower potential between 1970 and 2016 were determined using the Mann-Kendall test [37,38]. This test is widely used to detect trends in hydrological series, as it is a powerful tool for detecting monotonic trends [39]. As the statistical significance of the Mann-Kendall test is strongly sensitive to serial correlations [40], a variant accounting for serial correlation, which was developed by Yue [41], was used. Also, to evaluate the significance of the trends, we used the normalized test statistic Z [42] and *P-value*. In addition, for confidence levels of 99%, 95% and 90%, the null hypothesis of no trend is rejected if $Z > 2.575$, 1.960 and 1.645, respectively [42].

The magnitude of the historical hydropower potential trend was estimated through Sen's slope [43], as this approach is less sensitive to outliers and therefore provides a better estimate of slope for skewed data compared to regression methods, giving a robust estimation of the trend [39]. In addition, multi-temporal trend analysis was implemented [44,45]. This approach consists of calculating the trend for all possible segments (with a minimum length of 8 years) in the study period. For each time series, the multi-temporal trend analysis generates a diagram in which each possible pair of start and end dates is associated with a trend value.

3.4 Correlation between hydropower potential and long-term climate variability

Interpretations of global correlation patterns between hydropower potential and large-scale climate variability were first examined using four climate indices: PDO [46], NINO 3.4 [47], SAM [48] and AMO [49]. These indices were correlated with hydropower potential between 1970 and 2016. Relationships between hydropower and large-scale climate variability were then more objectively investigated through global SST. SST data sets from the extended reconstructed SST version 5 (ERSST.v5) from the National Climatic Data Center (NCDC) were used. At each grid point of the ERSST.v5 data sets from 1970 to 2016, Pearson's product moment correlation coefficients between SST and hydropower potential were computed. An ERSST.v5 gridded data set was generated using *in situ* data from the Comprehensive Ocean-Atmosphere Data Set (COADS) release 3, which employs new bias adjustments, quality control procedures and analysis methods, allowing for a reconstruction of sparse data over a 2° x 2°-resolution grid [50,51].

3.5 Developing future scenarios for hydropower potential amid climate change

Future hydropower potential scenarios in the four study basins were developed based on large-scale climate variability using 15 GCMs [52] for the 1970-2050 period. Historical runs and projection simulations forced with a representative concentration pathway, RCP 4.5 [53], were used. These long-term integrations are initiated from multi-century preindustrial control integration [52], and are consistent with a midrange mitigation emissions scenario. The GCMs used in this study are listed in Table 2. The set of GCMs includes models with different spatial resolutions and degrees of complexity. However, in our study all ocean grids have been remapped on a regular 2° x 2°-resolution grid using bilinear interpolation (*i.e.*, the same resolution as ERSSTv.5). In addition, to account for the contribution of internal climate variability, we used all individual members (Real Nb. in Table 5), *i.e.,* a total of 45 simulations.

Empirical statistical downscaling models were built in the following steps. First, the long-term mean for each data set (*i.e.,* ERSSTv.5,1970-2016, and GCMs, 1970-2050) was subtracted from that data at each grid point, and two data sets were then combined along the time axis to form a single data set covering the 1970-2050 period [54,55]. Second, a standard empirical orthogonal function (EOF) analysis [56] was applied to the anomalies of the combined data set with the common grid. The eigenvectors from the EOF analysis represent patterns of variability common to both ERSST.v5 and GCMs. The EOF analysis applied to the combined dataset was referred to as the common EOF analysis [54,55]. Third, using a stepwise screening process based on the Akaike information criterion (AIC) [57], a multiple linear regression analysis between the predictand (*i.e.,* observed hydropower potential) and the principal components (PCs) of the 20 leading EOFs of the combined data set (ERSST.v5 + GCMs) was performed to decide the number of PCs to include as predictors in the final models. During stepwise screening, a model that minimizes loss of information in simulating historical hydropower potential (*i.e.*, with a minimum AIC value) was retained for the downscaling process. A leave-one-out cross-validation was then performed to assess the prediction skill of the models. The leading 20 EOFs were used to allow the use of more regional detail in predictor fields in the downscaling models. Before model calibration, the best-fit linear trend was subtracted from each grid point in the observed predictor values (ERSST.v5) and from the predictand (hydropower estimations), as the presence of a linear trend may introduce systematic biases to the model calibration [58]. The downscaling models were calibrated with the part of the combined PCs that represents the actual observations (*i.e*. ERSST.v5), and for future projections the downscaling was generated using part of the combined PCs that represents the GCM simulations.

Tabla 5. Summarized information on CMIP5 models used in the study**.**

	Institution	Name	Real Nb.	Variable	Hist. period
CMIP5 Models (Historical + RCP4.5 runs)	BCC, China	bcc-csm1-1	1	SST	1970-2050
		bcc-csm1-1-m	1		
	CCCma, Canada	CanESM2	5	SST	1970-2050
	CMCC, Italy	CMCC-CM	1	SST	1970-2050
		CMCC-CMS	1		
	CNRM, France	CNRM-CM5	1	SST	1970-2050
	CSIRO-BOM, Australia	ACCESS1-0	1	SST	1970-2050
		ACCESS1-3	1		
	CSIRO-QCCCE, Australia	CSIRO-Mk3-6-0	10	SST	1970-2050
	NASA-GISS, USA	GISS-E2-H	6	SST	1970-2050
		GISS-E2-R	6		
	NCAR, USA	CCSM4	6	SST	1970-2050
	NOAA-GFDL, USA	GFDL-CM3	3	SST	1970-2050
		GFDL-ESM2M	1		1970-2050
	NSF-DOE-NCAR, USA	CESM1-BCG	1	SST	1970-2050

4. Results and discussion

4.1. Gap-filling perfomance

Figure 16 shows the validation results of the RF method of filling gaps, as determined through R^2, PBIAS, and KGE. Regarding random gaps (left column), all boxes are over the recommended value for R^2 and KGE and are within the recommended values for PBIAS, suggesting a satisfactory performance at least 75% of the times the gaps were filled; thus, RF presented good gap-filling performance. Regarding continuous gaps (right column), different behaviors are observed regarding the filling of medium and long gaps using RF. For long gaps, the three indicators are over the recommended values (within the recommended values for PBIAS), suggesting that RF is good at filling long gaps (> 365 days). In the case of medium gaps, RF performs worse, but R^2 the median is above the recommended value, indicating good performance at least 50% of the time. The PBIAS are also within the recommended values, except in the first percentile for gaps with lengths of 60 and 180 days, which means that RF tends to slightly overestimate the value of the daily flow in these cases. In addition, the most scattered results occurred for medium gaps according to PBIAS. Finally for KGE, the median is above the recommended value, except for 7-day gaps, indicating that at least 50% of the time RF performs well. Therefore, RF performs well at filling short and long gaps, but presents some deficiencies regarding the filling of medium gaps, tending to slightly overestimate the daily flow and have some difficulty filling the 7-day gaps. Furthermore, as our streamflow data were dominated by short and long gaps, and medium gaps longer than 14 days (Figure 16), and in agreement with Moriasi et al.[34] and Sidibe et al.[33], the results suggest that the RF method has a good gap-filling performance.

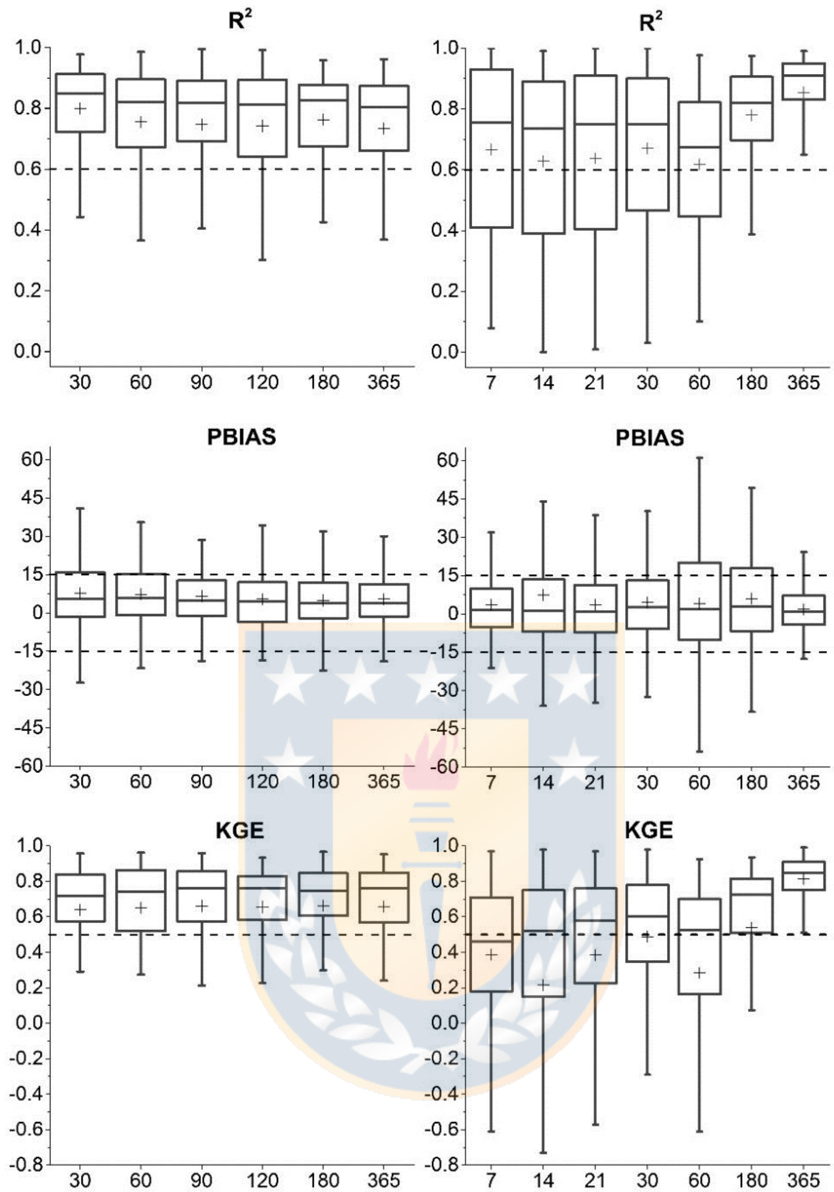

Figura 16. Validation of the RF method of filling the gaps in daily flow series, as determined through R^2, PBIAS and KGE. The left column shows the results for the random gaps and the right column shows the results for random continuous gaps. The crosses indicate the mean value and the dashed lines represent the recommend value.

4.2. Hydropower potential variability and trends

Figure 17 shows the time evolution of hydropower potential, and corresponding boxplots illustrating the variability, between 1970 and 2016 in the four study basins. Substantial variations and inter-basin differences are detected in all basins (Figure 17). For instance, in 1997, the Maule, Bío Bío and Bueno basins presented a high hydropower potential (7.15, 8.71 and 4.40 GW respectively), which drastically decreased in 1998 (2.58, 2.59 and 1.84 GW respectively). A similar behavior was identified in Maipo, but in different years (Figure 17): in 1986, the potential was 2.89 GW, increasing to 4.85 GW in 1987. As evidenced by the boxplots, the greatest variability is identified in the Bío Bío and Maule basins, with maximum differences of

8.23 and 6.29 GW, respectively (Figure 17). In addition, all basins show a decreasing trend from 1970 to 2016 (Figure 17). This is confirmed in Figure 18, which summarizes the statistics of the Mann-Kendall trend tests. The *S* statistics show decreasing trends in all basins. *Z* and *p* values show that the identified trends are significant at the 95% confidence level. A less pronounced trend is found in Bío Bío (Figure 18), and could reflect the climate transition zone defined by Muñoz et al. [59]. Sen's slope shows maximum decreasing rates between -47 and -45 MW/year in Bío Bío and Maule, respectively (Figure 18), where the highest hydropower potential variability was found (Figure 17). The smallest decreasing rates are observed in Maipo and Bueno (-23 and -22 MW/year, respectively; Figure 18), where the smallest hydropower potential variability was found (Figure 17). These results were consistent with reported precipitation [60,61] and river discharge trends [62,63].

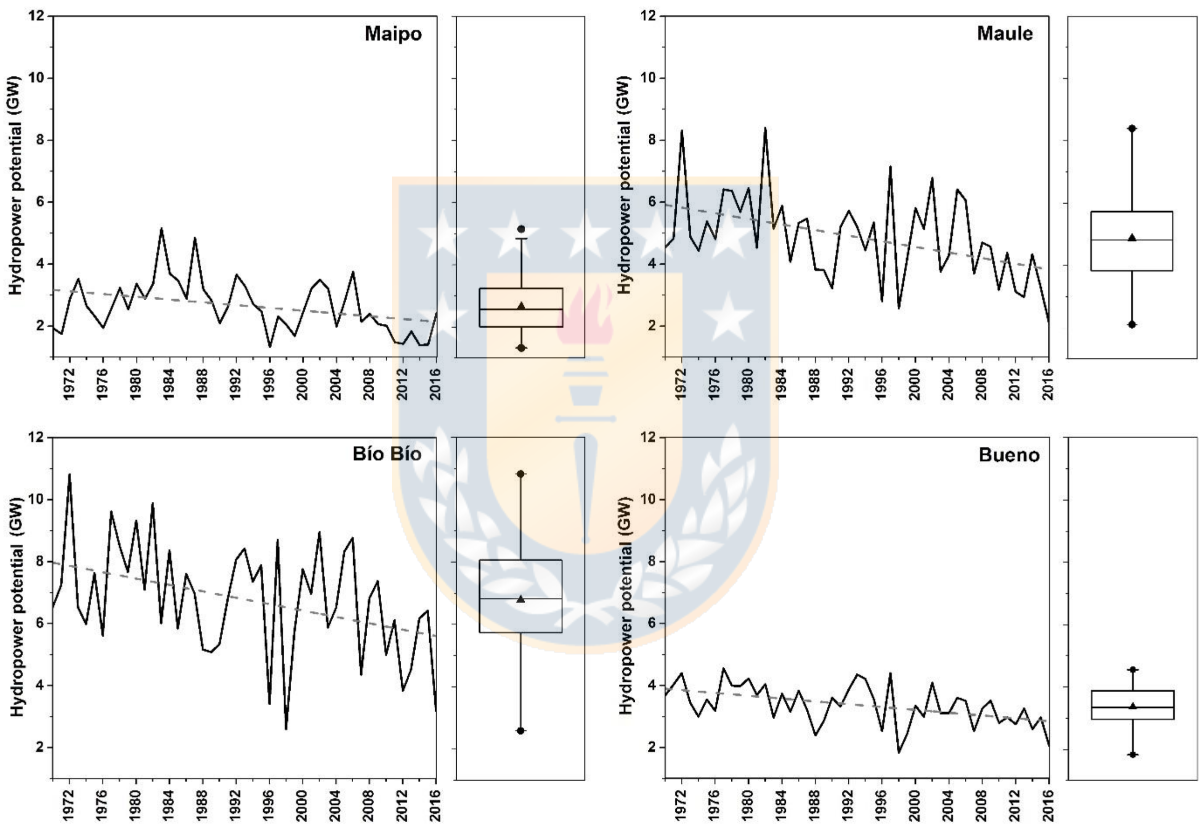

Figura 17. Time evolution of hydropower potential, and corresponding boxplots, between 1970 and 2016 in the four study basins. Dashed lines represent the trend. In the box plots, black circles show the maximum and minimum values, while the black triangle represents the mean value.

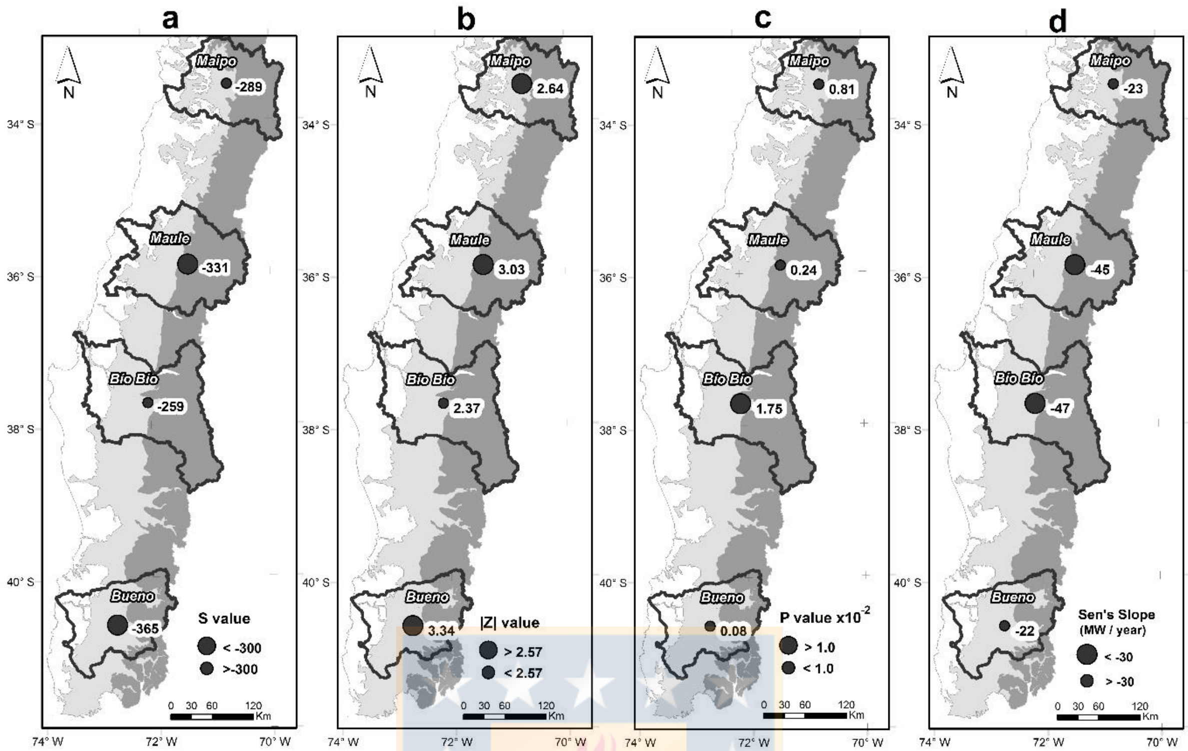

Figura 18. Hydropower trends in the four study basins. S value (a), Z values (b), p-values (c), and Sen's slope (d).

The relative importance of variability and trends in hydropower between 1970 and 2016 is analyzed using multi-temporal trend analysis in Figure 19.

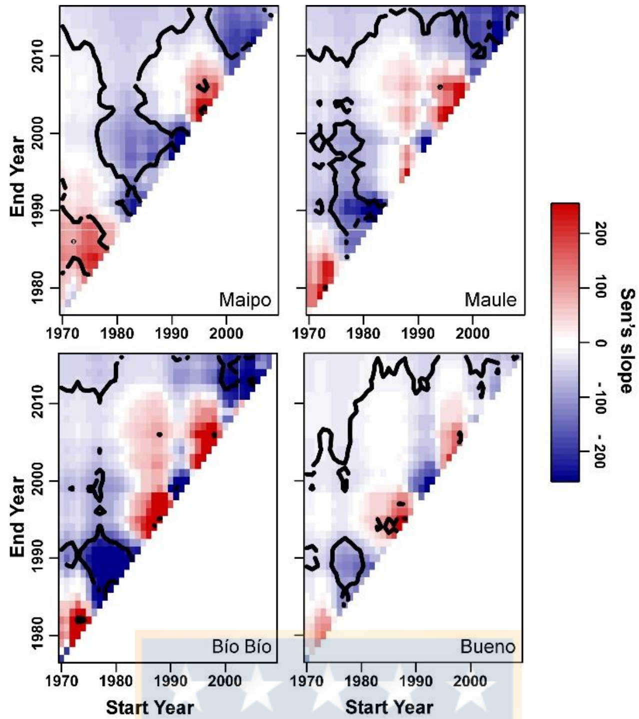

Figura 19. Multi-temporal trend diagrams for hydropower potential between 1970 and 2016 in the four study basins. Trends in MW are presented in red (positive), white (null) and blue (negative). Contour lines indicate the statistical significance at the 95% confidence level (p = 0.05).

Significant decreasing trends, at the 95% confidence level, are identified in all basins for periods greater than 40 years (upper left corner in each graph in Figure 19), consistent with the results obtained in Figure 18. Additionally, blue, *i.e.,* decreasing trends, is more frequent than red, especially in the recent period (2000 onward) in all the basins (Figure 19). Furthermore, alternating positive and negative trends, modulating the general trend, are observed in all basins over periods shorter than 20 years (Figure 19). These modulations show stronger magnitude than the general trend. For instance, the general trend in Maipo over the entire period was -23 MW·year^{-1} (Figure 18), but increasing and decreasing trends greater than 100 MW·year^{-1} were observed between 1970 to 1980 and 1980 to 1990, respectively (Figure 19). Similar results are found in Maule, Bío Bío and Bueno but in slightly different periods (Figure 19), suggesting different regional patterns. For instance, between 1970 and 1980, a significant (p=0.05) increasing trend was found only in Maipo (Figure 19), while the other basins present a weak increasing trend (Maule and Bío Bío) or no trend (Bueno), and in 1976 a significant decreasing trend begins (Maule, Bío Bío and Bueno), contrary to the increasing trend in Maipo.

These results highlight interannual to decadal modulations in hydropower potential in Chile, which are related to large-scale climate controls. In addition, regional patterns in hydropower variability were identified.

4.3 Correlation between hydropower potential and long-term climate variability

Figure 20 shows the correlation between hydropower potential and climate indices in the study basins.

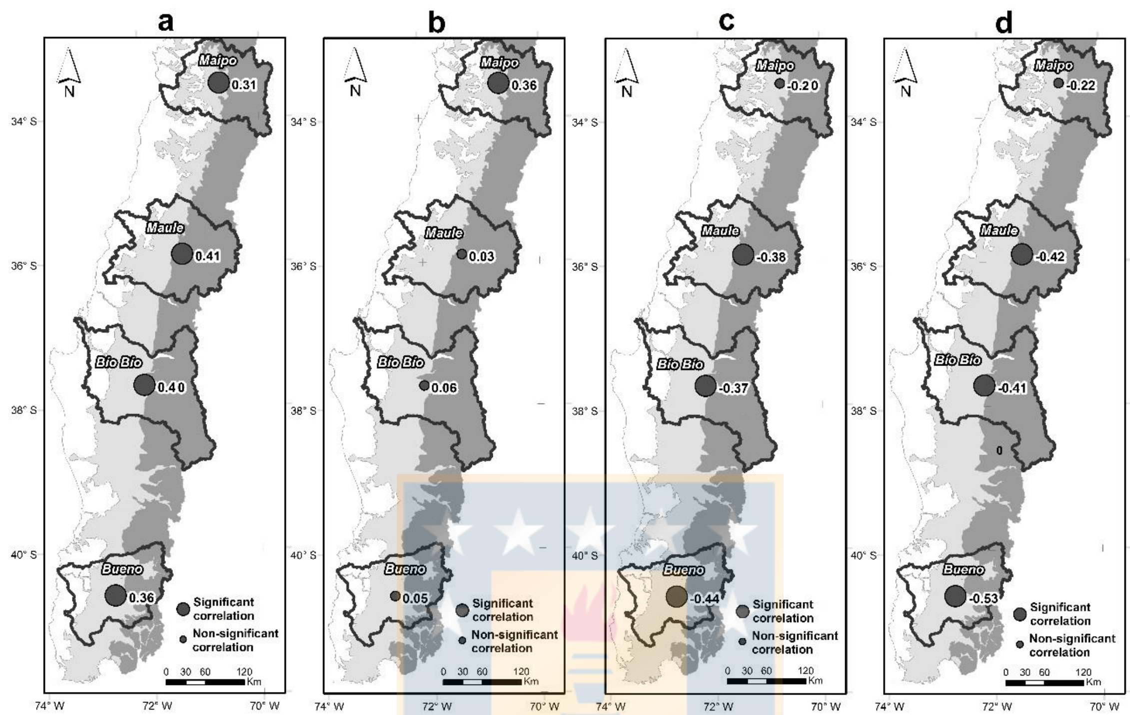

Figura 20. Correlation between hydropower potential and ENSO (a), PDO (b), SAM (c), and AMO (d) in the study basins.

Significant correlations between the Nino 3.4 index and hydropower were detected (Figure 20). This relationship is consistent with results from previous studies [61,62,64], which describe a strong ENSO impact on rainfall and streamflow variability in Chile. Significant correlations between the PDO index and hydropower potential, at a 95% confidence level, were detected only in Maipo (Figure 20), consistent with the regional patterns identified in Figures 17 and 19. This is also consistent with the findings of Valdés-Pineda et al. [65] and suggests important contributions of decadal climate fluctuations to hydropower potential in the northernmost basin. The correlation between hydropower potential and the AMO index indicates an influence of Atlantic SST on hydropower potential in the southern basins (Figure 20), consistent with the findings of Valdés-Pineda et al [65]. Similarly, the correlation between hydropower potential and the SAM index indicates an influence of Antarctic oscillation on hydropower potential in the southern basins (Figure 20).

Figure 21 shows pointwise correlations between global SSTs and hydropower potential between 1970 and 2016. Hydropower potential in all basins between 1970 and 2016 is significantly correlated, at a 95% confidence level, with SST anomalies in the Pacific Ocean (Figure 21): positive correlations in the tropical Pacific flanked by a horseshoe pattern of the opposite sign. This correlation pattern highlights the strong relationship between hydropower potential and ENSO in Chile. Some regional differences, however, emerge in the relationship between hydropower potential and global SSTs. Maipo is significantly negatively correlated with SST anomalies in the northern North Pacific, while there is no significant correlation in the southern basins (*i.e.,* Maule, Bío Bío and Bueno), confirming the influence of the PDO observed in Figure 20. At the same time, hydropower potential in southern basins (Maule, Bío Bío and Bueno) shows significant correlations with SST anomalies in the North to equatorial Atlantic (Figure 21), confirming the influence of the AMO observed in Figure 20. Hydropower potential in the basins south of Maule is significantly correlated with dipolar SST anomalies in the Southeast Pacific off the Chilean coast (Figure 21). This South Pacific dipolar SST anomaly could be associated with southward shifts of the mid-latitude westerlies, leading to colder than normal SSTs in the South and warmer than normal SST in the North of westerlies climatological location. This last result is consistent with the significant correlation between hydropower potential in the basins south of Maule and the SAM index, highlighting a greater sensitivity to regional changes in the mid-latitude westerlies in this region in accordance with Gillet et al.[66] and Quintana and Aceituno[60].

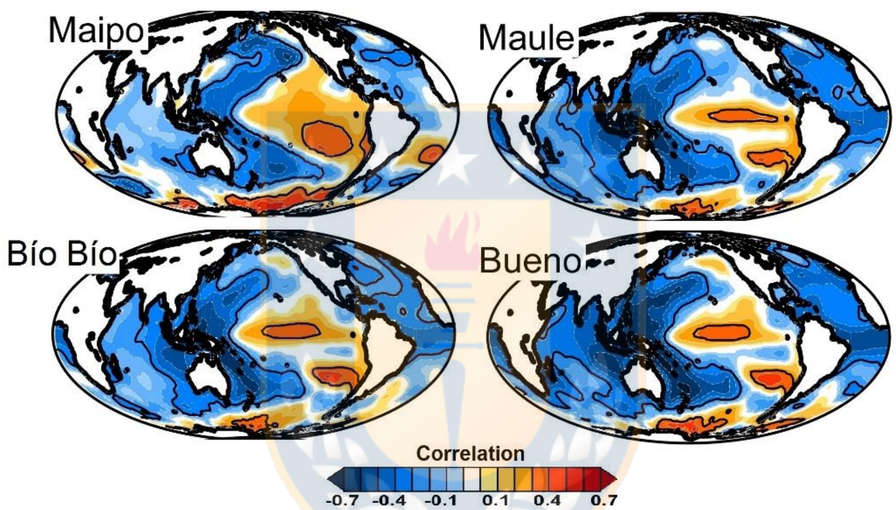

Figura 21. Pointwise correlations between hydropower and global SSTs between 1970 and 2016. Black contours indicate statistical significance at p = 0.05 according to the Pearson's product moment correlation coefficient.

In summary, hydropower potential in the four studied basins is primarily related to ENSO, with correlations greater than 0.65 in central Pacific, Figure 21. However, some regional differences appear in the relationships between large-scale climate variability and hydropower potential. For instance, hydropower potential in the basins south of Maule is also strongly related to SST anomalies in the Atlantic Ocean and appears very sensitive to changes in the mid-latitude westerlies. This suggests that a global domain is preferable to different regional domains (*e.g*., equatorial Pacific, North and South Pacific, North Atlantic) when developing the future scenarios based on the relationship with large-scale climate variability.

4.4 Future scenarios for hydropower amid climate change

Figure 22 shows the hydropower potential and installed hydropower capacity in the four study basins in the 1970-2050 period. The prediction skill of the models is summarized by the Pearson's correlation values between calibration and validation data.

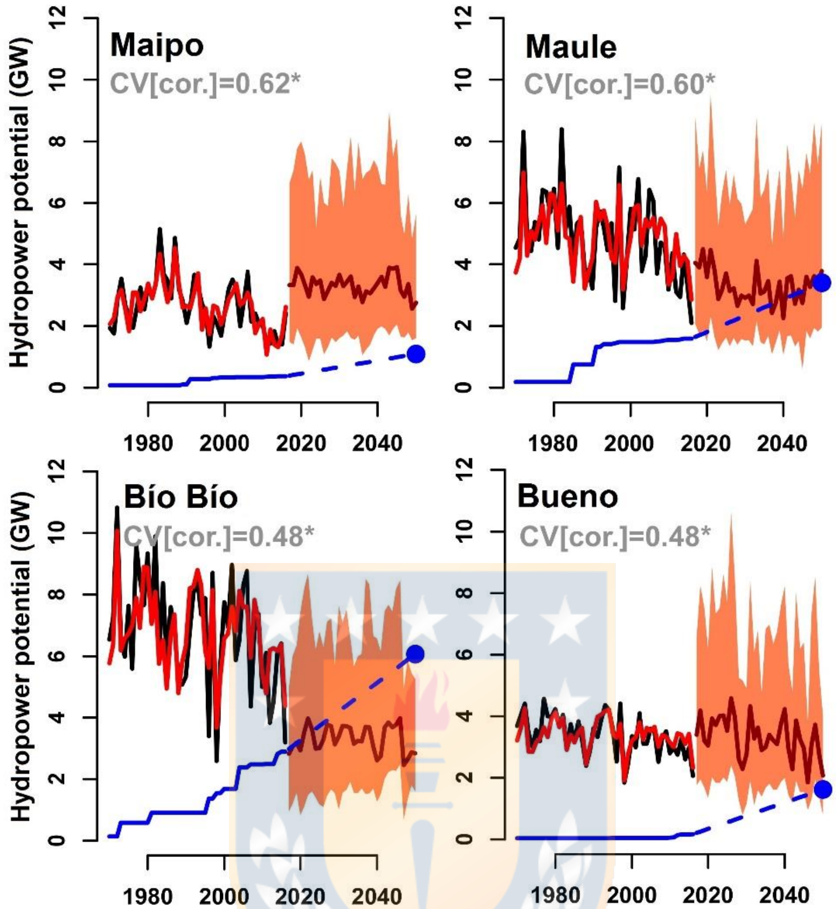

Figura 22. Hydropower potential and installed hydropower capacity in the four study basins in the 1970-2050 period. Black lines show observed hydropower potential. Red lines indicate computed hydropower over the calibration period. Dark red lines and associated coral polygons display the mean, max and min projected hydropower potential using all simulations from 15 GCMs (*i.e.,* 45 simulations). Installed hydropower capacity is displayed as blue lines, while blue dots indicate projected installed hydropower capacity. Results of the leave-one-out cross-validation are shown in grey.

The model skills were generally stronger in Maipo and Maule than in Bío Bío and Bueno (Figure 22). As also highlighted in Figure 19, northern basins showed more pronounced low-frequency variability and trends, which enhance predictability for the northern basins. Overall, the correlation coefficients between calibration and validation data are significant at $p = 0.05$, and range between 0.48 and 0.62 (Figure 22), suggesting moderate to good prediction skills. Statistical downscaling models performed well at simulating historical hydropower potential (1970 – 2016) in all basins. Observed discrepancies between the hydropower potential predictions of the different models could arise from discrepancies between the different GCMs, as well as between simulations of the same model, when computing future global SST variability (IPCC 2014). For instance, the future trends of ENSO, which is an important driver of hydro-climatic variability in Chile, are heavily model-dependent and generally within the range of natural variations [68].

Table 6 shows the average change in hydropower potential between the historic period and the projections obtained for the four study basins. The mean and median projected hydropower potential (2017-2050) remain in the same range as observed hydropower potential (1970-2016), suggesting high hydropower availability during the next 30 years. Nevertheless, the extreme values (minimum and maximum) present the greatest expected variations: the minimum values in Maipo, Maule and Bío Bío decrease by 40.4%, 30.9% and 13.9%, respectively; the maximum value decreases by 6.1% in Maipo, while it increases by 7.9% and 8.2% in Bío Bío and Bueno. In addition, Table 7 shows the results of the hydropower trend analysis of the future period, *i.e., S*, *Z* and *p-values* statistics, as well as Sen's slope. Projected hydropower presents decreasing trends in Maipo, Bío Bío, and Bueno at rates of -43, -25 and -40 MW/year, respectively (Table 7). Meanwhile, no projected hydropower potential trends are detected in Maule, in contrast with the decreasing trend observed in the past.

Tabla 6. Average projected change in hydropower potential in the four study basins.

		Hydropower potential (GW)		
Basin	**Statistic**	**Historic (1970-2016)**	**Future (2017-2050)**	**% change**
Maipo	Max.	5.15	4.84	-6.1%
	75%	3.23	3.21	-0.4%
	50%	2.58	2.64	2.3%
	25%	2.03	2.10	3.4%
	Min.	1.33	0.79	-40.4%
	Mean	2.66	2.67	0.5%
Maule	Max.	8.39	8.54	1.8%
	75%	5.71	5.77	1.1%
	50%	4.81	4.88	1.3%
	25%	3.95	3.96	0.2%
	Min.	2.10	1.45	-30.9%
	Mean	4.87	4.87	0.0%
Bío Bío	Max.	10.82	11.68	7.9%
	75%	7.97	7.99	0.2%
	50%	6.82	6.79	-0.5%
	25%	5.79	5.54	-4.3%
	Min.	2.59	2.23	-13.9%
	Mean	6.78	6.79	0.1%
Bueno	Max.	4.56	4.93	8.2%
	75%	3.86	3.78	-2.1%
	50%	3.35	3.36	0.2%
	25%	2.97	2.96	-0.4%
	Min.	1.84	1.87	2.1%
	Mean	3.37	3.37	0.0%

Tabla 7. Trend analysis of future period (2017 – 2050).

Statistic	**Maipo**	**Maule**	**Bío Bío**	**Bueno**
S	-475	-73	-309	-503
Z	4.78	0.73	3.09	5.09
P-value	0.00006	0.456	0.0019	0.00008
Sen's Slope (MW / year)	-43	No Trend	-25	-40

The future hydropower scenarios show high hydropower availability in the four study basins; however, the expected hydropower development should be reviewed, as Maule and Bío Bío exhibit more installed hydropower capacity than hydropower potential by 2050 (blue line, Figure 22), which means a significant risk of overinvestment in hydropower plants in these two basins. By contrast, in Maipo and Bueno, hydropower development would not exploit the all available resources by 2050. These results highlight the importance of considering climate variability when planning hydropower development at the basin scale; thus, for example, in Bío Bío projected hydropower developments should be reviewed to mitigate the risk of overinvestment, as the observed decreasing hydropower potential trends are very likely to persist over the next 30 years (Figure 22, Table 7) and could potentially lead to overinvestment in the very near term. In addition, expected climate change effects lead to decreases in the minimum values (Table 6), which means the lows flows in future will be smaller; therefore, reviewing turbine sizes in hydropower projects may be necessary, i.e., decreasing the power of the turbines or installing several small units to avoid inefficient use of hydropower resources.

5. Conclusions

The impacts of climate change on hydropower potential in a data-scarce region dominated by different climatic oscillations were analyzed by linking observed hydropower potential with the long-term climate variability, represented here by SST, in four basins of central Chile. This method of developing future scenarios is a good alternative to apply in regions where it is difficult to calibrate hydrological models, where clear links between hydropower and climate variability can be found, as is the case in the four study basins and in many regions of the world.

Decreasing trends in hydropower potential between 1970 and 2016, were found in all study basins at rates between -22 to -47 MW·year^{-1}. The multi-temporal trend analysis showed modulations in the general trends, *i.e.,* alternating positive and negative trends on a decadal scale. Contributions of these decadal modulations proved to be even more important than the general trends, and therefore, of crucial importance for hydropower resource management. To identify drivers of the controlling decadal modulations in hydropower potential in Chile, potential linkages with large-scale climate variability were investigated. In all basins, hydropower potential was primarily correlated with ENSO, highlighting a strong dependence on tropical climate variability. In particular, the impact of ENSO on hydropower potential was shown to be regionally modulated by other modes of climate variability. In the northernmost basin (*i.e.,* Maipo), hydropower potential was significantly correlated with the PDO, which means that the higher (or lower) availability of hydropower occurs during the positive (or negative) phases of the PDO. In the southern basins (*i.e.,* Maule, Bío Bío, and Bueno) hydropower potential was significantly negatively correlated with the SAM and AMO, highlighting a greater sensitivity to changes in the mid-latitude westerlies in this region. This means that there is higher hydropower availability in the negative phases of the SAM and AMO and lower availability in the positive phases. Therefore, it is concluded that availability of the hydroelectric resources is substantially modulated by large-scale climate fluctuations.

On the one hand, the future scenarios show high unexploited and thus available hydropower resources in the four study basins over the next 30 years. On the other hand, the scenarios show that the main effects of climate change on hydropower potential will be reflected in extreme values, especially minimums; e.g., in Maipo it is expected that minimum hydropower potential values will decrease by 40.4% respect to the present. In addition, these scenarios showed that hydropower development needs to consider the specific climate variability in a basin to optimize the energy generation minimizing the negative impacts, e.g., the expect installed hydropower capacity by 2050 in Maule and Bío Bío will reach a condition close to overinvestment in hydropower plants, while in Maipo and Bueno hydropower resources will remain nearly unexploited in 2050.

Finally, the results of this research show the need to generate policies that not only promote hydropower development in an area, e.g., the NCRE policy issued in 2008 in Chile, but also consider variability in hydropower resources and impacts of climate variability and change, especially in regions where massive investments in hydropower are planned, so as to achieve an optimal use and sustainable development of hydropower resources.

Author Contributions: All authors contributed extensively of the work of this paper. Conceptualization, O.L. and P.A.; methodology, P.A, B.D and M.S.; validation, P.A. and B.D; writing—original draft preparation, P.A and B.D..; writing—review and editing, O.L.

Acknowledgments: The authors thank the Energy Doctorate Program of the Universidad de Concepción for providing the institutional support to conduct this research and Dr. Martin Wilkes for his help in building the interdisciplinary team that conducted this study.

6. References

1. International Energy Agency *Energy Statistics*; **2018**;
2. Barros, R.M.; Tiago Filho, G.L. Small hydropower and carbon credits revenue for an SHP project in national isolated and interconnected systems in Brazil. *Renew. Energy* **2012**, *48*, 27–34.
3. Zarfl, C.; Lumsdon, A.E.; Tockner, K. A global boom in hydropower dam construction. *Aquat. Sci.* **2015**, *77*, 161–170.
4. Killingtveit, A. Hydropower. In *Managing Global Warmimng*; **2019**; pp. 265–315.
5. Y. Zhou, M. Hejazi, S. Smith, J. Edmonds, H. Li, L. Clarke, K. Calvin, A.T. A comprehensive view of global potential for hydrogenerated electricity. *Energy Environ. Sci.* **2015**, 2622–2633.
6. Zhang, X.; Li, H.Y.; Deng, Z.D.; Ringler, C.; Gao, Y.; Hejazi, M.I.; Leung, L.R. Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development. *Renew. Energy* **2018**, *116*, 827–834.
7. van Vliet, M.T.H.; Wiberg, D.; Leduc, S.; Riahi, K. Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Chang.* **2016**, *6*, 375–380.
8. Engeland, K.; Borga, M.; Creutin, J.-D.; François, B.; Ramos, M.-H.; Vidal, J.-P. Space-time variability of climate variables and intermittent renewable electricity production – A review. *Renew. Sustain. Energy Rev.* **2017**, *79*, 600–617.
9. Fabry, F. On the determination of scale ranges for precipitation fields. *J. Geophys. Res.* **1996**, *101*, 12819.
10. Garreaud, R.D.; Vuille, M.; Compagnucci, R.; Marengo, J. Present-day South American climate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2009**, *281*, 180–195.
11. Ng, J.Y.; Turner, S.W.D.; Galelli, S. Influence of El Niño Southern Oscillation on global hydropower production. *Environ. Res. Lett.* **2017**, *12*.
12. Carvajal, P.E.; Anandarajah, G.; Mulugetta, Y.; Dessens, O. Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—the case of Ecuador. *Clim. Change* **2017**, *144*, 611–624.
13. Turner, S.W.D.; Hejazi, M.; Kim, S.H.; Clarke, L.; Edmonds, J. Climate impacts on hydropower and consequences for global electricity supply investment needs. *Energy* **2017**, *141*, 2081–2090.
14. Hu, Y.; Jin, X.; Guo, Y. Big data analysis for the hydropower development potential of ASEAN-8 based on the hydropower digital planning model. *J. Renew. Sustain. Energy* **2018**, *10*.
15. Hamududu, B.H.; Killingtveit, Å. Hydropower production in future climate scenarios; the case for the Zambezi River. *Energies* **2016**, *9*, 1–18.
16. Hamududu, B.H.; Killingtveit, Å. Hydropower production in future climate scenarios: The case fro Kwanza River, Angola. *Energies* **2016**, *9*, 363.
17. Devia, G.K.; Ganasri, B.P.; Dwarakish, G.S. A Review on Hydrological Models. *Aquat. Procedia* **2015**, *4*, 1001–1007.
18. Emerson, D.G.; A. V. Vecchia; A. L. Dahi Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for the Red River of the North Basin , North Dakota and Minnesota Scientific Investigations Report 2005 – 5017 Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for th. *Sci. Investig. Rep.* **2005**, 5017.
19. Breiman, L. Random forests. *Mach. Learn.* **2001**, *45*, 5–32.
20. Stekhoven, D.J.; Bühlmann, P. Missforest-Non-parametric missing value imputation for mixed-type data. *Bioinformatics* **2012**, *28*, 112–118.
21. Chilkoti, V.; Bolisetti, T.; Balachandar, R. Climate change impact assessment on hydropower generation using multi-model climate ensemble. *Renew. Energy* **2017**, *109*, 510–517.
22. Estadísticas electricidad en Chile, Comision Nacional de Energía. Available online: https://www.cne.cl/estadisticas/electricidad/ (accessed on Mar 18, 2019).

23. Pollitt, M.G. Electricity reform in Chile: Lessons for developing countries. *J. Netw. Ind.* **2004**, *5*, 221–262.
24. Infraestructura de Datos Espaciales, Ministerio de Energía de Chile. Available online: http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/ (accessed on Jan 2, 2018).
25. Potencial hidroeléctrico de Chile. Available online: http://walker.dgf.uchile.cl/Explorador/DAANC/ (accessed on Jan 2, 2018).
26. Liang, X.; Lettenmaier, D.P.; Wood, E.F.; Burges, J. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res.* **1994**, *99*, 14415–14428.
27. Santana, C.; Falvey, M.; Ibarra, M.; García, M. *Energías Renovables en Chile. El Potencial Eólico, Solar e Hidroeléctrico de Arica a Chiloé.*; 2014;
28. Energía 2050: Política Energética de Chile. Available online: http://www.energia2050.cl/es/energia-2050/energia-2050-politica-energetica-de-chile/ (accessed on Oct 26, 2017).
29. Mapoteca Digital de Chile, Dirección General de Aguas. Available online: http://www.dga.cl/estudiospublicaciones/mapoteca/Paginas/default.aspx (accessed on Jan 2, 2018).
30. Rioseco R., Tesser, C. Cartografía interactiva de los climas de Chile. Available online: http://www7.uc.cl/sw_educ/geografia/cartografiainteractiva/index.htm (accessed on Jan 15, 2018).
31. Explorador Climático, Centro de Ciencia del Clima y Resiliencia CR^2. Available online: http://explorador.cr2.cl/ (accessed on Jan 30, 2018).
32. Valdés-Pineda, R.; Pizarro, R.; García-Chevesich, P.; Valdés, J.B.; Olivares, C.; Vera, M.; Balocchi, F.; Pérez, F.; Vallejos, C.; Fuentes, R.; et al. Water governance in Chile: Availability, management and climate change. *J. Hydrol.* **2014**, *519*, 2538–2567.
33. Sidibe, M.; Dieppois, B.; Mahé, G.; Paturel, J.E.; Amoussou, E.; Anifowose, B.; Lawler, D. Trend and variability in a new, reconstructed streamflow dataset for West and Central Africa, and climatic interactions, 1950–2005. *J. Hydrol.* **2018**, *561*, 478–493.
34. Moriasi, D.N.; Gitau, M.W.; Pai, N.; Daggupati, P. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Trans. ASABE* **2015**, *58*, 1763–1785.
35. Kling, H.; Fuchs, M.; Paulin, M. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *J. Hydrol.* **2012**, *424–425*, 264–277.
36. Earth Explorer, U.S. Department of the Interior, U.S.G.S. Available online: https://earthexplorer.usgs.gov/ (accessed on Dec 1, 2017).
37. Mann, H.B. Nonparametric Tests Against Trend. *Econometrica* **1945**, *13*, 245–259.
38. Kendall, M.G. Rank Correlation Methods. *Br. J. Stat. Psychol.* **1956**, *9*, 68.
39. Yue, S.; Pilon, P.; Cavadias, G. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.* **2002**, *259*, 254–271.
40. Kulkarni, A.; Storch, H. Von Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. *Meteorol. Zeitschrift* **1995**, *4*, 82–85.
41. Yue, S.; Wang, C.Y. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resour. Res.* **2002**, *38*, 4-1-4–7.
42. Sneyers, R. *On the statistical analysis of series of observations*; Technical Note Nº 143: Geneva, Switzerland, 1990; ISBN 9263104158.
43. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389.
44. McCabe, G.J.; Wolock, D.M. A step increase in streamflow in the conterminous United States. *Geophys. Res. Lett.* **2002**, *29*, 38-1-38–4.
45. Liebmann, B.; Dole, R.M.; Jones, C.; Bladé, I.; Allured, D. Influence of choice of time period on global surface temperature trend estimates. *Bull. Am. Meteorol. Soc.* **2010**, *91*, 1485–1491.
46. Mantua, N.J.; Hare, S.R. The Pacific Decadal Oscillation. *J. Oceanogr.* **2009**, *58*, 35–44.
47. Kevin E. Trenberth The definition of El Nino - ProQuest. *Bull. Am. Meteorol. Soc.* **1997**,

2771–2777.
48. Marshall, G. Trends in the Southern Annular Mode from Observation and Reanalysis. *J. Clim.* **2003**, *16*, 4134–4143.
49. Enfield, D.B.; Mestas-Nuñez, A.M.; Trimble, P.J. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.* **2001**, *28*, 2077–2080.
50. Huang, B.; Banzon, V.F.; Freeman, E.; Lawrimore, J.; Liu, W.; Peterson, T.C.; Smith, T.M.; Thorne, P.W.; Woodruff, S.D.; Zhang, H.M. Extended reconstructed sea surface temperature version 4 (ERSST.v4). Part I: Upgrades and intercomparisons. *J. Clim.* **2015**, *28*, 911–930.
51. Huang, B.; Thorne, P.W.; Banzon, V.F.; Boyer, T.; Chepurin, G.; Lawrimore, J.H.; Menne, M.J.; Smith, T.M.; Vose, R.S.; Zhang, H.M. Extended reconstructed Sea surface temperature, Version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *J. Clim.* **2017**, *30*, 8179–8205.
52. Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 485–498.
53. Moss, R.H.; Edmonds, J.A.; Hibbard, K.A.; Manning, M.R.; Rose, S.K.; Van Vuuren, D.P.; Carter, T.R.; Emori, S.; Kainuma, M.; Kram, T.; et al. The next generation of scenarios for climate change research and assessment. *Nature* **2010**, *463*, 747–756.
54. Barnett, T.P. Comparison of near-surface air temperature variability in 11 coupled global climate models. *J. Clim.* **1999**, *12*, 511–518.
55. Benestad, R.E. A comparison between two empirical downscaling strategies. *Int. J. Climatol.* **2001**, *21*, 1645–1668.
56. Lorenz, E.N. Empirical Orthogonal Functions and Statistical Weather Prediction. *Tech. Rep. Stat. Forecast Proj. Rep. 1 Dep. Meteorol. MIT 49* 1956, *1*, 52.
57. Akaike, H. A new look at the statistical model identification. *IEEE Trans. Automat. Contr.* **1971**, *19*.
58. Benestad, R.E. The cause of warming over Norway in the ECHAM4/OPYC3 GHG integration. *Int. J. Climatol.* **2001**, *21*, 371–387.
59. Muñoz, A.A.; González-Reyes, A.; Lara, A.; Sauchyn, D.; Christie, D.; Puchi, P.; Urrutia-Jalabert, R.; Toledo-Guerrero, I.; Aguilera-Betti, I.; Mundo, I.; et al. Streamflow variability in the Chilean Temperate-Mediterranean climate transition (35°S–42°S) during the last 400 years inferred from tree-ring records. *Clim. Dyn.* **2016**, *47*, 4051–4066.
60. Quintana, J.M.; Aceituno, P. Changes in the rainfall regime along the extratropical west coast of south America (Chile): 30-43º S. *Atmósfera* **2012**, *25*, 1–22.
61. Valdés-Pineda, R.; Valdés, J.B.; Diaz, H.F.; Pizarro-Tapia, R. Analysis of spatio-temporal changes in annual and seasonal precipitation variability in South America-Chile and related ocean–atmosphere circulation patterns. *Int. J. Climatol.* **2016**, *36*, 2979–3001.
62. Rubio-Álvarez, E.; McPhee, J. Patterns of spatial and temporal variability in streamflow records in south central Chile in the period 1952-2003. *Water Resour. Res.* **2010**, *46*, 1–16.
63. Cortés, G.; Vargas, X.; McPhee, J. Climatic sensitivity of streamflow timing in the extratropical western Andes Cordillera. *J. Hydrol.* **2011**, *405*, 93–109.
64. Montecinos, A.; Aceituno, P. Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies. *J. Clim.* **2003**, *16*, 281–296.
65. Valdés-Pineda, R.; Cañón, J.; Valdés, J.B. Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals. *J. Hydrol.* **2018**, *556*, 1153–1170.
66. Gillett, N.P.; Kell, T.D.; Jones, P.D. Regional climate impacts of the Southern Annular Mode. *Geophys. Res. Lett.* **2006**, *33*, 1–4.
67. IPCC (Intergovernmental Panel on Climate Change) *Climate Change 2014: Synthesis Report*; 2014; ISBN 9781107661820.
68. Chen, C.; Cane, M.A.; Wittenberg, A.T.; Chen, D. ENSO in the CMIP5 Simulations: Life Cycles, Diversity, and Responses to Climate Change. *J. Clim.* **2017**, *30*, 775–801.

IV.2 Fragmentación de los sistemas fluviales de Chile Central causada por el desarrollo hidroeléctrico actual y proyectado

El presente capítulo corresponde a la síntesis de un análisis científico de los impactos del desarrollo hidroeléctrico sobre la conectividad fluvial, específicamente sobre la fragmentación de los sistemas fluviales, realizado por un equipo interdisciplinario, que ha sido publicado en dos artículos: Díaz *et al.* (2019) y Habit *et al.* (2019). Ambos se incluyen en esta tesis como Anexos 1 y 2, respectivamente.

Los paisajes fluviales se encuentran entre los más vulnerables del mundo (Vörösmarty *et al.*, 2010), siendo la construcción de presas y los cambios hidrológicos, los impactos antropogénicos más generalizados, irreversibles y dramáticos sobre los paisajes fluviales (Petts, 1984). A nivel mundial, más de 58.000 grandes presas regulan y gestionan regímenes de caudal para una variedad de problemas, incluida la generación de energía hidroeléctrica (Poff y Schmidt, 2016). Existe un desequilibrio geográfico en los futuros desarrollos hidroeléctricos del mundo, siendo los países en desarrollo de Asia y América del Sur los con mayor potencial hidroeléctrico no explotado y con aumentos de desarrollo previstos de varios órdenes de magnitud en países como Chile y China (Bartle, 2002). Por otro lado, se sabe relativamente poco acerca de los efectos de las presas y la generación hidroeléctrica en los ecosistemas de las regiones en desarrollo, en comparación con las de las regiones desarrolladas, sin embargo, se puede inferir que la mayor alteración será sobre la conectividad fluvial (Pringle *et al.*, 2000).

Las alteraciones en la conectividad fluvial interfieren con la capacidad de la biota acuática para absorber y adaptarse a las alteraciones de las presas, así como a otros factores de estrés inducidos por los cambios en condiciones ambientales, como el cambio climático. Por lo tanto, los ríos están cada vez más sujetos a múltiples factores estresantes que podrían resultar en una pérdida de capacidad de resiliencia (Thoms *et al.*, 2018), y a una escala temporal evolutiva de largo plazo, la pérdida de especies migratorias y endémicas, con preferencias de hábitat específicas (Hall et al., 2011). Se requiere entonces un enfoque interdisciplinario de la ciencia fluvial para comprender las complejas interacciones entre los sistemas sociales y ecológicos, así como la respuesta de las comunidades acuáticas a las perturbaciones inducidas por el hombre (Thoms *et al.*, 2018).

La legislación ambiental para la conservación y gestión de los ríos no ha seguido el ritmo del rápido crecimiento de la energía hidroeléctrica en muchos países en desarrollo (Bauer, 2009). La ciencia y gestión fluvial han sido reactivas en los intentos de mejorar la limitada base de conocimientos sobre la comprensión de los ecosistemas fluviales antes y después de la energía hidroeléctrica. En algunos países, como Chile, existen respuestas sitio-específicas de los ecosistemas al desarrollo de la energía hidroeléctrica (*cf.*, Habit *et al.*, 2007). Sin embargo, se necesitan modelos más amplios en donde se analice la respuesta de los ecosistemas regionales a rápidas modificaciones antropogénicas, como el actual desarrollo de energía hidroeléctrica, basados en la ciencia de los ecosistemas y la sustentabilidad.

Chile, específicamente la zona central (25°S a 47°S), es un caso de estudio de alto interés debido a que es uno de los 25 “Hotspots” de biodiversidad a nivel mundial (Myers et al., 2000), donde la historia geológica de Chile ha contribuido a la singularidad de su fauna acuática, por ejemplo, el endemismo en especies de peces de agua dulce es del 83%. En particular, las especies de peces nativos han conservado sus características primitivas y endémicas, donde la ictiofauna nativa de agua dulce de

Chile está compuesta por 12 familias, 17 géneros, 46 especies, de las cuales el 52% están en peligro de extinción (Vila y Habit, 2015). Existiendo evidencia de una disminución en la abundancia y variedad de especies de peces nativos como resultado de los efectos sinérgicos de los múltiples factores estresantes en las cuencas hidrográficas, tales como, la introducción de especies no nativas, cambios en el uso de la tierra, extracción de agua, contaminación y fragmentación de los ríos, y el desarrollo hidroeléctrico (Vila y Habit, 2015). La información sobre el efecto de las presas y la generación de energía hidroeléctrica está limitada por los requisitos legislativos impuestos por el derecho ambiental y el proceso de Evaluación de Impacto Ambiental (EIA), que no se realizan utilizando bases de investigaciones científicas (Habit *et al.*, 2002).

Se han reconocido las deficiencias del sistema chileno de EIA con respecto a la energía hidroeléctrica (Lacy *et al.*, 2017). Los proyectos son vistos de manera independiente sin reconocer los desarrollos hidroeléctricos existentes o planificados dentro de la cuenca, o incluso otros proyectos de uso del agua. Los términos de referencia de las EIAs (es decir, qué, dónde, cómo y cuándo medir) son definidos por los propietarios del proyecto, quienes son responsables de la designación de los agentes que llevarán a cabo la EIA. La evaluación gubernamental se restringe solamente a si la EIA cumple con las regulaciones establecidas en la legislación ambiental chilena, con una limitada capacidad del gobierno para modificar las condiciones para el desarrollo del proyecto (Lacy *et al.*, 2017). Además, en el caso específico de la fauna íctica, existe otra legislación que guía las decisiones para el desarrollo hidroeléctrico, la "Ley General de Pesca y Acuicultura", que establece la obligación de implementar acciones de mitigación cuando un proyecto incluye estructuras que obstruyen un río. Esto puede dar lugar a estructuras que permitan los desplazamientos de peces, como pasos de peces (*e.g.* Laborde et al., 2016), o procedimientos que mantengan su abundancia, lo cual se realiza con frecuencia a través de programas de translocación. Sin embargo, estas medidas no tienen peso en el rechazo de un proyecto hidroeléctrico en el proceso de EIA y la mayor parte de esta legislación está dirigida a las especies de peces introducidas, como los salmónidos, que tienen beneficios económicos para la recreación y la acuicultura, con pocas directrices para la conservación de las especies de peces nativos.

Para entender el contexto del desarrollo de la energía hidroeléctrica frente al contexto político del desarrollo energético en Chile, y las interacciones entre los ecosistemas fluviales chilenos, con especial referencia a los impactos potenciales sobre la fauna piscícola nativa, se adjunta como Anexo 1 en esta tesis el trabajo: ***"River science and management issues in Chile: Hydropower development and native fish communities"*.** En este manuscrito se presentan algunos de los impactos del desarrollo hidroeléctrico basado en tres estudios de caso que consideran: i) la alteración del hábitat aguas abajo de la represa de Rucúe; ii) los efectos del hidropeaking en el río Biobío; y, iii) estrategias de mitigación para reducir la alteración del hábitat aguas arriba de la represa de San Pedro. Estos casos de estudio ilustran problemáticas comunes asociadas con el desarrollo de la energía hidroeléctrica en los ríos chilenos, incluyendo el impacto de la pérdida de hábitat tanto aguas arriba como aguas abajo de las presas, y los intentos de restauración para contrarrestarlo. Además se introducen enfoques a mayor escala para comprender el efecto del desarrollo hidroeléctrico; la inclusión de las relaciones flujo-pez en los EIAs chilenos; y la necesidad de enfoques interdisciplinarios más fuertes en la construcción de modelos de ecología fluvial en toda la región. Los casos presentados se encuentran en las cuencas del río Biobío (caso uno y dos) y Valdivia (caso tres) y se sintetizan a continuación:

Caso I: Hidroeléctrica Rucúe, con potencia instalada de 178 MW y del tipo *"run on the river"* o hidroeléctrica de pasada. Extrae agua desde el río Laja (120 m^3s^{-1}) y Rucúe (10 m^3s^{-1}), disminuyendo los caudales aguas abajo de las presas. Los resultados mostraron una respuesta compleja a los cambios de régimen de flujo, con diferencias entre ambos ríos (Habit et al., 2007). En el río Laja la abundancia de especies fue menor que en el río Rucúe, especialmente para *Percilia irwini* y *Trichomycterus areolatus*. Además, las especies que ocupan hábitats de aguas medias, *i.e.* la trucha introducida y *P. irwini*, mostraron importantes disminuciones en la abundancia durante los períodos de construcción y operación de la presa, mientras que las especies nativas de bagres bentónicos (*T. areolatus y Diplomystes nahuelbutaensis*) no mostraron cambios en la abundancia a lo largo del tiempo. Se concluyó que las reducciones en los caudales bajos y la consecuente pérdida de hábitat en el río Laja eran más perjudiciales para las especies de peces que ocupan hábitats de aguas medias en este sistema fluvial (Habit *et al.*, 2007). En general, el cambio en la estructura de la comunidad de peces en el río Laja en comparación con el río Rucúe (un río no afectado por las operaciones hidroeléctricas) sugiere una pérdida de resiliencia como resultado de cambios en el régimen de caudales durante 40 años. Para mitigar el efecto del proyecto hidroeléctrico de Rucúe se probó la translocación de dos especies en peligro (*P. irwini y D. nahuelbutaensis*) y una especie vulnerable (*T. areolatus*), siendo la primera translocación de peces nativos realizada en Chile. En los ríos Laja y Rucúe se registró una tasa de supervivencia del 90% después de cuatro años. Este experimento inicial fue considerado un éxito, pero se requiere un mayor monitoreo para determinar la efectividad a largo plazo de las translocaciones de peces para mitigar los efectos de las represas hidroeléctricas.

Caso II: Hidropeaking (*i.e.* generación hidroeléctrica en horarios de alta demanda) en el río Biobío. García *et al.* (2011) modeló el uso del hábitat de dos especies de peces nativa (*Basilichthys microlepidotus* y *Percilia irwini*) a lo largo de un tramo de 2 km situado a 98 km aguas abajo de la presa de la central hidroeléctrica Pangue (potencia instalada de 467 MW y del tipo embalse). Realizando una comparación del área utilizable ponderada para los escenarios anteriores a la presa (verano 1978-1979) y posteriores a la presa (verano 2005). Se observaron importantes cambios en la disponibilidad y ubicación del hábitat, afectando especialmente las condiciones de hábitat óptimos de ambas especies producto de la operación del tipo hidropeaking de la central.

Caso III: Hidroeléctrica San Pedro (en construcción, potencia de 170 MW). Ubicada 14 km aguas abajo del río Riñiue e impactará el 31,2% de la red fluvial. El desarrollo de este proyecto amenaza 5 especies nativas y en particular a *Galaxias platei* endémica de la Patagonia (Cussac *et al.* 2004). El EIA para el desarrollo hidroeléctrico de San Pedro propuso mejorar el hábitat en el tramo entre la cola del embalse y el lago Riñihue, con el objetivo de mantener las poblaciones del río *G. platei* (Link and Habit, 2012). Se propusieron estructuras del tipo *"Rock Groin"* (rompeolas), grandes escombros leñosos y presas de roca, con el objetivo de generar diversas estructuras de hábitat que proporcionan una variedad de condiciones de sustrato y vegetación riparia nativa utilizable durante todo el año para G. platei. Este esfuerzo de restauración en curso aumentó la disponibilidad de hábitat en un orden de tres con respecto a aquellos sin estructuras de hábitat. Este es el primer proyecto de restauración de ríos en Chile para mejorar la calidad del hábitat de especies de peces nativos basado en criterios eco-hidráulicos (Link and Habit, 2012).

Finalmente, el trabajo presentado permite concluir que la debilidad de la legislación ambiental y la existencia de una estrategia nacional de planificación relativamente inmadura para el desarrollo energético, han permitido a las empresas privadas desarrollar los recursos hídricos chilenos basándose principalmente en razones económicas. Además, el trabajo sugiere las siguientes medidas a considerar para la comprensión y protección de los ecosistemas fluviales chilenos. En primer lugar, el gobierno debe fomentar programas interdisciplinarios de ciencias fluviales que proporcionen líneas de base hidrológicas y ecológicas de los sistemas fluviales. Estas líneas de base servirían para priorizar las áreas de conservación que mantienen la biodiversidad acuática. En segundo lugar, los términos de referencia (*i.e.* especificaciones técnicas, objetivos y estructuras) del proceso de EIA para nuevos proyectos hidroeléctricos deben requerir una evaluación científica independiente. Estos términos de referencia también deben considerar la escala de la EIA con extensiones para evaluar toda la red fluvial (según lo recomendado por Dollar *et al.*, 2007). Los términos de referencia también deben requerir el desarrollo de EIAs en el contexto de las actividades existentes y proyectadas, considerando los efectos sinérgicos potenciales (como debería haber sido el Caso Uno y Dos en el Río Biobío). Tercero, cuando se determina la ubicación de una nueva presa, la EIA debe exigir normas específicas en el procedimiento de muestreo (períodos, ubicación, duración y esfuerzo), en la calidad de los datos y en el análisis de los datos para permitir una caracterización adecuada del sistema y análisis eco-hidráulicos detallados de los efectos potenciales y las acciones de mitigación. Cuarto, todos los proyectos hidroeléctricos, incluyendo las represas existentes, deben tener programas de monitoreo de ecosistemas fluviales a largo plazo, incluyendo opciones para el desmantelamiento de las represas. Quinto, se debe implementar un proceso de relicenciamiento para tomar en cuenta las mejoras en la tecnología, los cambios en los usos del agua en las cuencas, y para considerar los cambios en los valores sociales que apoyan/rechazan proyectos particulares.

Por otro lado, la fragmentación de las redes fluviales por las presas tiene efectos a corto y largo plazo en el movimiento de los peces. En el corto plazo (anual), se han registrado reducciones en la abundancia de individuos migratorios en las corrientes de cabecera, y en el largo plazo (décadas) se ha producido la diversificación genética de especies aisladas (Esguícero y Arcifa, 2010). El aumento de la fragmentación de la red probablemente tendrá efectos graves sobre la viabilidad de la población (Neraas y Spruell, 2001), restringiendo aún más la migración, aislando las poblaciones y restringiendo el flujo de genes (Esguícero y Arcifa, 2010). Por lo tanto, es probable que una cascada de presas hidroeléctricas a lo largo de la red fluvial tenga un efecto sinérgico en las poblaciones de peces a mayor escala, y entonces a medida que aumente el número de represas, los ecosistemas fluviales de Chile se degradarán y los grandes ríos que fluyen libremente desaparecerán rápidamente del paisaje chileno. Por lo anterior, se investigó la fragmentación de los ecosistemas fluviales chilenos en el trabajo ***"Fragmentation of Chilean Andean rivers: expected effects of hydropower develoment",*** incluido en el Anexo 2, el cual se resume a continuación.

Los sistemas fluviales son redes dendríticas jerárquicas y su funcionamiento depende en gran medida de la conectividad física (Campbell *et al.*, 2007; Fullerton *et al.*, 2010; Fuller *et al.*, 2015). La fragmentación (establecimiento de cualquier tipo de barreras, por ejemplo, presas, embalses para el riego) y la consiguiente pérdida de conectividad se consideran una de las mayores amenazas para la conservación de los sistemas fluviales en todo el mundo (Lehner *et al.*, 2011). Impide procesos eco-hidrológicos fundamentales en los sistemas fluviales que afectan a los regímenes hidrológico, sedimentario y de temperatura; la morfología de los canales, el ciclo de los nutrientes, las interacciones con las llanuras aluviales y, en consecuencia, afecta a la biota fluvial

(Bunn & Arthington, 2002; Elosegui & Sabater, 2013; Olden & Naiman, 2010; McCluney *et al.*, 2014).

Se han propuesto varios marcos conceptuales para avanzar en la comprensión de los aspectos físicos, hidrológicos y ecológicos de la conectividad y se han desarrollado métricas e índices para cuantificar la fragmentación (Cote *et al.*, 2009; Grill, *et al.*, 2014; Diebel, *et al.*, 2015). Los índices para cuantificar la fragmentación deben basarse en principios teóricos de conectividad y naturaleza jerárquica de las redes fluviales (Delong & Thoms, 2016). A menudo, la fragmentación de la red fluvial se representa a través de índices de conectividad longitudinal del hábitat físico de las especies de peces, debido a que los peces son los organismos acuáticos más vágiles y sus movimientos son cruciales para completar su ciclo de vida y el mantenimiento de las poblaciones (Liermann, *et al.* 2012; Arthington *et al.*, 2016). De esta manera, Cote *et al.* (2009) propusieron el Índice de Conectividad Dendrítica (DCI) para evaluar la conectividad del hábitat de peces con diferentes historias de vida (potádromas; DCI_P y diádromas; DCI_D) a escala de una red fluvial (cuenca), considerando tres aspectos cantidad, ubicación y pasabilidad (probabilidad de los peces de atravesar) de las barreras. Este índice ha sido efectivo para para evaluar los efectos de la fragmentación sobre la diversidad, abundancia y distribuciones de peces ribereños, sin embargo, se ha reconocido algunas limitaciones del DCI, especialmente en la ubicación de la barrera, ya que sólo se considera como una aproximación teórica expresada como la distancia al punto más bajo de la red (Grill et al., 2014), sin considerar la jerarquía de esta. Grill *et al.* (2014) incluyeron el volumen de agua del río como una métrica adicional para considerar la jerarquía de la red, pero este enfoque depende en gran medida de la disponibilidad de datos y presenta dificultades de aplicación en cuencas con escases de información fluviométrica.

La investigación realizada analizó la fragmentación física de ocho cuencas andinas de Chile, evaluándola en tres escenarios: natural, *i.e.*, antes de la intervención antropogénica, actual (2018), y futuro (2050), basado en los actuales planes de desarrollo hidroeléctrico. Proponiendo dos nuevos índices para evaluar la fragmentación en zonas con baja densidad de información hidro-meteorológica, Índice de fragmentación (FI) e índice de fragmentos más largos (LF). Se utilizó el orden de Strahler como una métrica simple para representar la ubicación jerárquica de las barreras presentes en una cuenca. Posteriormente, se aplicaron ambos índices en la cuenca del río Biobío (la que posee el mayor potencial hidroeléctrico), para una serie de configuraciones hipotéticas de potenciales centrales hidroeléctricas que se planifican en la cuenca, evaluando así alternativas que permitan mitigar los impactos de las presas de las centrales sobre la conectividad fluvial de la red hídrica, específicamente sobre la distribución de peces nativos.

IV.2.1 Metodología

El área de estudio comprende ocho cuencas Andinas ubicadas en Chile central (32°S - 38°S): Aconcagua, Maipo, Rapel, Mataquito, Itata, Biobío e Imperial. Desde el Aconcagua hasta el Biobío, los ríos se caracterizan por regímenes de caudal dominados por las lluvias y el deshielo, con fuertes pendientes medias (5% a 10%, Link & Habit, 2015). El Río Imperial se origina a menor altitud en el piedemonte de los Andes y por lo tanto, carece de flujos torrenciales (Niemeyer & Cereceda, 1984; Vila *et al.* 1999). Estas cuencas pertenecen a la misma provincia ictiogeográfica (Dyer, 2000), la más diversa de Chile, albergando un total de 21 especies de peces nativos y 15 no nativos (Vila & Habit, 2015). Los peces nativos de agua dulce presentan un alto nivel de endemismo y primitivismo, y son de alto interés para la conservación (Habit *et al.*, 2006).

Las redes hídricas de las cuencas fueron obtenidas desde la base cartográfica del Ministerio de Desarrollo Social (MDS, 2009), las cuales fueron procesadas con el software ArcGIS v10.4 para cuantificar longitudes y ordenes de Strahler. La información de las barreras fue obtenida desde diferentes fuentes según cada escenario: (1) Natural, se consideraron sólo cascadas mayores a 20 m e identificadas mediante Google Earth. (2) Actual, se consideró infraestructura física que obstruyera completamente la sección transversal del río, es decir, bocatomas de canales de riego y presas de: centrales hidroeléctricas con potencia mayor a 3 MW, embalses de riego y relaves mineros; información obtenida desde la base datos cartográfica del ministerio de Bienes Nacionales (MBN, 2015). (3) Futuro, se consideraron las potenciales centrales hidroeléctricas con potencia mayor a 3 MW, proyectadas por el Ministerio de Energía (ME, 2018).

Índice de fragmentación (FI).

El índice FI se estima a través de la ecuación:

$$FI = 1 - 1.5^{-\sum_{i=1}^{N} IFI(i)}$$

Donde, N corresponde al número total de barreras en la cuenca e IFI al impacto individual de cada barrera sobre la red hídrica, el cual se estima por la ecuación:

$$IFI(i) = \frac{\sum_{j=1}^{M} L_j S_j}{T}$$

Donde M es el número de tramos de la red fluvial aguas arriba de la presa, mientras que L y S son la longitud y el orden de Strahler, respectivamente, de cada j-ésimo tramo de la red fluvial aguas arriba de la presa. T corresponde al valor máximo que podría alcanzar IFI, *i.e.*, $T = \sum_{j=1}^{R} L_j S_j$ donde R es el número de tramos de toda la red fluvial. El denominador T cumple la función de normalizar IFI, para que así IF sea comparable entre diferentes cuencas. Por lo tanto, FI varía entre 0 y 1; valores cercanos a 0 indican poca o ninguna fragmentación, mientras que valores cercanos a 1 indican una fuerte fragmentación de la red.

Índice de fragmentos más largos (LF).

LF corresponde a la sección de la red hídrica disponible para el movimiento de peces y se calcula a través del fragmento más largo de la cuenca (L_M), dividido por la longitud total de la red hídrica (L_T), es decir:

$$LF = \frac{L_M}{L_T}$$

LF cuantifica la longitud máxima disponible para que los peces se muevan dentro de la red fluvial. Esta longitud se encuentra entre dos barreras o una barrera y el límite de una red fluvial (cabecera o desembocadura). Sus valores son cercanos a 0 cuando la movilidad disponible en la red para los peces es baja y cercano a 1 en el caso contrario.

Aplicación de FI y LF en la cuenca del río Biobío.

Se evaluaron 4 potenciales escenarios de desarrollo hidroeléctrico, donde las nuevas barreras poseen diferentes ubicaciones: (1) sólo en el cauce principal (4001 MW), (2) en tributarios de la cuenca baja (3.512 MW), (3) tributarios aguas arriba de las barreras existentes (3.943 MW), (4) se desarrollan todos los potenciales presentes en la cuenca (5.696 MW). La distribución de las especies nativas se estimó a través de muestreo en terreno en 25 sitios diferentes (mayor información ver sección *"Assessment of fish distribution in the Biobío basin"* en Anexo 2)

IV.2.2 Principales resultados

En el escenario natural sólo se detectaron barreras en las cuencas de los ríos Maule, Itata y Biobío con valores de IF cercanos a 0. Para el escenario actual (2018), las cuencas de los ríos Rapel y Biobío mostraron los valores más altos de IF (0,463 y 0,436, respectivamente), mientras que los más bajo fueron en la cuenca del río Imperial (0,002) e Itata (0,044). En el escenario futuro (2050), incremento considerablemente el índice en todas las cuencas, siendo el caso más crítico el del río Biobío (0,936), equivalente a una fuerte fragmentación. La cuenca del río Aconcagua fue la que mostró el menor aumento de IF entre el escenario Actual (0,350) y Futuro (0,406), mientras que el río Imperial mostró el mayor incremento (de 0,002 a 0,381). Además, se espera que el aumento más rápido de la fragmentación ocurra en los ríos pequeños y medianos (orden Strahler 1, 2 y 3).

En el caso de LF, las cuencas mostraron el valor óptimo (1, *i.e.,* la máxima movilidad en la red) a excepción de los ríos Maule (0,995), Itata (0,872) y Biobío (0,776) donde se detectaron la presencia de cascadas. En el escenario actual (2018) baja la movilidad en todas las cuencas, donde las menores movilidades se detectaron en las cuencas de los ríos Rapel (0,651) y Biobío (0,706), mientras que las mayores fueron en Imperial (0,995) e Itata (0,872). Para el escenario futuro (2050), LF aumentó en seis de las ocho cuencas, Aconcagua (0,768) y Maule (0,750) no sufrieron cambios. Maipo mostró la mayor disminución en la movilidad (LF disminuye de 0,729 a 0,410), mientras que la menos disminución ocurre en Mataquito (LF disminuye de 0,782 a 0,773).

La aplicación de IF y LF para los escenarios de desarrollo hidroeléctrico propuestos en la cuenca del río Biobío, mostraron que la mejor alternativa es desarrollar los potenciales sobre las barreras existentes (IF = 0,905 y LF = 0.508), debido a que es el escenario que presenta la mayor movilidad y afecta en menor medida a la distribución de peces nativos. El escenario de desarrollo hidroeléctrico en la zona baja (IF = 0,852 y LF = 0,360) fue el caso que más impacta la distribución de los peces nativos.

IV.2.3 Conclusión

El índice de fragmentación (IF) y el de fragmentos más largos (LF) mostraron ser herramientas útiles para evaluar la fragmentación en zonas con baja densidad de información hidro-meteorológica. Mostraron que el nivel actual de fragmentación de los ríos andinos chilenos aumentará sustancialmente en un futuro próximo, como efecto de la estrategia gubernamental de fomentar el desarrollo de centrales hidroeléctricas no convencionales y se espera que el aumento más rápido de la fragmentación ocurra en los ríos pequeños y medianos (orden Strahler 1, 2 y 3). Además, su aplicación en la cuenca del río Biobío mostró que el desarrollo de los potenciales hidroeléctricos sobre las barreras existentes, *i. e.,* en la cuenca superior, es la alternativa que menos impacta la distribución de especies nativas.

IV.2.4 Referencias

Arthington, A. H., Dulvy, N. K., Gladstone, W. and Winfield, I. J. (2016). Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(5), 838-857.

Bartle, A. (2002). Hydropower potential and development activities. *Energy Policy* 30: 1231-1239.

Bauer, C. (2009). Dams and markets: Rivers and electric power in Chile. *Natural Resources Journal* 49: 583-651.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental management*, *30*(4), 492-507.

Campbell Grant, E. H., Lowe, W. H., & Fagan, W. F. (2007). Living in the branches: population dynamics and ecological processes in dendritic networks. *Ecology letters*, *10*(2), 165-175.

Cote, D., Kehler, D. G., Bourne, C., & Wiersma, Y. F. (2009). A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*, *24*(1), 101-113.

Cussac, V., Ortubay, S., Iglesias, G., Milano, D., Lattuca, M., Barriga, J., Battini, M. and Gross, M. (2004). The distribution of South American galaxiid fishes: the role of biological traits and post-glacial history. *Journal of Biogeography* 31: 103-121.

Delong, M. D., Thoms, M. C., Gilvear, D. J., Greenwood, M. T., & Wood, P. J. (2016). An ecosystem framework for river science and management. *River science: Research and management for the 21st century*, 11-36.

Diebel, M. W., Fedora, M., Cogswell, S. and O'Hanley, J. R. (2015). Effects of road crossings on habitat connectivity for stream-resident fish. *River Research and Applications*, *31*(10), 1251-1261.

Dollar, E.S.J., James, C.S., Rogers, K.H. and Thoms, M.C. (2007). A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology* 89: 147-162

Dyer, B. (2000). Systematic review and biogeography of the freshwater fishes of Chile. *Estudios Oceanológicos,* 19**,** 77-98

Elosegi, A. and Sabater, S. (2013). Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. *Hydrobiologia*, *712*(1), 129-143.

Esguícero, A.L. and Arcifa, M.S. (2010). Fragmentation of a Neotropical migratory fish population by a century-old dam. *Hydrobiologia* 638: 41-53.

Fuller, M. R., Doyle, M. W., & Strayer, D. L. (2015). Causes and consequences of habitat fragmentation in river networks. *Annals of the New York Academy of Sciences*, *1355*(1), 31-51.

Fullerton, A. H., Burnett, K. M., Steel, E. A., Flitcroft, R. L., Pess, G. R., Feist, B. E., ... & Sanderson, B. L. (2010). Hydrological connectivity for riverine fish: measurement challenges and research opportunities. *Freshwater biology*, *55*(11), 2215-2237.

García, A., Jorde, K., Habit, E., Caamaño, D. and Parra, O. (2011). Downstream environmenal effects of dam operations: Change in hábitat quality for native fish species. *River Res. Applic.,* 27, 312-327

Grill, G., Dallaire, C. O., Chouinard, E. F., Sindorf, N. and Lehner, B. (2014). Development of new indicators to evaluate river fragmentation and flow regulation at large scales: A case study for the Mekong River Basin. *Ecological Indicators*, *45*, 148-159.

Habit, E., Victoriano P., Parra O. (2002). Translocación de peces nativos en la cuenca del río Laja (Región del Biobío, Chile). *Gayana (Concepcion)* 66: 181-190.

Habit, E., Dyer, B., Vila I. (2006). Estado de conocimiento de los peces dulceacuícolas de Chile. *Gayana* 70: 100-113.

Habit, E., Belk, M. and Parra, O. (2007). Response of the riverine fish community to the construction and operation of a diversion hydropower plant in central Chile. *Aquatic Conserv: Mar. Freshw. Ecosust.* 17: 37-49

Hall, C.J., Jordaan, A. and Frisk M.G. (2011). The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. *Landscape Ecology* 26: 95–107.

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, M., Habit, E. and Link, O. (2016). Hydropower development, riverine connectivity, and non-sport fish species: Criteria for hydraulic design of fishways. *River res. Applic.* 32, 1949-1957

Lacy, S.N., Meza, F.J. and Marquet, P.A., 2017. Can environmental impact assessments alone conserve freshwater fish biota? Review of the Chilean experience. *Environmental Impact Assessment Review* 63: 87-94.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., …, and Nilsson, C. (2011). High‐resolution mapping of the world's reservoirs and dams for sustainable river‐flow management. *Frontiers in Ecology and the Environment*, 9(9), 494-502.

Liermann, C. R., Nilsson, C., Robertson, J. and Ng, R. Y. (2012). Implications of dam obstruction for global freshwater fish diversity. *BioScience*, *62*(6), 539-548.

Link, O. and Habit. E. (2012). Informe de medidas de manejo especie-específicas 1: Estructuras para generación de hábitat para Galaxias platei. Informe Técnico preparado para Colbún S.A. Oficina de Asistencia Técnica, Centro de Ciencias Ambientales EULA, Universidad de Concepción. 70 págs + 1 Anexo

Link, O. and Habit, E. (2015). Requirement and boundary conditions for fish passes of non-sport fish species based on Chilean experiences. *Reviews in Environmental Sciences and Biotechnology,* 14 (1), 9-21

McCluney, K., Poff, N., Palmer, M., Thorp, J., Poole, G., Williams, B., Williams, M., and Baron, J. (2014) Riverine macrosystems ecology: sensitivity, resistance, and resilience of whole river basins with human alterations. *Frontiers in Ecology and the Environmental,* 12(1), 48–58

Ministerio de Bienes Nacionales (MBN, 2015). Visor de datos geoespaciales. http://www.geoportal.cl/visorgeoportal/.

Ministerio de Desarrollo Social (MDS, 2009). Red hidrográfica chilena. Disponible en http://datos.gob.cl/dataset/27896

Ministerio de Energía (ME, 2018). Módulo cartográfico. Disponible en http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/

Myers, N., Fonseca, G., Mittermeier, R., Fonseca, G., and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–8.

Niemeyer, H., & Cereceda, P. (1984). Hidrografía, Geografía de Chile, Tomo VIII. Santiago: Instituto Geográfico Militar.

Olden, J. D., & Naiman, R. J. (2010). Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology*, *55*(1), 86-107.

Petts, G.E. (1984). Impounded Rivers. Wiley, Chichester.

Poff, N.L. and Schmidt, J.C. (2016). How dams can go with the flow. *Science* 353, 1099-1100.

Pringle, C.M., Freeman, M.C. and Freeman, B.J. (2000). Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. *Bioscience*, 50: 807-823.

Vila, I., Fuentes, L., & Contreras, M. (1999). Peces límnicos de Chile. *Boletín del Museo Nacronal de Historia Natural. Chile*, *48*, 61-75.

Vila, I. and Habit, E. (2015). Current situation of the fish fauna in the Mediterranean region of Andean river systems in Chile*. Fishes in Mediterranean Environments* 2: 19-29.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. and Davies, P.M. (2010). Global threats to human water security and river biodiversity. Nature 467: 555-561.

IV.3 Brechas y falencias existentes en la evaluación de impactos causados por proyectos mini-hidro sobre el medio humano

Manuscrito en preparación

IV.3.1 Introducción

En Chile, el Servicio de Evaluación Ambiental (SEA) es un organismo público que tiene por misión "*contribuir al desarrollo sustentable, la preservación y conservación de los recursos naturales y la calidad de vida de los habitantes del país*" (SEA, 2018), a través del Sistema de Evaluación de Impacto Ambiental (SEIA), el cual es un instrumento de gestión ambiental, encargado de evitar el deterioro del medio ambiente. Los proyectos o actividades que se deben someter al SEIA se encuentran establecidos en el artículo 3 del DS N°40/2013 o en el artículo 10 de la Ley N°19.300 modificada por la Ley N°20.417. Estos proyectos deben presentar una Declaración de Impacto Ambiental (DIA) salvo que generen al menos uno de los efectos, características o circunstancias mencionadas en el artículo 11 de la Ley N°19.300, que en este caso el titular del proyecto deberá realizar un Estudio de Impacto Ambiental (EIA). La ley establece seis situaciones ante las cuales se debe realizar un EIA y de las cuales dos aplican directamente al medio humano: la letra a) sobre el "Riesgo para la salud de la población, debido a la cantidad y calidad de efluentes, emisiones o residuos" y en la letra c) sobre actividades o proyectos que generan "Reasentamiento de comunidades humanas, o alteración significativa de los sistemas de vida y costumbres de grupos humanos". Los requerimientos mínimos están establecidos en el artículo 19 del DS N°40/2013, para el caso de las DIA; mientras que los de un EIA se encuentran en artículo 18 del DS N°40/2013 como muestra la Figura 23.

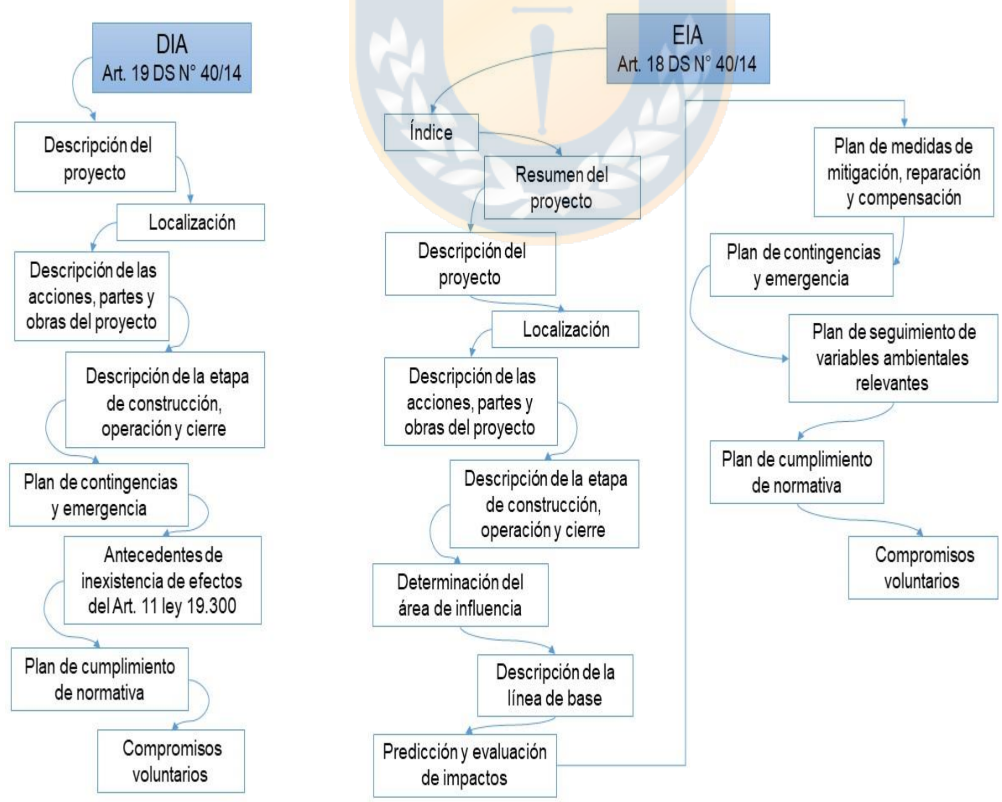

Figura 23: Contenidos mínimos exigidos por el SEIA a las DIA y EIA. Fuente: Modificado de DS N°40/2013.

Si el proyecto o actividad cumple con estos requisitos ingresará a evaluación ambiental, donde los diferentes organismos públicos lo revisarán y realizarán solicitudes de aclaración de información, presentarán correcciones y/o consultas en un documento llamado Informe Consolidado de Solicitud de Aclaraciones, Rectificaciones y/o Ampliaciones (ICSARA). El titular por su parte, debe responder las observaciones de todos los organismos mediante un informe llamado ADENDA. Una vez aclaradas y respondidas todas las observaciones de los organismos con competencia ambiental (OECA), se emite un Informe Consolidado de Evaluación (ICE), el cual contiene los pronunciamientos ambientales fundados por parte de los OECA que participaron en la evaluación, la evaluación técnica de las observaciones planteadas por la comunidad (cuando corresponda), así como la recomendación de aprobación o rechazo del proyecto. Finalizada la evaluación ambiental, se califica el proyecto, aprobándolo o rechazándolo, mediante una Resolución de Calificación Ambiental (RCA, SEA 2018). Pese a las muchas exigencias que tiene el SEIA, presenta algunas limitaciones como instrumento, siendo la principal, el sólo ser es una herramienta de evaluación y no poder realizar propuestas de modificaciones al proyecto o actividad. El titular por su parte, tampoco puede presentar un listado de alternativas para sus acciones y/o partes, sino que debe optar por una única opción de evaluación.

Dentro de los EIA, es obligatorio realizar una participación ciudadana no vinculante, lo que genera en muchos casos la obvia frustración de la comunidad que participa cuando sus observaciones y demandas no son atendidas, originando conflictos sociales e induciendo la judicialización. Por otra parte, habitualmente se detectan serias falencias en la cantidad y calidad de la información utilizada para la elaboración de la línea base del medio humano, la que típicamente se realiza sobre la base de datos secundarios, tales como: Censo y estadísticas nacionales oficiales, omitiendo la aplicación de herramientas específicas de mayor precisión como: Entrevistas a actores clave, encuestas, talleres participativos, entre otras. Lo anterior, se atribuye principalmente a los pocos recursos económicos que destinan los titulares para desarrollar la línea base del medio humano. Además, el documento que se elabora no contempla un capítulo que sintetice toda la información levantada, donde sea posible visualizar los efectos sinérgicos que puede generar el proyecto o actividad. Más bien, los capítulos son levantados, generalmente por separado, sin una conexión más profunda entre las componentes a evaluar (Walker e Irarrázabal, 2016).

Hasta el año 2013 estuvo vigente el DS N° 95/2002 que era el antiguo reglamento del SEIA. En su artículo 12 letra f.3, se establecían los contenidos mínimos de la línea de base para el medio humano como muestra la Figura 24. Sin embargo, a partir del 2014 entra en vigencia el DS N° 40/2013, actual reglamento del SEIA, el cual en su artículo 18 letra e.10, entrega directrices más detalladas para realizar esta línea base, descritas a continuación (ver Figura 25):

- Dimensión geográfica: distribución de los grupos humanos en el territorio y la estructura espacial de sus relaciones, contemplando la densidad y distribución espacial de la población, flujos de comunicación y transporte, tamaño de los predios y tenencia de la tierra.

- Dimensión demográfica: estructura de la población local por edades, sexo, categoría ocupacional y estatus migratorio, contemplando la estructura urbano rural; la estructura según rama de actividad económica y categoría ocupacional; población económicamente activa; escolaridad y nivel de intrusión; y migraciones.

➢ Dimensión antropológica: características étnicas de la población y manifestaciones de cultura, como creencias religiosas, peregrinaciones, procesiones, celebraciones, festivales, torneos, ferias y mercados.

➢ Dimensión socioeconómica: empleo, desempleo y la presencia de actividades productivas dependientes de la extracción y/o uso de recursos naturales por parte de los grupos humanos presentes, de manera individual o asociativa.

➢ Dimensión de bienestar social básico: acceso de los grupos humanos a bienes, equipamiento y servicios, como vivienda, transporte, energía, salud, educación, servicios sanitarios y de recreación.

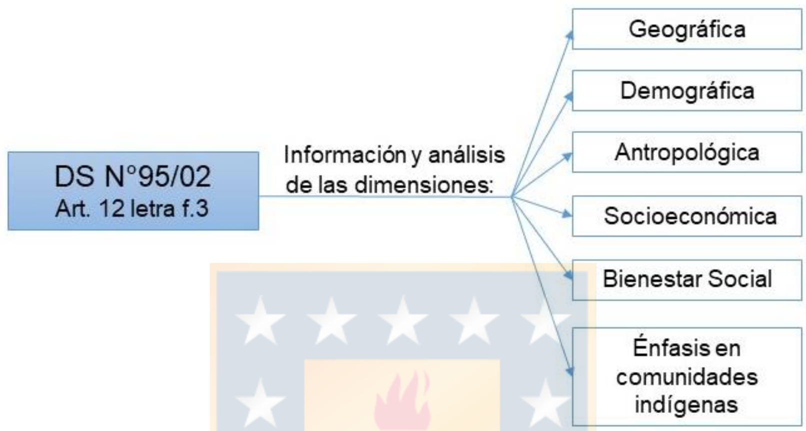

Figura 24: Contenidos exigidos en la línea de base para el medio humano según DS N°95/2002.

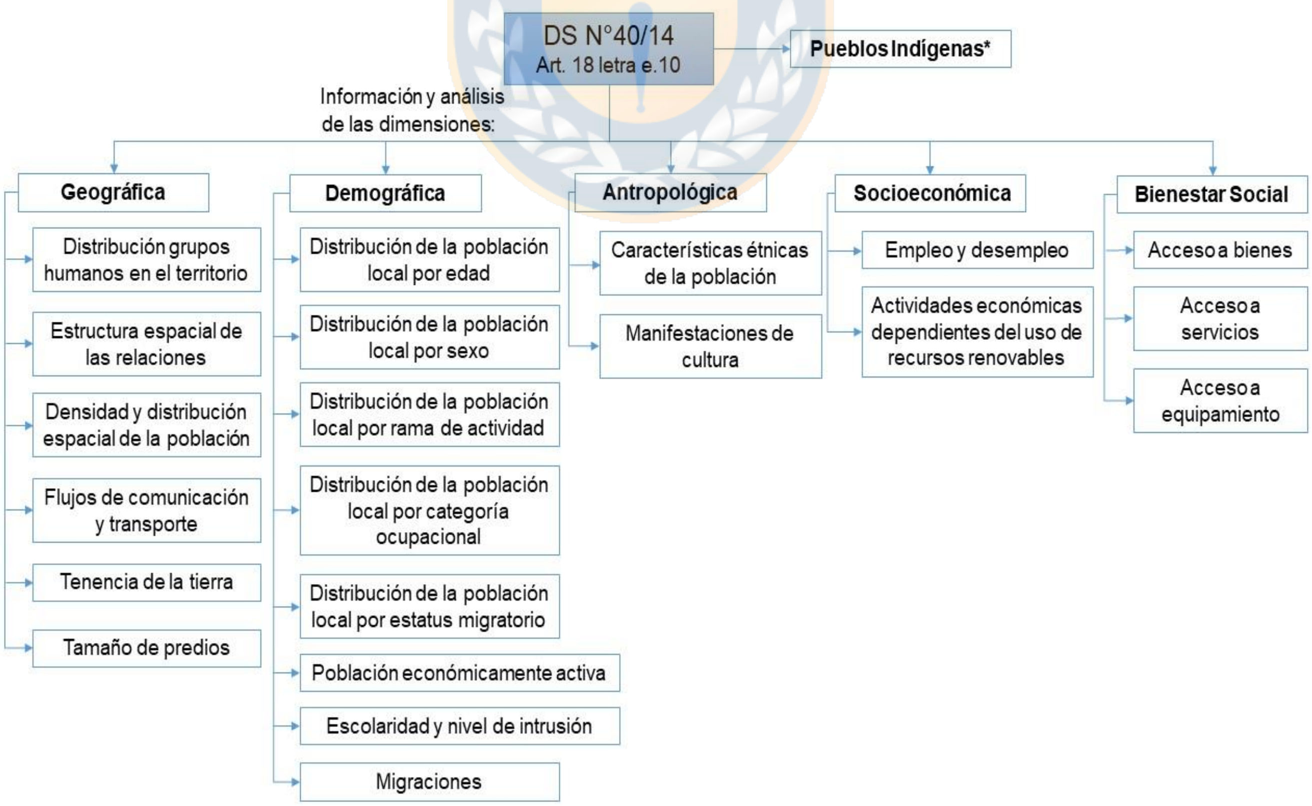

Figura 25: Contenidos exigidos en la línea de base para el medio humano según DS N°40/2013.

Para facilitar el levantamiento de la información y posterior evaluación de impacto ambiental, el SEA publicó en el año 2014 una guía de evaluación de impacto ambiental para el reasentamiento de comunidades humanas. Esta guía establece un lineamiento de cómo realizar la evaluación ambiental a grupos humanos que son afectados por la relocalización o reasentamiento. Sin embargo, no trata en mayor profundidad la evaluación de los impactos producto de la alteración significativa a los medios de vida de los grupos humanos, siendo que también forma parte de la letra c) del artículo 11 de la Ley N° 19.300. Adicionalmente, existe un apartado especial para los grupos humanos que pertenezcan a pueblos indígenas (ley 19.253), ya que se debe describir con particular énfasis el uso y valorización de los recursos naturales, prácticas culturales, estructura organizacional, apropiación del medio ambiente (uso medicinal, preparación de alimentos, etc.), patrimonio cultural indígena, identidad grupal mediante elementos culturales, sistema de valores, ritos comunitarios y símbolos de pertenencia grupal (SEA, 2018).

Una alternativa para realizar un diagnóstico de la evaluación de impactos sobre el medio humano de un grupo de proyectos dentro de un área son los marcos de referencia, los cuales enfatizan distintos aspectos y componentes del sistema socio-territorial. No obstante, previo a la aplicación de algún marco, es necesario conocer cómo las comunidades y grupos humanos aledaños se desempeñan, conviven y enmarcan en el territorio, de manera que la elaboración de un estudio de línea de base social no sea interpretado como datos estadísticos del área de influencia, sino que se trate de la socio-morfología interna de la sociedad, esto es, su cohesión, valores practicados por la comunidad, interrelaciones humanas, tipo de vecindario, historia del poblamiento, niveles de confianza y desconfianza existentes, la valoración y percepción de los ecosistemas, las condiciones de vida y de trabajo (Rojas, 2017). Se entiende entonces que la línea de base social es una caracterización exhaustiva, y específica del área y la comunidad afectada por una intervención, que abarca el conjunto de factores y dimensiones que componen la historia y la calidad de vida social, cultural, territorial, laboral y vecinal (Rojas, 2017).

En la academia, diversos equipos de investigadores han creado e implementado metodologías que evalúan y analizan el impacto en la dimensión social, el reasentamiento de las comunidades y los efectos en el medio humano de cualquier proyecto de ingeniería. Según Kirchherr & Charles (2016), algunas de las metodologías más recurrentes para la determinación de los impactos sobre el medio humano de un proyecto hidroeléctrico son:

- *Relocation framework (RF)* de Scudder y Colson (1992): Modelo que describe mediante cuatro etapas "…*cómo se espera que la mayoría de los reasentados se comporten durante un proceso de reasentamiento exitoso*…" (Scudder, 2012).

- *Impoverishment risks and reconstruction model (IRR)* de Cernea (1997): Modelo que describe siete riesgos potenciales de empobrecimiento producto del desplazamiento de las comunidades.

- *Sustainable livelihoods framework (SL)* de DFID (1999): Marco que describe los factores principales que influyen en los medios de vida de las personas y estrategias de los medios de subsistencia para alcanzar los resultados esperados y descritos.

- *World commission of dams framework* de la WCD (2000): Marco que esboza siete prioridades estratégicas para la construcción sostenible de represas.

➢ *Integrative dam assessment model (IDAM)* de Kliber et al. (2012): Modelo multidisciplinario sobre el impacto en el medio humano de las represas, el cual detalla siete componentes socioeconómicos del impacto, siete componentes geopolíticos del impacto y siete componentes biofísicos del impacto.

Kirchherr & Charles (2016) a través de una meta-síntesis, lograron identificar cinco brechas en la investigación social para proyectos hidroeléctricos: falta de perspectiva (45% negativa, 5% positiva y un 50% no significativa), tamaño de la represa (las grandes represas están sobrerrepresentadas en los estudios), carencia de enfoque espacial (estudios orientados sólo en el área de reasentamiento), falta de enfoque temporal (la mayoría realizado 5-10 años luego de finalizado la construcción del proyecto) y sesgos en los puntos de vista de los desarrolladores de las represas. Así, con la información obtenida, generaron un marco alternativo a los 5 mencionados llamado "Marco Matriz", el cual establece componentes y dimensiones en las que deben ser evaluados los impactos sobre el medio humano (Figura 26).

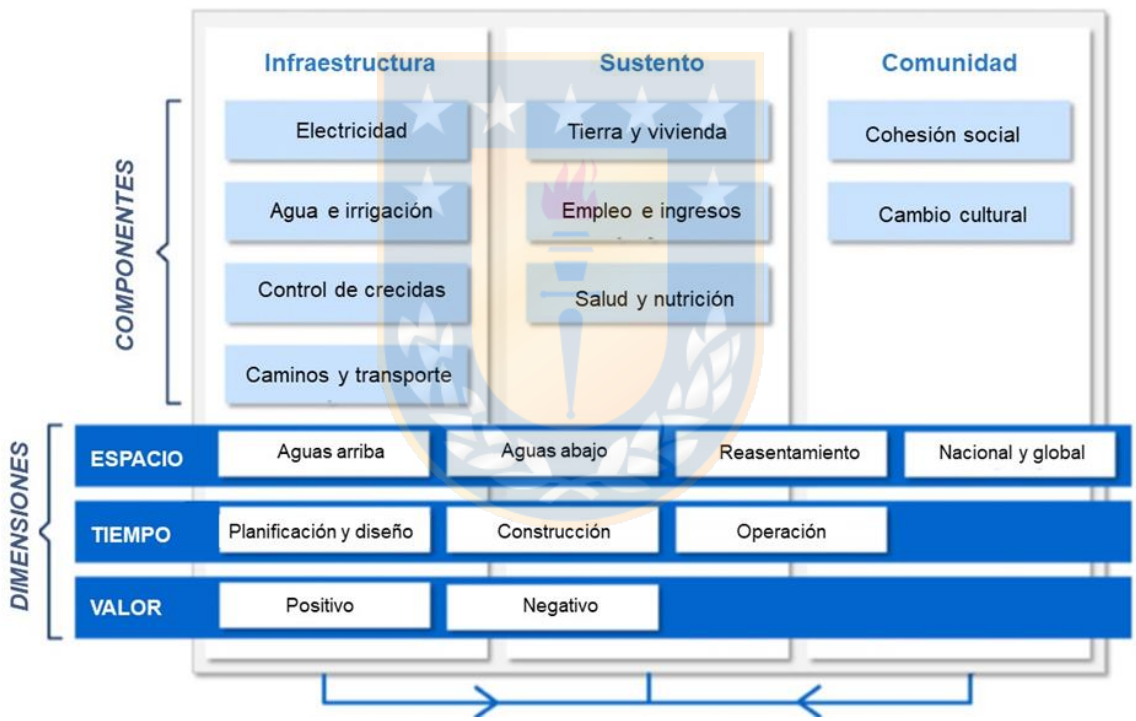

Figura 26. Marco matriz para evaluación de impactos sobre el medio humano de proyectos hidroeléctricos. Fuente: Kirchher & Charles 2016.

Frente al explosivo aumento de pequeñas centrales hidroeléctricas que se ha observado desde el año 2008 entre las cuencas de los ríos Maipo y Maullín y dada la actual evaluación de impactos sobre el medio humano centrada en el reasentamiento de las comunidades, más que en las modificaciones a los sistemas de vida y costumbres de grupos humanos, es necesario comprender y analizar el estado actual de las EIAs sobre el medio humano, en base a un diagnóstico que permita determinar las principales brechas y falencias existentes.

IV.3.2 Metodología

Área de Estudio

El área de estudio comprende a once cuencas andinas ubicadas entre los ríos Maipo al Maullín (Figura 27), situadas entre las latitudes 32°55’ y 41°48’ S, correspondientes a la zona centro-sur de Chile. Abarcan las regiones administrativas: Metropolitana, Gral. Libertador Bernardo O’Higgins, Maule, Ñuble, Biobío, Araucanía, Los Ríos y Los Lagos, con una población cercana a los 13.280.496 habitantes (75.6% de total del país, INE 2018), concentradas principalmente en las cuencas de los ríos Maipo y Biobío. La superficie total de las cuencas es 152.351 km^2, siendo la de mayor tamaño la del río Biobío con 24.369 km^2, y la menor la cuenca del río Mataquito con 6.332 km^2 (DGA, 2016). Existen tres climas dominantes según la clasificación de Köppen (actualizada por Beck 2018), correspondientes a: *Csa,* templado con verano seco y caluroso; *Csb,* Templado con verano seco y cálido; *Cfb,* templado cálido sin estación seca. Además, las cuencas en estudio concentran el 95,4% de desarrollo hidroeléctrico nacional (equivalente a 6.37 GW de potencia instalada, Ministerio de Energía 2019).

Tabla 8. Ubicación, datos geomorfológicos y climáticos para cada cuenca en el área de estudio.

Cuenca	Latitud (° ’)	Longitud (° ’)	Área (km^2)	Altura máxima (m)	Clasificación climática	Q_{MA} (m^3/s)
Maipo	32°55’ – 34°18’ S	69°48’ – 71°38’ O	15.273	6.546	Csa-Csb	134
Rapel	33°54’ – 35°00’ S	70°01’ – 71°51’ O	13.766	5.138	Csa-Csb	169
Mataquito	34°48'– 35°38' S	70°24' – 72°11' O	6.332	4.058	Csb	113
Maule	35°06' – 36°35' S	70°21' – 72°27' O	21.052	3.931	Csb	495
Itata	36°12' – 37°20' S	71°02' – 72°52' O	11.326	3.178	Csb	331
Biobío	36°52’ – 38°54' S	70°50' – 73°12' O	24.369	3.487	Csb	971
Imperial	37°49'- 38°58' S	71°27' – 73°30' O	12.668	3.066	Csb-Cfb	264
Toltén	38°36' – 39°38' S	71°24' – 73°14' O	8.448	3.710	Cfb	540
Valdivia	39°18' – 40°12' S	71°36' – 73°24' O	10.244	2.824	Cfb	546
Bueno	39°54' – 41°17' S	71°40' – 73°43' O	15.366	2.410	Cfb	394
Maullín	40°15' – 41°48' S	71°50' – 73°56' O	13.507	3.428	Cfb	90

Por otro lado, los usos principales del agua en las cuencas son: riego, abastecimiento de agua potable, desarrollo de actividades industriales, hidroelectricidad, sitios prioritarios de conservación. Con respecto a los principales usos de suelo, destacan: terrenos agrícolas, bosque nativo y mixto, y plantaciones forestales. (DGA, 2016)

2.2 Análisis de la evaluación de impacto ambiental para el medio humano

Se analizaron los proyectos hidroeléctricos ingresados al SEIA entre los años 2008 y 2016, correspondientes a 105 proyectos hidroeléctricos (como se observa en la Figura 27), de los cuales 79 corresponden a centrales hidroeléctricas no convencionales (CHNC) entre las cuencas de los ríos Maipo al Maullín.

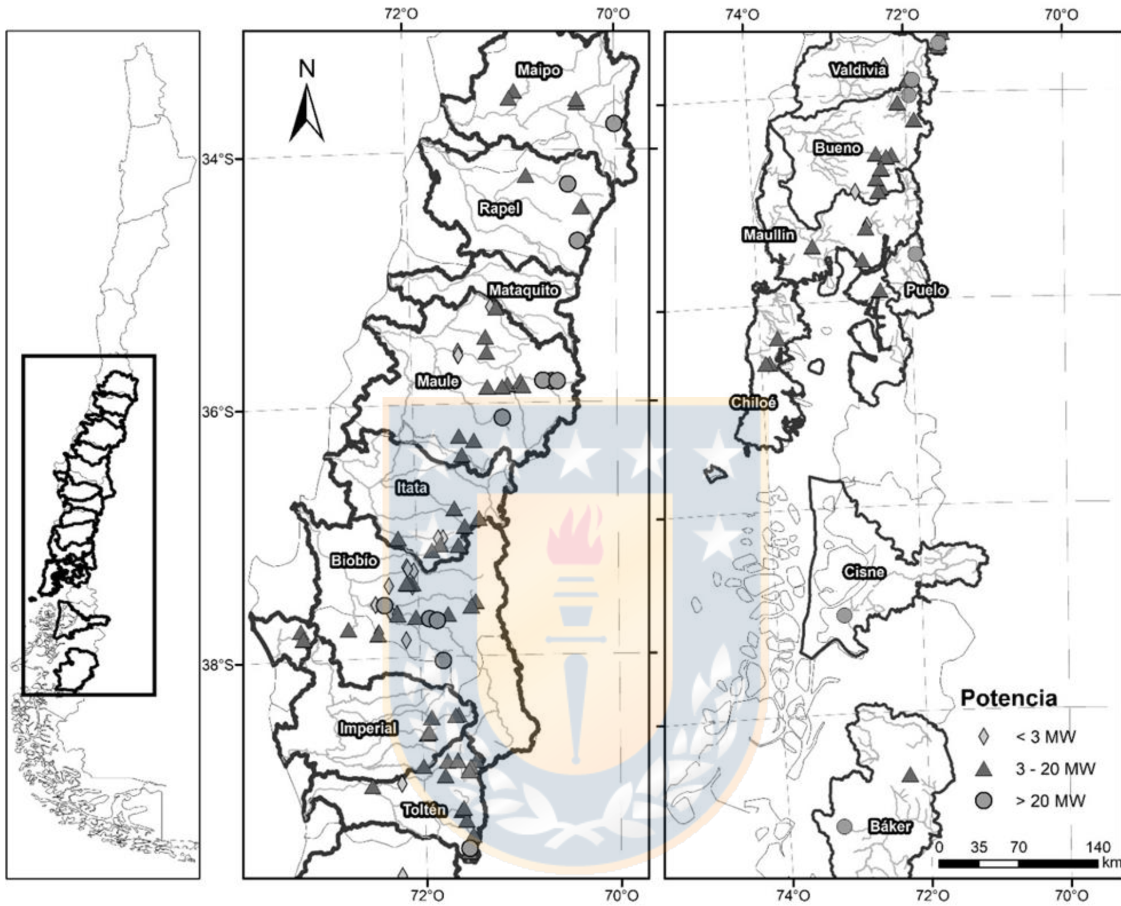

Figura 27. Proyectos hidroeléctricos ingresados al SEIA durante el periodo 2008-2016. Fuente: Rodríguez (2018).

En cuanto a las DIA ingresadas en el periodo, debido a que éstas no hacen un levantamiento de línea base para el medio humano, se procedió a revisar cómo justificaban la inexistencia de impactos sobre los sistemas de vida y costumbres de los grupos humanos (letra c) del artículo 11 de la Ley 19.300).

En el caso de proyectos que presentaron EIA, se revisaron las categorías: (1) localización del proyecto, (2) descripción del proyecto, (3) línea de base: Medio Humano, (4) predicción y evaluación de impactos, (5) medidas de mitigación, reparación y/o compensación, (6) ICSARA, (7) ADENDA, (8) ICE y (9) RCA. Además, se realizó una identificación aparte de los impactos sobre el medio humano que afectan a pueblos indígenas, revisando adicionalmente en estos casos la consulta indígena, predicción y evaluación de impactos en el medio humano, y medidas de mitigación, reparación y/o compensación relacionadas con las comunidades indígenas.

Marco matriz de Kirchherr & Charles (2016) y aplicación a la evaluación actual de impactos sobre el medio humano.

El marco matriz se conforma por componentes y dimensiones (Figura 26), las componentes son las variables en las que se debe identificar el impacto y debiesen estar presentes como impactos declarados en la totalidad de los proyectos hidroeléctricos. Dichas componentes son: "Infraestructura", "Sustento" y "Comunidad", cada una de ellas con subcomponentes asociadas.

Componente Infraestructura:

- Electricidad: Impactos asociados con el acceso al suministro eléctrico.
- Agua e irrigación: Impactos asociados al uso y sentido de pertenencia del recurso hídrico, así como los efectos temporales y permanentes sobre el regadío.
- Control de crecidas: Impactos asociados a los riesgos en la seguridad de las personas a causa de la infraestructura de la central hidroeléctrica.
- Caminos y transporte: Impactos asociados con el acceso a caminos, efectos sobre la infraestructura vial, equipamiento de rutas de acceso y en el flujo vehicular.

Componente Sustento:

- Tierra y vivienda: Impactos asociados con la tenencia de la tierra, efectos en el uso de ésta y sobre los hogares (entiéndase como pérdida o ganancia de patrimonio).
- Empleo e ingresos: Impactos asociados a la empleabilidad de personas económicamente activas y los efectos en los ingresos que genera la construcción y operación de una central hidroeléctrica próxima a una localidad.
- Salud y nutrición: Impactos asociados al acceso a servicios de salud, y al riesgo potencial en la salud de las personas a causa de la construcción y operación de una central hidroeléctrica.

Componente Comunidad:

- Cohesión social: Impactos asociados con la estructura de las relaciones de los grupos humanos y efectos en su distribución espacial.
- Cambio cultural: Impactos relacionados con las características étnicas de la población, efectos sobre sus manifestaciones culturales, rituales y/o festividades.

Las dimensiones son los ejes en los cuales se debe analizar la evaluación de los impactos sobre el medio humano.

- Dimensión Espacio: Área física donde deben ser evaluados los impactos sobre el medio humano, es decir, desde una visión aguas arriba y aguas abajo del proyecto, desde la perspectiva del reasentamiento (si existiese), y en un marco local y nacional. Esta dimensión está estrechamente relacionada con la determinación y justificación del área de influencia de los EIA.

- Dimensión Tiempo: Correspondiente a las etapas del proyecto en las cuales se deben identificar los impactos para el medio humano. La escala temporal corresponde a la etapa de planificación y diseño, construcción y operación.
- Dimensión Valor: Carácter que se obtiene al evaluar las componentes (impactos en el medio humano) en las distintas dimensiones (espacio y tiempo).

Para la aplicación del marco matriz no se consideró la componente "Control de crecidas", debido a que sólo grandes centrales hidroeléctricas con embalses de varios millones de m^3 pueden tener el efecto de amortiguar una crecida, que no es el caso de un central de potencia menor a 20 MW. Tampoco se consideró la dimensión "Planificación y diseño", porque el SEIA en su reglamento no exige una predicción y evaluación de impactos en una etapa previa a la de construcción.

El marco matriz de Kirchher & Charles (2016) se aplicó con la información recopilada de los EIA de proyectos hidroeléctricos, diferenciando aquellos que ingresaron por DS N°95/2002 y DS N°40/2013. Se vincularon las componentes y dimensiones del marco matriz con lo que exige el SEIA en la evaluación de impactos en el medio humano de la siguiente forma:

- Componentes: Capítulo del EIA "Predicción y evaluación de impactos ambientales", específicamente el subcapítulo correspondiente al medio humano, donde se contabilizó si los proyectos declararon impactos asociados a las componentes del marco matriz.

- Dimensión espacial: Capítulo "Línea de base" del EIA, específicamente en la determinación y justificación del área de influencia para el medio humano, donde se contabilizó si los proyectos en la determinación del área de estudio tenían enfoque nacional o global, aguas arriba y aguas abajo del proyecto.

- Dimensión temporal: Capítulo del EIA "Predicción y evaluación de impactos ambientales" pero diferenciando los identificados en la etapa de construcción y en la etapa de operación.

- Dimensión valor: Capítulo "Predicción y evaluación de impactos ambientales" del EIA, pero enfocado en la metodología de evaluación de impacto y la jerarquía en la valoración, es decir, si la metodología utilizada considera el valor ambiental por elemento (VAE), donde se contabilizó si los impactos declarados asociados a las componentes, tenían una valoración positiva, negativa o no significativa.

IV.3.3 Resultados

Los resultados muestran que un 67% (53 proyectos), ingresaron al SEIA mediante una DIA, las que no evalúan los potenciales efectos sobre el medio humano. El año 2013 registró el mayor número de ingresos (24) coincidente con la transición entre el DS Nº95/2002 y DS Nº40/2013, y además ninguno de los 79 proyectos ingresado en el periodo 2008-2016 fue rechazado. La Figura 28 muestra una síntesis del catastro realizado.

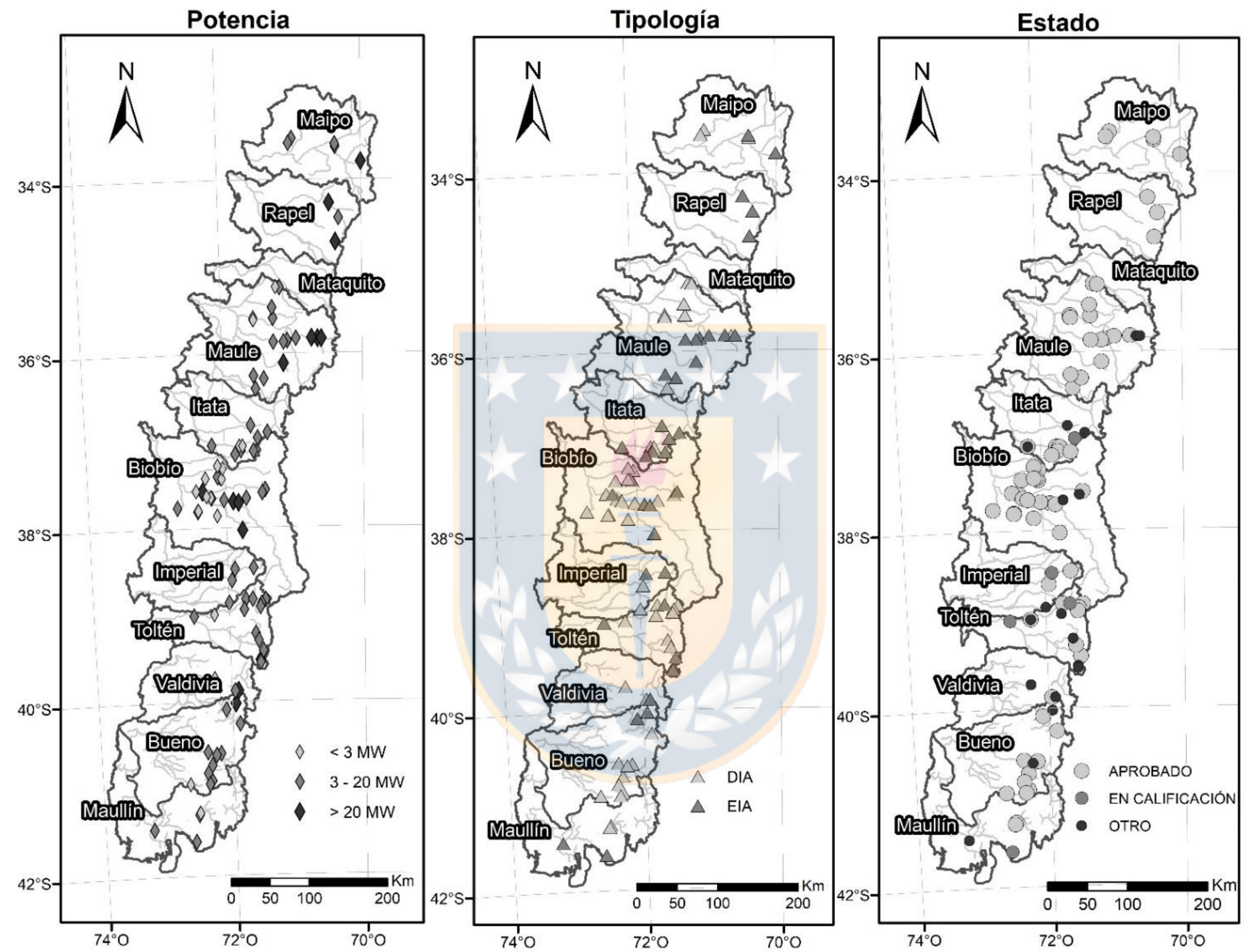

Figura 28. Proyecto hidroeléctricos ingresados a evaluación ambiental en el área de estudio por a) Potencia; b) Tipología; c) Estado (otro corresponde a los estados: no admitido a calificación, desistido o no calificado).

El análisis por cuenca identificó que la mayor cantidad de ingresos de proyectos de CHNC fueron en la cuenca del río Biobío (18 proyectos), río Maule (13 proyectos), y los ríos Itata, Toltén y Bueno (10 proyectos cada una). En cuanto a la tipología de los proyectos, el mayor número de EIA catastrados fue en la cuenca del río Itata (8 EIA y 2 DIA) y el río Maule (6 EIA y 7 DIA), mientras que la cuenca que presenta mayor ingreso por DIA es la cuenca del río Biobío (17 DIA y 1 EIA). Por último, las cuencas donde han sido aprobados más proyectos de CHNC son el río Biobío (16 proyectos), el río Maule (13 proyectos) y el río Bueno (9 proyectos).

Los 53 proyectos que ingresaron a través de DIA, se concentran mayoritariamente en el valle central y precordillera andina, con potencia desde 0,75 MW a 19,2 MW, donde el 36% (19) de estos proyectos se encuentran situados en canales de regadío. Respecto de la no pertinencia de realizar un EIA, el principal fundamento es el argumento técnico "las cotas de inundación de los proyectos no es suficiente para generar reasentamientos". En el caso de la alteración a los sistemas de vida de los grupos humanos, sólo justifican que no afectarán a las dimensiones demográfica, geográfica, antropológica, socioeconómica y de bienestar social, utilizando los argumentos: (1) no existirán cambios en los patrones económicos ni de empleo, (2) no habrá alteración de la oferta y demanda de servicios en las comunidades locales, (3) el lugar físico donde se instalará el proyecto está despoblado, por lo que no perturbará ceremonias ni el patrimonio cultural y (4) la envergadura del proyecto no generará un incremento de población flotante en las localidades cercanas.

En el caso de los proyectos que realizaron EIA (26), se encontraron las siguientes características comunes:

- Localización del proyecto: La totalidad de los proyectos ingresados se sitúan en sectores precordilleranos o de la depresión intermedia. Además, entregan una aproximación de las zonas pobladas colindantes al proyecto. En casos específicos, se indican las centrales hidroeléctricas operativas situadas aguas arriba o abajo del proyecto.

- Descripción del proyecto: Los 26 proyectos analizados corresponden a centrales hidroeléctricas de pasada tipo *"high-head"*, cuya cota de inundación no es suficiente para generar reasentamiento de población, por lo que ninguno de estos proyectos ingresó como EIA debido a la letra c) del artículo 11 de la Ley 19.300.

- Línea de base para el medio humano: Se evidenciaron falencias significativas en la determinación del área de influencia (AI) de los proyectos. Debido principalmente a que previo al año 2017 no existía la guía para la descripción del AI (SEA, 2017), y sólo 5 de los EIA revisados están en concordancia con las directrices de esta guía. Además, se detectó una carencia de información primaría en las líneas base, 7 proyectos sólo utilizan fuentes secundarias, y el resto un enfoque mixto, siendo la entrevista semiestructura y abierta a actores clave (13 proyectos) la principal fuente primaria de información, seguido de las encuestas (8 proyecto).

- Predicción y evaluación de impactos: En los EIA revisados se reconocen impactos en la etapa de construcción y operación, no así en la etapa de abandono. Respecto a las metodologías utilizadas, predominan aquellas que incluyen el VAE (17 proyectos), siendo la evaluación de los impactos en una mayor proporción negativos, pero no significativos (58% de impactos son de carácter negativo), es decir, no requieren medidas de mitigación, reparación y/o compensación obligatorios.

En los 26 EIA analizados se encontraron 161 impactos declarados sobre el medio humano, los que se agrupan en 17 clases (la Figura 29 muestra las clases con mayor frecuencia en los EIA):

1. Generación de empleo.*
2. Afectación a las rutas de acceso.*

3. Alteración a los patrones de actividad económica*
4. Afectación a la calidad de vida.*
5. Afectación a la estructura de la población.*
6. Afectación a la seguridad ciudadana.*
7. Afectación a las prácticas de crianza de animales.
8. Aumento de la seguridad energética.**
9. Alteración al uso del territorio (suelo).*
10. Alteración a los sitios de importancia cultural, ritual y arqueológica.
11. Alteración a los usos recreativos del recurso hídrico.**
12. Alteración en el modo de uso del recurso hídrico (bebida animal, riego, etc).**
13. Alteración a las actividades turísticas. *
14. Riesgos de afectación a la salud de las personas.*
15. Afectación en la valorización cultural y ambiental para comunidades no indígenas.
16. Alteración del entorno por realización de actividades en cercanía de comunidades indígenas.
17. Afectación en la valorización cultural y ambiental para pueblos indígenas.

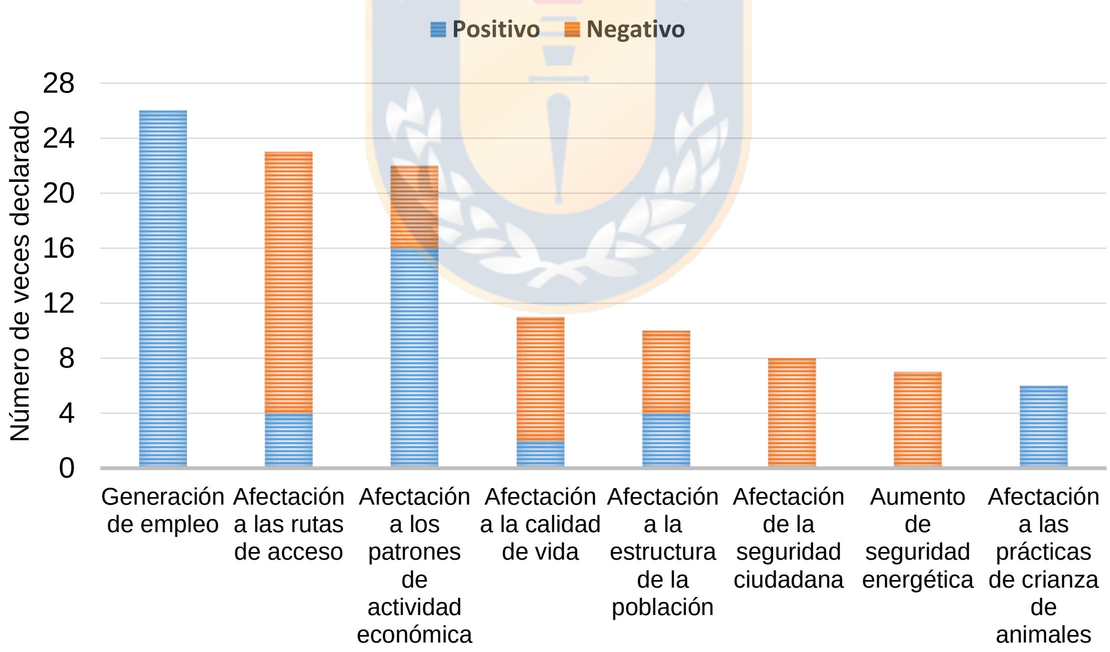

Figura 29. Clases de impactos sobre el medio humano declarados con mayor frecuencia en los proyectos hidroeléctricos (<20 MW) para las cuencas entre el río Maipo y Maullín, en el periodo 2008-2016.

Estos impactos son concordantes y similares a los reportados por Kumar Sharma & Thakur (2017), Kelly-Richards et al. (2017) y Environmental Justice Atlas (2019), donde 9 de las 17 clases (marcadas con un *) se reconocen en los impactos atribuibles a cualquier proyecto de infraestructura y 3 clases (marcadas un con **) comunes para cualquier proyecto hidroeléctrico. Por otro lado, de los 161 impactos declarados sólo 17 corresponden a impactos sitio-específicos, quedando en evidencia la falta de recolección y posterior análisis de la información utilizada para predecir los impactos en el medio humano. No obstante, cabe señalar que los proyectos que afectan a comunidades indígenas o sus territorios constituyen una excepción a lo detectado en el párrafo anterior, ya que están afectos a la ley 19.253 que exige mayores estándares de calidad a la elaboración de EIA. Los impactos declarados que afectan directamente a comunidades indígenas o sus territorios son tres, cuyo carácter es negativo significativo en todos los casos analizados:

1. Actividades exógenas en cercanía de poblaciones indígenas protegidas por ley 19.253.
2. Transformación del espacio territorial, lo que cambia la valoración cultural y ambiental que la población indígena tiene del territorio.
3. Proximidad a sitios de significancia cultural y ceremonial para la comunidad indígena.

- Medidas de mitigación, reparación y/o compensación: A pesar de la jerarquización que presentan los impactos negativos (poco o no significativos), 20 de los 26 EIA consideran medidas de mitigación, compensación y/o reparación. Además, adquieren compromisos voluntarios con las comunidades afectadas, siendo los principales: (1) capital para emprendimientos de los habitantes del sector, (2) becas para estudiantes de la educación superior, (3) apoyo técnico en postulaciones para fondos concursables.

- ICSARA y ADENDA: Las acotaciones realizadas por los OECAS en el medio humano, tienen relación con la predicción de impactos, la evaluación de éstos y sus posteriores medidas de manejo. De los 26 proyectos, 15 presentan observaciones y solicitudes de ampliaciones respecto a lo que describe el impacto y su evaluación. Además de considerar otros y añadir nuevas medidas de mitigación, reparación y/o compensación, según corresponda.

- ICE y RCA: Un total de 17 proyectos cuenta con una RCA vigente, por tanto, permite verificar si las observaciones y solicitudes presentadas en las ICSARA son consideradas oficialmente como exigencias propias del proyecto, donde ocho de estos proyectos incorporan la información obtenida del proceso de evaluación.

La aplicación del marco matriz de Kirchher & Charles (2016) dejó en evidencia que en la componente Infraestructura los impactos que se encuentran mayormente considerados corresponden a “caminos y transporte” con 21 proyectos, existiendo falencias en los impactos asociados a “electricidad” e “irrigación y agua”, donde sólo ocho y tres proyectos los consideran respectivamente. En la componente Sustento, los impactos mayormente considerados corresponden a “ingresos y empleo” y “tierra y vivienda” con 24 y 14 proyectos respectivamente. Existen falencias en los impactos asociados a la “salud y nutrición” con sólo siete proyectos que consideran afectaciones en esta área. En la componente Comunidad, los impactos que se encuentran mayormente considerados son los relacionados con la “cohesión social” con 19 proyectos, siendo el “cambio cultural” el menos considerado con sólo 12 proyectos.

En el caso de las dimensiones que componen el marco matriz, la mayormente evaluada es la dimensión temporal, mientras que la dimensión espacial presenta un 90% de inconformidad en la evaluación social. Los resultados muestran que para la dimensión Espacio, en la determinación del área de influencia, ocho proyectos consideraron una visión "global y nacional", mientras que sólo cinco consideraron una visión "aguas arriba" y "aguas abajo" en la determinación y justificación del área de influencia. Ninguno de los proyectos generó reasentamiento de comunidades, por lo que no se identificó una zona de relocalización para los grupos humanos afectados. En la dimensión Tiempo, todos los proyectos consideraron impactos en la etapa de construcción, mientras que 22 proyectos los consideraron en la etapa de operación. En la dimensión Valor, de los 161 impactos declarados, 63 tienen carácter positivo, 94 impactos son declarados negativos y el resto son neutros. En los 26 proyectos revisados, sólo uno no declara impactos negativos y dos no declaran impactos positivos.

IV.3.4 Conclusiones

Se detectó que un 67% de los proyectos de CHNC ingresados al SEIA en el periodo 2008-2016 lo realiza mediante una DIA, generando un vacío de información en la evaluación de los impactos en el medio humano y sus posteriores consecuencias. En el caso de los EIA el análisis realizado permite que concluir: (1) falta de levantamiento de información primaria en las líneas base para el medio humano, (2) determinación insuficiente del área de influencia de los proyectos, (3) carencia en la detección de impactos sitio-específicos en el medio humano, (4) escasa participación de las comunidades locales en el proceso de evaluación del proyecto y (5) la evaluación de impactos ambientales son mayoritariamente de carácter negativo no significativo, por lo que se observan principalmente compromisos voluntarios más que medidas de mitigación, compensación y/o reparación.

La aplicación del marco matriz dejó en evidencia que un 44% de las componentes que recomienda Kirchher & Charles para la evaluación social, están presentes en la predicción de impactos de los EIA, siendo las mayormente representadas: "ingresos y empleo" y "caminos y transporte"; mientras que las con menor representación son "agua e irrigación" y "salud y nutrición".

La dimensión espacial es la dimensión que presenta mayores falencias para la evaluación de impactos sobre el medio humano, ya que según las directrices del marco matriz, las áreas de influencia establecidas en los EIA simplemente no permitieron la evaluación de impactos sobre el medio humano. En el caso de las dimensiones temporal y valor, ambas se encuentran suficientemente representadas por los EIA.

Desde la entrada en vigencia del actual reglamento del SEIA (DS N°40/2013) se detectaron mejoras en la información levantada por los EIA y en las evaluaciones de impactos sobre el medio humano.

IV.3.5 Referencias

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future köppen-geiger climate classification maps at 1-km resolution. Sci. Data 5, 1–12. https://doi.org/10.1038/sdata.2018.214

Cernea, M., 1990. Poverty risks from population displacement in water resources development. Working Paper. Disponible en https://www.cabdirect.org/cabdirect/abstract/19916712675.

DFID, 1999. Sustainable Livelihoods Guidance Sheets. Disponible en http://www.livelihoodscentre.org/documents/20720/100145/Sustainable+livelihoods+guidance+sheets/8f35b59f-8207-43fc-8b99-df75d3000e86

Direccion General de Aguas (DGA), 2016. Atlas del agua Chile. Disponible en http://bibliotecadigital.ciren.cl/handle/123456789/26705

Environmental Justice Atlas, (2019). Atlas de la justicia ambiental. Disponible en https://ejatlas.org/

Instituto nacional de Estadística (INE), 2018. Síntesis de resultados censo 2017. Disponible en https://www.censo2017.cl/descargas/home/sintesis-de-resultados-censo2017.pdf

Kelly-Richards, S., Silber-Coats, N., Crootof, A., Tecklin, D., & Bauer, C. (2017). Governing the transition to renewable energy: A review of impacts and policy issues in the small hydropower boom. Energy Policy, 101, 251–264. https://doi.org/10.1016/j.enpol.2016.11.035

Kirchherr, J. & Charles, K. (2016). The social impacts of dams: A new framework for scholarly analysis. Environmental Impact Assessment Review, 60, 99-114

Kibler, K., Tullos, D., Tilt, B.,Wolf, A.,Magee, D., Foster-Moore, E., Gassert, F., 2012. Integrative Dam Assessment Model (IDAM) Documentation: Users Guide to the IDAM Methodology and a Case Study from Southwestern China. Oregon State University, Corvallis, Oregon. Disponible en https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Facilitations/IDAM%20Manual%20on%20Methodology%202012.pdf

Kumar Sharma, A., & Thakur, N. S. (2017). Assessing the impact of small hydropower projects in Jammu and Kashmir: A study from north-western Himalayan region of India. Renewable and Sustainable Energy Reviews, 80(May), 679–693. https://doi.org/10.1016/j.rser.2017.05.285

Ministerio de Energía (2019). Módulo cartográfico. Disponible en http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/

Rodriguez C, (2018). Diagnóstico de la evaluación ambiental del medio humano para centrales hidroeléctricas de potencia menor a 20 MW en Chile. Universidad de Concepción, Concepción, Chile

Rojas, J. (2017). Participación ciudadana, calidad de vida y justicia trans-regional territorial: Una línea de base social de bien común. Ambiente & sociedad, 20, v.1, 21-42

Scudder, T. (2012). Resettlement outcomes of large dams. Impacts of large dams: A global assessment, 37-67

SEA. (2014). Guía de evaluación de impacto ambiental: Reasentamiento de comunidades humanas. Servicio de evaluación ambiental

SEA. (2017). Guía para la participación anticipada de la comunidad en proyectos que se presentan al SEIA. Disponible en https://www.sea.gob.cl/sites/default/files/imce/archivos/2017/05/03/guia_area_de_influencia_ajuste_10.pdf

SEA. (2018). Servicio de Evaluación Ambiental. Gobierno de Chile. Recuperado: http://www.sea.gob.cl/sea

Walker, P. & Irarrázabal, R. (2016). Los efectos acumulativos y el Sistema de Evaluación de Impacto Ambiental. Revista de Derecho Ambiental, IV, 67-91

WCD, 2000. Dams and Development — A New Framework for Decision-Making. World Commission on Dams. Disponible en https://www.internationalrivers.org/resources/dams-and-development-a-new-framework-for-decision-making-3939

V. Conclusión y Recomendaciones

La presente tesis doctoral constituye un aporte al desarrollo sustentable de los recursos energéticos, un reto crucial para el siglo XXI, específicamente el recurso hidroeléctrico. Se analizaron tres elementos críticos para el desarrollo sustentable del sector hidroeléctrico a través de pequeñas centrales hidroeléctricas (<20MW) relacionados con cada una de las dimensiones de la sustentabilidad y proporciona una base para delinear propuestas conceptuales a nivel de política para la adecuada planificación del desarrollo del sector mini-hidro en Chile Central.

La aplicación de inteligencia artificial mediante el algoritmo “MissForest”, resultó ser una herramienta altamente eficaz y precisa para el relleno de estadística hidrológica de caudales diarios en las cuencas de Chile Central que corresponde a una región con baja densidad de datos que además tienen muy mala calidad. De este análisis, resultó evidente la necesidad de densificar la red de monitoreo de caudales, llegando al menos a los estándares mínimos recomendados a nivel mundial (WMO, 2008).

En la dimensión económica se investigaron los efectos del clima sobre la disponibilidad del recurso, concluyendo que: (1) existen tendencias decrecientes significativas del potencial hidroeléctrico aprovechable en todas las cuencas analizadas que van desde los -22 a -47 MW/año y que dichas tendencias se mantendrán en el futuro. (2) Las tendencias observadas en el potencial hidroeléctrico aprovechable se encuentran moduladas por la variabilidad climática presentando periodos crecientes y decrecientes alternados. En el caso de estudio, i.e. en Chile Central, el potencial hidroeléctrico está correlacionado significativamente con la oscilación de El Niño en la escala interanual en todas las cuencas estudiadas. En la escala interdecadal se encontraron correlaciones significativas con la oscilación decadal del Pacífico (PDO), oscilación multidecadal del Atlántico (AMO) y el modulo anular del sur (SAM), donde el dominio de cada oscilación presenta diferencias entre cuencas. (3) La disponibilidad del recurso hidroeléctrico, es decir, los valores medios y medianos, se mantendrán hasta el año 2050. Sin embargo, se observaron reducciones en los valores extremos, sobre todo en los potenciales mínimos que pueden reducirse a un 40% en los escenarios más extremos. (4) Existe un riesgo de sobreinversión al no considerar los efectos de la variabilidad climática sobre el recurso hidroeléctrico, por ejemplo, de seguir la tendencia de desarrollo, la capacidad instalada para aprovechar hidroelectricidad en las cuencas del Biobío y Maule podría llegar a superar la disponibilidad del recurso.

Se recomienda establecer políticas de desarrollo hidroeléctrico que consideren la variabilidad temporal y espacial del clima en la disponibilidad del recurso hidroeléctrico. Por ejemplo, las leyes Nº 20.257, 2008, y Nº 20.698, 2013, mostraron ser efectivas para potenciar el desarrollo hidroeléctrico del país, sin embargo, deberían complementarse a fin de establecer niveles máximos de desarrollo considerando los potenciales esperados en cada cuenca. Además, se recomienda a inversionistas y desarrolladores de proyectos hidroeléctricos considerar la variabilidad climática en el dimensionamiento de las turbinas de PCH, para así maximizar el aprovechamiento global del recurso.

En la dimensión ambiental se analizaron los efectos del aprovechamiento del recurso sobre la conservación de especies, donde la investigación realizada dejó en evidencia que: (1) Existe un importante desconocimiento sobre la distribución espacial y los hábitats críticos de los organismos, sus rasgos funcionales y cómo interactúan con otras especies, además del efecto de las actividades antropogénicas sobre los ecosistemas fluviales, que en el caso de Chile, este conocimiento se ha generado mayoritariamente en base al desarrollo de Estudios de Impacto Ambiental. (2) Enfoques eco-hidráulicos han ayudado a definir procedimientos que ayudan a mitigar los impactos de las actividades antropogénicas (como el desarrollo hidroeléctrico) sobre los ecosistemas, por ejemplo, translocación de peces, diseño de estructuras de restauración de hábitat o modelos rudimentarios de ecología de flujo. Sin embargo, la legislación actual en Chile no fomenta la aplicación de estas herramientas. (3) Se espera que la fragmentación de los sistemas fluviales andinos aumente severamente en el corto y mediano plazo, afectando la conectividad y función ecológica, así como su resistencia a los factores de stress antropogénicos. (4) El potencial hidroeléctrico puede ser aprovechado disminuyendo los impactos sobre la conectividad fluvial priorizando los afluentes de la cuenca alta de fragmentos por encima de barreras ya existentes, como se muestra en la aplicación del índice de fragmentación para diferentes escenarios de desarrollo hidroeléctrico en la cuenca del río Biobío.

Se recomienda diseñar e implementar políticas con un enfoque interdisciplinario desde la Ciencia de Ríos que permitan asegurar la sostenibilidad a largo plazo de los ecosistemas fluviales, es decir, diseñar leyes que exijan herramientas como las eco-hidráulicas en los diseños de los proyectos y planes de seguimiento de impactos ambientales; obras de infraestructura que permitan mitigar los efectos en la conectividad longitudinal de las fauna fluvial, como los pasos de peces para especies nativas; modelos de resiliencia de los ecosistemas fluviales chilenos frente a diferentes escenarios, por ejemplo, cambios en el uso de la tierra y el agua, cambio climático. Además de modificar las competencias del servicio de evaluación de impacto ambiental, de manera que pueda proponer alternativas a la ubicación y diseño de los proyectos, como los hidroeléctricos, basadas en una planificación territorial sustentable que permita conservar los recursos naturales de los ecosistemas fluviales.

En la dimensión social se encontró que: (1) Existe un vacío de información de los efectos del desarrollo hidroeléctrico sobre las comunidades locales, ya que el actual desarrollo de centrales con potencia menor a 20 MW realiza principalmente Declaraciones de Impacto Ambiental, las cuales no evalúan adecuadamente estos impactos, sino que sólo justifican la no significancia de ellos. (2) Los EIA presentan falencias en la determinación de las áreas de influencia de los proyectos hidroeléctricos y una falta de levantamiento de información primaria en las líneas bases del medio humano. (3) Se omite la detección de impactos sitio-específicos. (4) Hay escasa participación ciudadana en la evaluación de los proyectos hidroeléctricos, y en el caso de existir, no es vinculante lo que genera descontento, frustración, induce la judicialización y provoca el conflicto social. (5) La valoración de los impactos en el medio humano es mayoritariamente de carácter negativo no significativo, observándose principalmente compromisos voluntarios por parte de los desarrolladores de proyectos en vez de medidas de mitigación, compensación y/o reparación. La aplicación del marco matriz permitió identificar brechas en la evaluación de impactos en el medio humano asociados a las componentes “agua e irrigación”, “salud y nutrición”, y consistentemente deficiencias en la determinación de áreas de influencia de los proyectos. Se observaron mejoras en la evaluación social tras la aplicación del decreto supremo Nº40, de 2013, del Ministerio del Medio Ambiente.

Se recomienda incorporar políticas que fomenten la participación ciudadana vinculante, sobre todo de comunidades locales, en los EIA y que se mejoren los estándares de calidad de las líneas de base, propendiendo a la generación de antecedentes sitio específicos.

El análisis realizado de la variabilidad y cambio climático sobre el potencial hidroeléctrico dejó en manifiesto la necesidad de incluir estas variables en la planificación hidroeléctrica y el diseño de las centrales, con el objeto de optimizar los recursos financieros y el aprovechamiento del potencial hidroeléctrico. La planificación hidroeléctrica debe considerar la fragmentación del ecosistema fluvial que provocará el desarrollo hidroeléctrico, como una variable crítica que limitará las capacidades de desarrollo de una cuenca, debido a que la explotación masiva del recurso, podría provocar efectos sinérgicos graves, que en el corto plazo disminuirán la abundancia de las especies acuáticas e incluso podría llegar a la extinción de las más sensibles en el largo plazo. Además, el no considerar a las comunidades locales involucradas en el desarrollo de los proyectos, ha generado importantes conflictos sociales, llegando incluso a la judicialización, por lo cual, se debe incorporar una participación vinculante desde la conceptualización del proyecto, buscando encontrar soluciones en común acuerdo que permitan mitigar, de manera efectiva y benéfica para todas las partes involucradas, los impactos negativos que pueda generar el desarrollo de un proyecto, evitando la mala práctica de solo asumir compromisos voluntarios realizados por los titulares en la actualidad. Por lo anterior, se acepta la hipótesis planteada en esta investigación. Como línea futura de trabajo se propone investigar con mayor énfasis los efectos sinérgicos que generará el desarrollo productivo en las cuencas hidrográficas, con el objeto de generar políticas efectivas, con un enfoque interdisciplinario, que permitan la sustentabilidad del desarrollo hidroeléctrico.

VI. Anexo 1. River science and management issues in Chile: Hydropower development and native fish communities

Evelyn Habit[1*], Alex García[2], Gustavo Díaz[1], Pedro Arriagada[3], Oscar Link[4], Oscar Parra[1], Martin Thoms[5]

1. Departamento de Sistemas Acuáticos. Facultad de Ciencias Ambientales y Centro de Ciencias Ambientales EULA-Chile, Universidad de Concepción, Barrio Universitario s/n, Casilla 160-C, Concepción, Chile
2. OITEC Ltda. Avenida Prat 199 A, of 1307, Concepción.
3. Departamento de Ingeniería Civil. Facultad de Ingeniería, Universidad de Concepción, Barrio Universitario s/n, Casilla 160-C, Concepción, Chile
4. Departamento de Ingeniería Ambiental. Facultad de Ciencias Ambientales y Centro de Ciencias Ambientales EULA-Chile, Universidad de Concepción, Barrio Universitario s/n, Casilla 160-C, Concepción, Chile
5. Riverine Landscapes Research Laboratory, University of New England, Armidale, NSW 2350, Australia

* Author for correspondence.

Publicado en: River Research and Applications

Abstract

The magnitude of hydropower developments in emerging regions threatens the sustainability of their riverine landscapes. Fragmentation of river networks by multiple barriers, and the imposition of new hydrological regimes influences the ability of these river ecosystems to absorb and adapt to these developments, and other stressors. Direct transfer of paradigms built from a restricted geographical base to a global context is fraught with issues because of regional differences in eco-hydro-geomorphology, biological communities, and nonlinear interactions between the two. In this manuscript some impacts of hydropower development on Chilean riverine ecosystems are presented. To understand the context of hydropower we provide the political context of energy development in Chile. Interactions between hydropower generation and Chilean river ecosystems, with special reference to native Chilean fish fauna are outlined. Three case studies are presented that considers: i) habitat alteration downstream of the Rucúe Dam; ii) the effects of daily hydropeaking in the Biobío River; and, iii) mitigation strategies to reduce habitat alteration upstream of the San Pedro Dam. These case studies illustrate the expanding scientific knowledge on Chilean riverine landscapes. Finally, new measures to reduce ecosystem impacts of hydropower development on native Chilean fish communities are outlined. While specific scientific information is available, developing regional ecohydrological models, and improving knowledge of ecosystem and sustainability science is required. The scientific approach on which solutions are sought to address present and future river ecosystem problems in Chile are inherently interdisciplinary nature.

Keywords: Large river ecosystems, fragmentation, hydrological modifications, endemic fish communities

1. Introduction

Globally, more than 58,000 large dams regulate and manage flow regimes for a variety of concerns, including hydropower generation (Poff and Schmidt, 2016). Hydropower accounts for 80% of the world's renewable energy (Zarfl et al., 2015), and investments in hydropower developments are predicted to increase exponentially over the next 20 years (Edenhofer et al., 2011). In 2000, hydropower generated 2659 TWh, with an estimated global potential of 5400 TWh (Koch, 2002). Increases in hydropower investment is fostered, in part, by recent climate agreements that actively encourage a transition from non-renewable power sources to renewable energy sources (Hermoso, 2017). The growing demand for renewable and relatively inexpensive electricity means further dam construction and hydropower developments will occur (Zarfl et al., 2015).

There is a geographical imbalance to the world's future hydropower developments and dam construction. Developing countries in Asia and South America have the greatest unexploited hydropower-potential with projected development increases of several orders of magnitude in countries like Chile and China (Bartle, 2002). Despite the advantages of hydropower as an inexpensive and renewable power source, riverine landscapes are threatened by hydropower developments. Riverine landscapes are among the most vulnerable worldwide (Vörösmarty et al., 2010), but dam construction and the subsequent hydrological changes are known to be one of the most widespread, irreversible and dramatic anthropogenic impacts upon riverine landscapes (Petts, 1984). Thus, there is tension between the societal need for hydropower and the impacts of hydropower developments on river landscapes.

Relatively little is known about the ecosystem consequences of dams and hydropower generation on rivers in developing regions compared with those in developed regions (Pringle et al., 2000). Environmental legislation for river conservation and management has not kept pace with the rapid rate of hydropower development in many developing countries (Bauer, 2009). Thus science and management have been reactive in attempts to improve the limited knowledge base of river ecosystem understanding pre and post hydropower, rather proactively adding to it. However, frameworks exist to unravel the impact of dams on riverine landscapes (cf. Petts, 1984), and some have been applied in developing regions (e.g. Winemiller et al., 2016). Disruptions in riverine connectivity interfere with the abilities of aquatic biota to absorb and adapt to disturbances by dams, and also other stressors induced by changes in other environmental conditions, such as climate change. Rivers are increasingly subjected to multiple stressors that could result in a loss of resilience capacity (Thoms et al., 2018). On a longer evolutionary time scale, migratory and endemic species, with specific habitat preferences are being lost (Hall et al., 2011). Questions about how riverine landscapes will respond to extensive and rapid fragmentation, and subsequent hydrological modification in developing regions have been raised. Specific ecosystem responses to hydropower development are available in some developing countries, like Chile (cf., Habit et al., 2007). However, broader, regional ecosystem response models are required to address the rapid hydropower developments, supported by the overall development of ecosystem and sustainability science, in developing regions. Moreover, ecosystem science solutions to present and future river ecosystem problems must be interdisciplinary in nature (Dollar et al., 2007). Broad-scale studies have quantified the extensive fragmentation of riverine landscapes by dams but similar comprehensive assessments have been limited in many developing regions. Only recently has information about the degree of river ecosystem alteration by dams in South America begun to be synthesized (García et al., 2011).

Rivers in South America have been increasingly subject to hydropower development since the 1980’s. Hydropower development is widespread and expanding to develop local, regional and national economies, with the construction of thousands of small and large hydropower dams (Pelicice et al., 2017). This is especially the case in Chile, where hydropower is an important source of electricity for the country. New dams are viewed as a primary means for meeting the demand for electricity, which is estimated to grow by up to 6.5% annually (Hall et al., 2009) to over 90.000 GWh by 2035 (CEDEC-SIC, 2015). To meet this demand more than 70 new dams were proposed to be built in Chile during the 1990s, and at least double that number have been proposed by 2020 (Hall et al., 2009). As the number of dams increase, Chile’s river ecosystems will be degraded and large free-flowing rivers will quickly vanish from the Chilean landscape. The direct transfer of paradigms and theories built from knowledge assimilated from a restricted geographical base (eg. Australasia, Europe, N America) to a global context is fraught with issues. Regional differences in the effects of hydrological alterations on riverine ecosystems have been articulated by Pringle et al., (2000). These are hypothesized to result from the nature of water developments – size, location and operation of the dam – and character of the freshwater biota, notably the degree of endemism, body size, migratory behaviour, and specific habitat preferences. An overview of the knowledge of river science, the impact of hydropower on rivers, and broader decision making environment, in which science operates, is important when commencing the construction of region wide ecosystem models that can predict responses to stressors like dams and hydropower in emerging countries (Pringle et al., 2000).

This manuscript outlines the potential impacts of hydropower development on native Chilean fish communities. In order to address the issue of the effect of hydropower we first provide a political context of energy development in Chile, with special reference to hydropower generation; the corresponding environmental legislative framework; and, the geography of future hydropower developments. Second, interactions between hydropower generation and Chilean river ecosystems, with special reference to native Chilean fish fauna are provided. Third, three case studies are documented illustrating issues of habitat alteration and loss, and attempts to reduce the environmental effect of hydropower developments via a series of integrative local measures. Finally, we propose new measures to assess and reduce the ecological impacts of the current hydropower activities on native Chilean fish communities.

2. Hydropower, environmental legislative frameworks and freshwater fish biodiversity in Chile

Large rivers are social-ecological systems, in which ecological processes and human activities are closely interwoven. Rivers offer valuable ecosystem services to humans, including hydropower that may help build and sustain the economic and social well-being of emerging countries like Chile. River ecosystem services have been exploited and degraded at a rate that exceeds their ability to absorb or adapt to anthropogenic stressors (Yeakly et al., 2016). This has potential societal and political implications for many developing regions. To begin to understand the concept of rivers as social – ecological systems within a Chilean context the following sections provide background on hydropower development in Chile, the environmental legislative frameworks that govern these developments, and the status and threats to freshwater fish biodiversity in Chilean river systems.

A geography of hydropower in Chile

There is an intense debate in Chile about energy strategies to enable expansion of the national economy. Hydropower is attractive because Chilean river systems are well suited to hydropower generation because of their geomorphology. The river systems of Chile drain high-elevation areas of the Andes that experience elevated rainfall, have high rainfall/runoff ratios, and flow a short distance to the coast. Harnessing of this natural hydropower potential dates back to 1909, and increased slowly until the early 1990s. Since 1994, with the introduction of the first Chilean environmental legislation, 70 hydropower projects with a total power of 7722 MW have been submitted to the government for environmental evaluation. Sixty-two of these projects, with individual capacities <20 MW, have been submitted for evaluation since 2004 (Figure 30a). Currently there are 137 dams across the river networks of Chile (Figure 30b). Most of these dams (67%) are located in the central valley region of the country (Figure 30b). Overall, there are 126 dams in the central region of Chile generating 25% or 49.26 MW of the countries hydropower. By 2050 the number of hydropower dams will increase by 1467 providing an additional 101.32 MW of electricity. Many new dams will be built in the central region of the county (Figure 30c) although six large dams are to be built in Patagonia in the southern region of the country. Thus, there is a geographical imbalance to the potential stress placed on the riverine landscapes and their aquatic ecosystems.

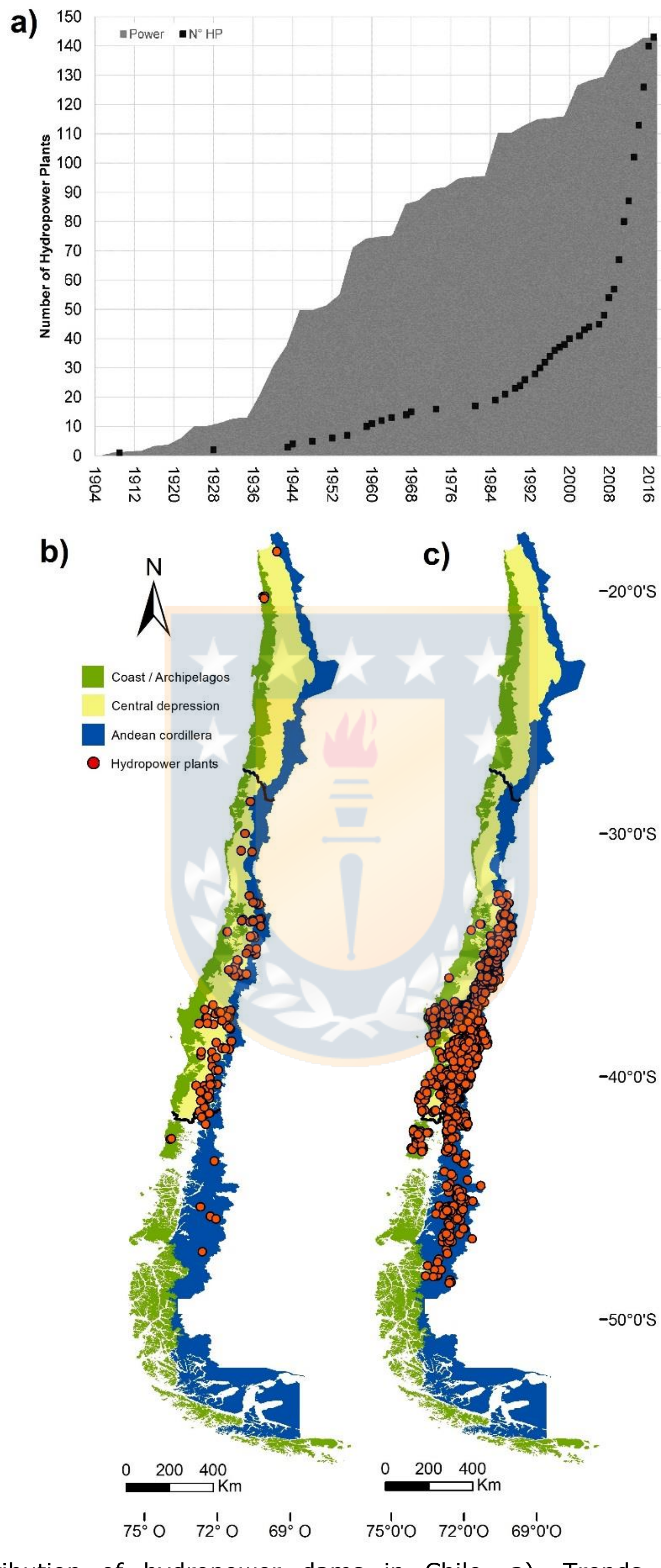

Figura 30. Distribution of hydropower dams in Chile. a). Trends in hydropower plant construction and power generation 1928-2016; b). The location of dams in Chile as of 2018; and, c). Additional dams planned by 2050. Data source: www.cne.cl

Environmental legislative framework guiding hydropower development

Hydropower projects are viewed as providing benefits to society, but they also entail environmental costs. Well-informed decision-making processes are necessary to ensure the best social and environmental outcomes for the country, but the concept of integrated river basin management has not been applied in Chile. Since the mid-1970s, Chile has been a leading example of pro-market policies for water resources and is advanced as a model for emerging countries to follow (Bauer, 2009). The Water Code, adopted by Chile in 1981, privatized water rights, reduced state administration, and attempted to stimulate a free market in water rights.

The first Chilean environmental law ('*Ley Sobre Bases Generales del Medio Ambiente*') was enacted in 1994. This required hydroelectric companies to submit an environmental impact assessment (EIA) for new projects with a generating capacity > 3 MW. The main objective of the EIA is to ensure hydropower projects conform to Chilean environmental laws and regulations. The EIA must provide technical details of the project, a base line description of the impacted area, an evaluation of environmental and cultural effects, and define mitigation and compensation actions. Deficiencies with the Chilean EIA system have been recognized with respect to hydropower (Lacy et al., 2017). Hydropower projects are viewed independently with no recognition of existing or planned hydropower developments within the catchment, or indeed other water use projects. The EIA terms of reference (i.e. what, where, how and when to measure) is defined by the owners of the hydropower development which are private companies, and they are responsible for the appointment of agents to undertake the EIA. The EIA does includes citizen engagement, where stakeholders (i.e. local communities, indigenous groups, and NGOs) are invited to comment on the proposed project. Government evaluation of the EIA is restricted to whether the EIA fulfils regulations set under Chilean environmental law. The EIA process is further complicated by a lack of procedural precision, the limited ability of the government to modify conditions for development, and limited scientific information on river ecosystem functioning (Lacy et al., 2017).

Other legislation guiding decisions about hydropower includes '*Ley General de Pesca y Acuicultura'* which establishes obligations to implement mitigation actions when a project includes structures that obstruct a river. This may result in structures to enable fish movements or procedures that maintain fish abundance, which is frequently undertaken through translocation programs. Conservation regulations also call for similar mitigation actions, but have no weight in the rejection of a hydropower project in the EIA process. Most of this legislation is directed towards introduced fish species such as salmonids that have economic benefits for recreation and aquaculture, with few guidelines for conserving native fish species.

Chilean freshwater fish biodiversity: Status and threats

The geological history of Chile has contributed to its unique aquatic fauna. In particular, native fish species have retained primitive and endemic characteristics. The native freshwater ichthyofauna of Chile is composed of 12 families, 17 genera, 46 species; of which 52% are endangered (Vila and Habit, 2015). Most native fish are small bodied, have narrow distribution ranges, with specific hydraulic habitat and feeding requirements (Vila et al., 1999). The south central region of Chile (25°S to 47°S - the Chilean winter rainfall-Valdivian forests) is a biodiversity hotspot (Myers et al., 2000), where endemism in freshwater fish species is 83%. There has been a decrease in the abundance and range of native fish species as a result of the synergistic effects of multiple stressors in river basins (Vila and Habit, 2015). These stressors include the introduction of non-native species, changes in land use, water extraction, pollution, and river fragmentation (Vila and Habit, 2015).

The impacts of dams and hydropower generation on native fish communities in Chile are not well researched, but the evidence base is growing. There have been a few studies on instream flow requirements and the reintroduction of native fish, but these are only exploratory in nature (cf. Habit et al., 2002). Knowledge of the response of fish communities to flow regime changes as a result of the operation of hydropower facilities is limited. Information on the effect of dams and hydropower generation is constrained by the legislative requirements imposed by environmental law and the EIA process, which do not require any investigation of the effects of flow regime changes on fish. Given the biodiversity and endemism of Chilean freshwater fish, there is much at stake for river ecosystems. It seems prudent that the development of regional and local response models for native fish communities becomes essential in the EIA process, for predicting and mitigating the effect of hydropower developments on Chilean river ecosystems.

Dams and hydropower generation modify natural flow regimes, alter downstream channel morphology and affect aquatic community structures (cf. Petts, 1984). Preliminary research by Elgueta et al., (in press) suggests the magnitude of the effect of dams on Chilean river ecosystems depends on their ecogeomorphological character, the location of the dam within the river network and its operation (run-of-river or hydropeaking). Fragmentation of river networks by dams has short and long-term effects on fish movement. In the short term (annual), reductions in the abundance of migratory individuals in headwater streams have been recorded, and in the long term (decades) genetic diversification of isolated species has occurred (Esguícero and Arcifa, 2010). The construction of fishways has been a popular mitigation strategy to overcome river network fragmentation. Despite an increase in the number ecohydraulic projects focused on fish way design in Chile (e.g. Laborde et al., 2016) this has not translated to operational fishways associated with hydropower dams.

3. Case studies: Ecological implications of hydropower developments in Chile

The case studies presented illustrate common issues associated with hydropower development in Chilean rivers, including the impact of habitat loss both upstream and downstream of hydropower dams, and restoration attempts to counter the impact of dams and hydropower generation. Collectively they also argue for larger scale approaches in understanding the effect of hydropower developments; the inclusion of flow-fish relationships in Chilean EIAs; and, the need for stronger interdisciplinary approaches in constructing region wide flow-ecology models. These case studies presented are from the Biobío River (case study one and two) and the Valdivia River (case study three) basins (Figure 31) and typical of those issues faced by Chilean rivers from hydropower development.

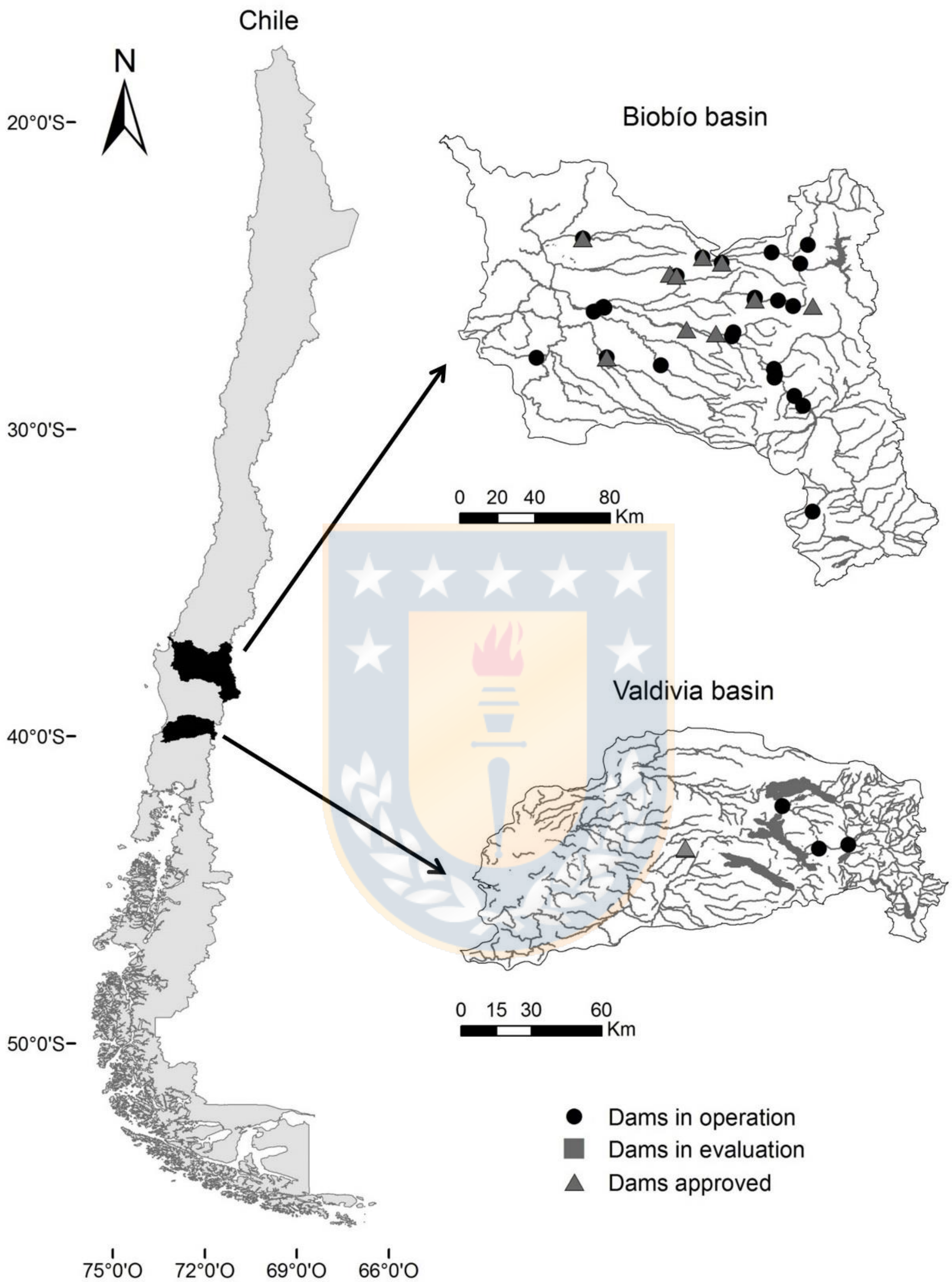

Figura 31. Location of hydropower projects in the three case study areas. Case study one – Habitat loss downstream of the Rucúe Dam and Case study two – Hydropower in the Biobío River, were undertaken in the Biobío River basin; and, Case study three - Upstream habitat loss in the San Pedro Reservoir, was undertaken in the Valdivia River basin.

Case study one: Habitat loss downstream of the Rucúe dam

The Rucúe hydroelectric project (178 MW) is a small run-of-river scheme on the Rucúe River; a left bank tributary of the Laja River (Figure 32). The Rucúe project commenced operations in 1998, diverts 120 m^3s^{-1} from the Laja River and 10 m^3s^{-1} from the Rucúe River to an 18 km side channel. This combined flow is routed through the Quilleco hydropower station before its return to the Laja River.

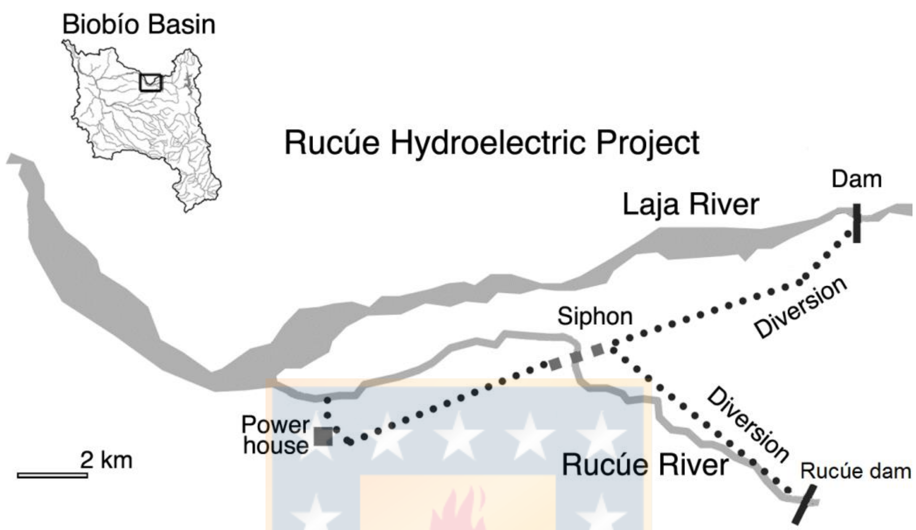

Figura 32. Case study one: The Rucúe hydroelectric project. Modified from Habit et al., 2007.

Conservation of native fish communities, through habitat loss and migration impediments in the diverted reaches of the Laja and Rucúe River, was identified as a concern of this project. Species composition, community and population structure of the ichthyofauna were studied seasonally from 1997 to 2002 (cf. Habit et al., 2007). The results showed a complex response to flow regime changes, with the impact of flow regime changes differing between the Laja and Rucúe Rivers (Habit et al., 2007). In the Laja River species abundance was lower than the Rucúe River, especially for *Percilia irwini* and *Trichomycterus areolatus* (Figure 33). Moreover, species occupying mid-water habitats, i.e. introduced trout and the native *P. irwini*, showed disproportionately larger declines during the construction and dam operation periods, while the native benthic catfish species (*T. areolatus* and *Diplomystes nahuelbutaensis*) showed no change in abundance over time (Figure 33). It was concluded that reductions in low flows and the consequent habitat loss in the Laja River were more detrimental to fish species occupying mid water habitats in this river system (Habit et al., 2007). Overall, the change in fish community structure in the Laja River compared to the Rucúe River (a river not impacted by hydropower operations) suggests a loss of resilience as a result of 40 years flow regime changes.

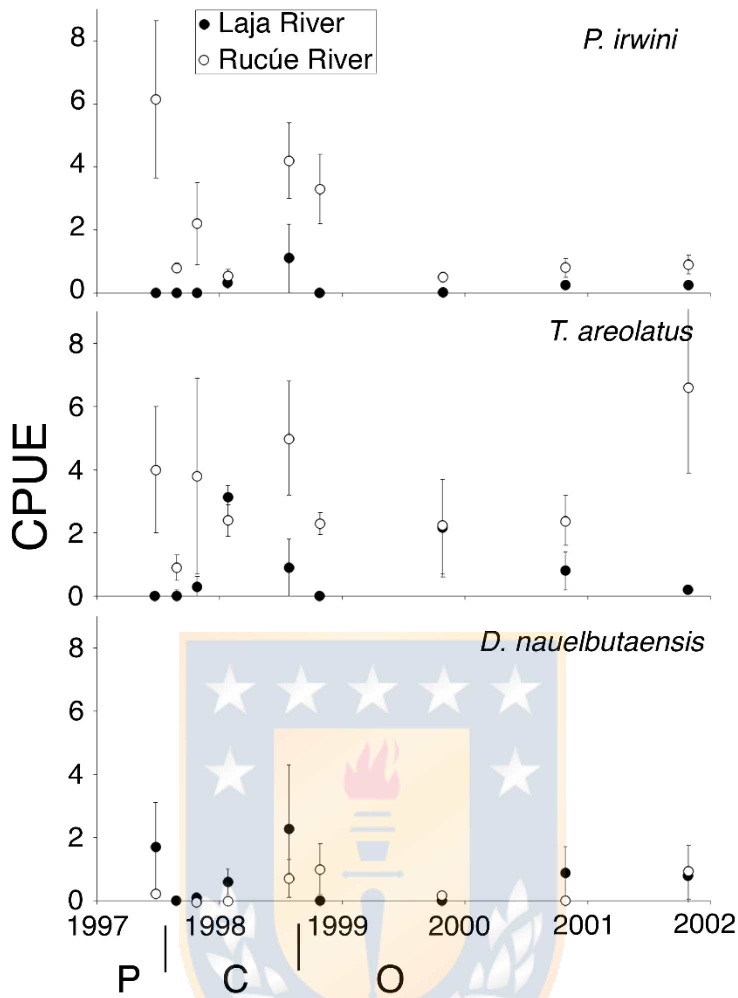

Figura 33. Case study one: Fish abundance as Catch Per Unit Effort – CPUE - (mean±SE) of three native fish species in the Laja and Rucúe Rivers during pre-construction (P), construction (C), and operation periods (O). Modified from Habit et al., 2007.

Translocation is considered a novel approach to conserve native fish species in Chile (Habit et al., 2002). To mitigate the effect of the Rucúe hydropower project the translocation of two endangered species (*P. irwini* and *D. nahuelbutaensis*) and one vulnerable species (*T. areolatus*) was trialed. The specific goals of this translocation experiment were to: i) study the ichthyofauna of the impacted area and fish community composition, abundance, condition, genetic structure, parasite composition and population size distribution; ii) define and have approved by the national environmental authorities a translocation protocol; and, iii) assess the performance of the translocation of 1835 individuals of three species. This was the first translocation of native fish undertaken in Chile. A survival ratio of 90% was recorded in the Laja and Rucúe Rivers after four years. This initial experiment was considered a success but further monitoring is required to determine the long term effectiveness of fish translocations for mitigating the effects of hydropower dams.

<u>Case study two: Hydropeaking in the Biobío River</u>

The downstream effects of hydropeaking in Chilean river systems are well illustrated in the Biobío River. This river system is part of the Chilean biodiversity hotspot (Myers et al., 2000), with high levels of endemism (Villagrán and Hinojosa, 1997). The Biobío

River has the highest fish species richness in Chile with 18 native species, two of which are endemic to the Biobío River (Habit et al., 2006). However, the river and its tributaries have seen significant hydropower development since the 1950s with the construction of 11 additional dams. Seven more are currently in evaluation or have just been approved for construction, and 222 are expected to be built by 2050 (Figure 34).

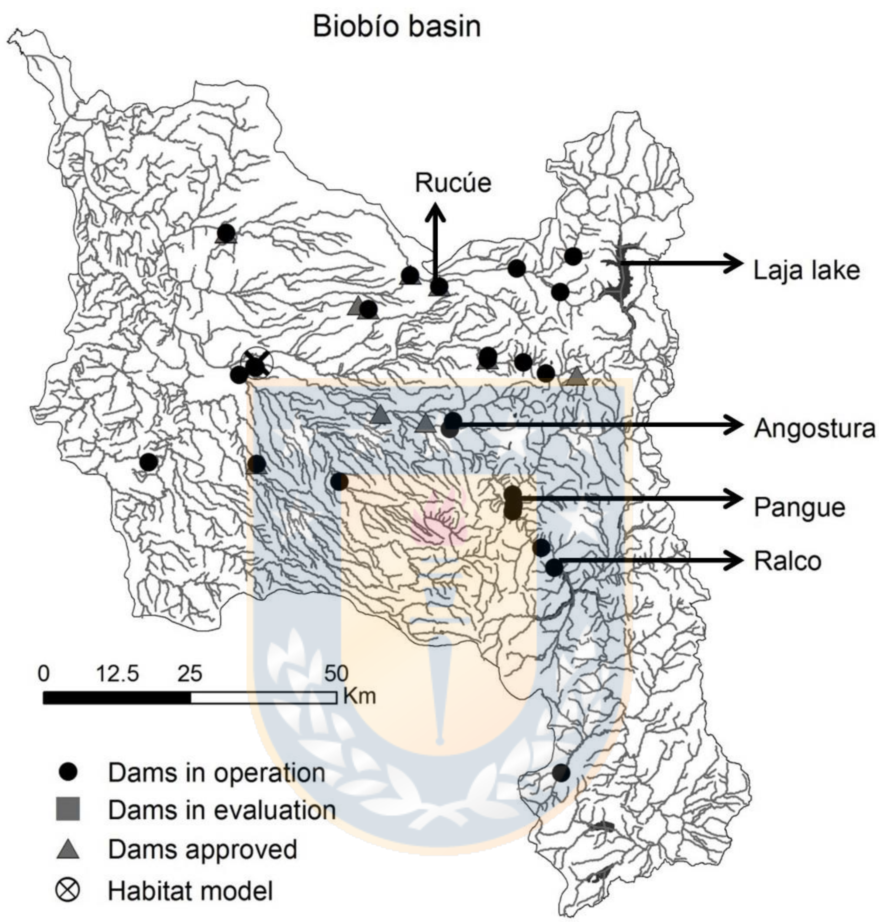

Figura 34. Dams in the Biobío River basin (case studies one and two).

The effects of hydropeaking on habitat availability for native fish in the Biobío River were reported by García et al. (2011). In this study, the habitat use of native fish species were modelled along a 2 km reach located 98 km downstream of the Pangue Dam. A comparison of pre-dam (summer 1978-1979) and post-dam (summer 2005) time series scenarios of weighted usable area for two native species show marked changes in the availability and location of suitable habitat (Figure 35), especially optimal habitat conditions as result of hydropeaking operations.

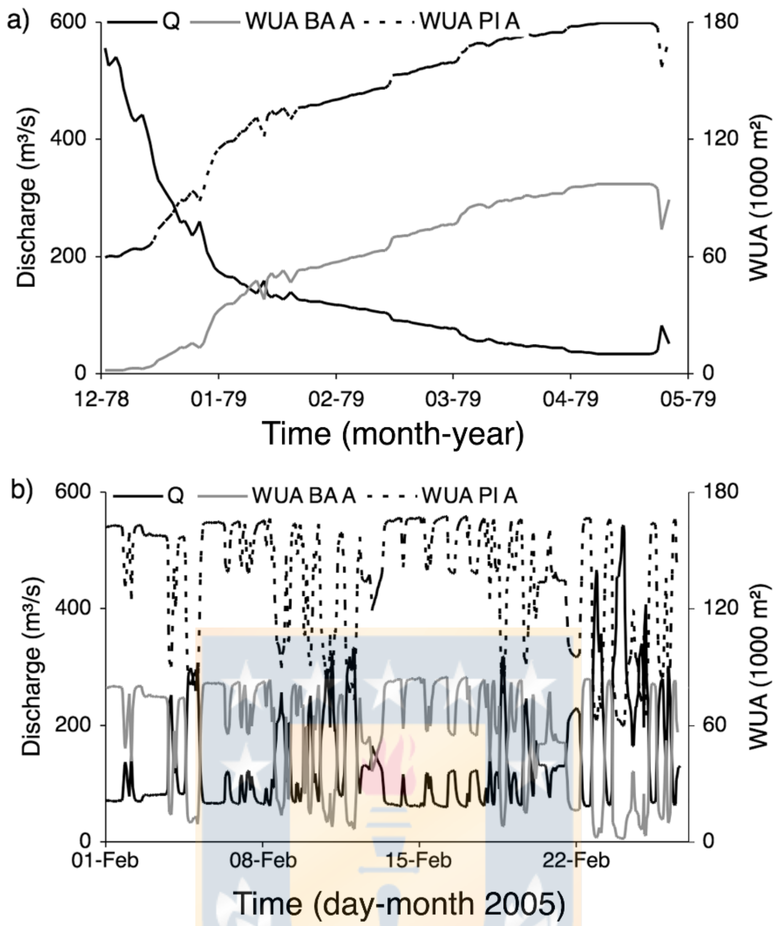

Figura 35. Case study two: Weighted usable area (WUA) time series under natural a) and current b) discharge scenarios for *Basilichthys microlepidotus* adults (BA A) and *Percilia irwini* adults (PI A). WUA was estimated using the CASIMIR model, as a measure of usable area of physical habitat available to this specific life stage of the two species, as described in García et al. (2011).

The construction of additional dams will lead to further fragmentation of the river network and imposed modified flow regimes. Increasing network fragmentation will likely have severe effects on population viability (Neraas and Spruell, 2001), further restricting migration, isolating populations, and restraining gene flow (Esguícero and Arcifa, 2010). High gene flow among Chilean native species populations has been described by Vera-Escalona et al. (2015). Thus, a cascade of hydropeaking dams throughout the river network will likely have a synergistic effect on fish populations at a larger scale.

<u>Case study three: Upstream habitat loss in the San Pedro reservoir</u>

The San Pedro hydroelectric project, in the Valdivia River basin, located 14 km downstream of Riñihue Lake, includes a 56 m high dam with a run-of-the-river hydropower operation (Figure 36). The impoundment extends 12.5 km upstream from the dam wall or 31.2 % of the river network. As a result only a 1.5 km reach of the river in this part of the network retains lotic conditions. This hydropower development threatens five native species. In particular, *Galaxias platei* is a Patagonian endemic species (Cussac et al., 2004) and although it is mainly a lacustrine species, lake populations act as source for riverine populations (Habit et al., 2010). *Galaxias platei* is a key species impacted by the presence of the San Pedro Dam because of the marked loss of lotic habitat downstream of Riñihue Lake. Maintenance of lotic habitat between Riñihue Lake and the reservoir tail water has been identified as essential to the persistence of riverine populations (COREMA Región de Los Ríos, 2008). The construction of hydropower plants have been shown to lead to a rapid reduction in the genetic diversity of *Galaxias platei*, with population extirpation expected within 50–80 years after dam construction (Vera-Escalona et al., 2018).

The EIA for the San Pedro hydropower development proposed habitat enhancement (cf. Link and Habit, 2012) in the reach between the reservoir tail water and Riñihue Lake to maintain *Galaxias platei* riverine populations (Figure 36). Habitat segregation between juveniles and adults occurs mainly by water depth and velocity, and detritus coverage on substrate. Adult *G. platei* occur mostly in habitats with flow depth ranging from 0.35 to 1.50 m and flow velocities slower than 0.1 ms^{-1} (Link and Habit, 2012). The aim of the various habitat-generating structures was to provide a variety of substrate and native riparian vegetation conditions (Figure 36) required under seasonal flow ranges and the provision of year round usable habitat for *G. platei*. Rock groin structures, large woody debris and rock weirs were engineered within the channel for habitat enhancement. The habitat structures were 2 m high with slopes of 1:2.175 (H:V) and partially submerged (with 0.57 m of water) during low flows and fully submerged (under 0.35 m of water) during high flows. The structures were engineered to allow individuals to remain at habitats during the high-water season and low-flow dry season, i.e. discharges ranging from 487 (Q_{25}) to 149 (Q_{75}) m^3s^{-1}, respectively. This ongoing restoration effort increased habitat availability by an order of three with respect to those without habitat structures. To our knowledge, this is the first river restoration project in Chile to improve habitat quality of native fish species based on ecohydraulic criteria (Link and Habit, 2012).

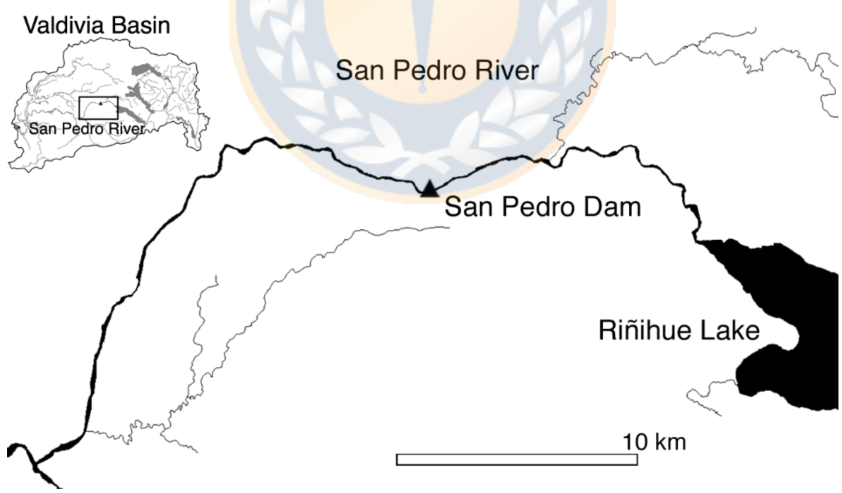

Figura 36. Case study three: San Pedro hydroelectric project in the Valdivia Basin. a) Planform view; and, b) cross section view of the structures for habitat generation in the San Pedro River.

4. Future challenges

Scientific research on specific components of Chilean freshwater ecosystems is developing a knowledge base with which to contribute to the sustainability of Chilean riverine landscapes. Nonetheless, weak environmental legislation, and the existence of a relatively immature national planning strategy for energy development have allowed private companies to develop Chilean water resources based primarily on economic grounds. Comprehensive assessments of technical, economic, environmental and

social alternatives are not well developed. However, the use of indigenous (Mapuche) knowledge in Chile to assess the effect of water developments is increasing. The "Mesa Participativa para la Hidroelectricidad Sustentable" project for example, had the active involvement of multiple stakeholders, including the Mapuche – the indigenous inhabitants of south-central Chile and south-western Argentina. Nonetheless, the use and integration of indigenous knowledge in biodiversity conservation is generally limited (Aigo and Ladio, 2016) in comparison to other regions of the world (Te Aho, in press).
Patagonia is one of the last pristine regions of the world, and a global biosphere reserve (Vince, 2010). Thus approval of the 'Proyecto Hidroeléctrico Aysén' (PHA, Aysén hydroelectric project or Hidroaysén) in 2011 raised national and international condemnation. This project will construct five large dams on the Baker and Pascua Rivers with a combined generation capacity of 2750 MW. The Baker and Pascua rivers are two of the largest pristine rivers in Patagonia (Jaramillo et al., 2008). Although fish diversity in western Patagonia is relatively low (10 species), the Baker River is the only basin which supports all 10 native fish species in Patagonia. In addition, the within-species morphological and genetic diversity is very high because of the regions unique geomorphology (Ruzzante et a*l*., 2003). Overall, the fish fauna of this region of Chile is poorly researched. Baseline studies undertaken as part of the regulatory EIA recorded a fish species not described for Chile before; the primitive catfish *Olivaichthys viedmensis* (Arratia and Quezada, 2017). The proposed hydropeaking operations in the Baker River were expected to have daily stage fluctuations >3 m, with water level changes of 10 cm min^{-1} over a 30 minute cycle in a section of river network important for the reproduction of *Olivaichthys viedmensis.* The EIA also raised questions about the economic goals of the development, with issues of short-term financial gain over protection of the countries' natural environment. Eventually, public pressure and scientific information resulted in the rejection of the project by the Chilean Government and the Environmental Court of Chile in 2017.

Scientific and local communities have urged the Chilean government to have a more active participation in the development of the energy sector. As a result there has been a change in the energy matrix where renewable energy will account for 70% of the country's energy supply by 2050 (Ministerio de Energía, 2016). This will result in a relatively unstable energy supply system thus promoting the full capacity of hydropower. To support the national debate on power supply and hydropower in Chile we suggest the following measures to be considered for the understanding and protection of river ecosystems. First, the government needs to encourage interdisciplinary river science programs that provide hydrological and ecological baselines of Chilean river systems. These baselines would serve to prioritise conservation areas that maintain aquatic biodiversity. Second, the terms of reference of the EIA process for new hydropower projects should require independent scientific assessment. These terms of reference should also consider the scale for the EIA with extensions to assessing the entire river network (*sensu* Dollar et al., 2007). The terms of reference should also require the development of EIA's in the context of existing and projected activities, considering potential synergistic effects (as it should have been in Case Study One and Two in the Biobío River). Third, when the location of the new dam is determined, the EIA should require specific standards in the sampling procedure (periods, location, duration and effort), in the quality of the data and data analysis to allow an adequate characterization of the system and detailed ecohydraulic analyses of potential effects and mitigation actions. Fourth, all hydropower projects, including existing dams, should have long-term river ecosystem monitoring programs, including options for the decommissioning of dams. Fifth, a relicensing process should be implemented to account for improvements in technology, changes in water uses in the basins, and to consider the changes in societal values supporting/rejecting particular projects.

5. Summary and ways forward

Riverine landscapes and their associated aquatic ecosystems face major threats in Chile under the current hydropower development scenario. Knowledge of habitat requirements, reproduction strategies, and species ecology is limited in Chile (c.f. García et al., 2011). Therefore, assessing ecosystem responses from anthropogenic activities is difficult, and requires basic information about riverine landscapes at multiple scales. Nonetheless, research over the last decade has contributed to the knowledge base of these threatened landscapes, but most of this information has been derived from undertaking EIAs. This has fostered the use of ecohydraulic approaches to define procedures for the translocation of native fish species, design habitat restoration structures, and to build rudimentary flow-ecology models. Incorporating this type of knowledge in the early stages of a hydropower project can be useful to ensure the design of environmentally friendly dams as was done for the San Pedro hydroelectric project. However, the application of these tools is not currently encouraged under Chilean legislation.

An interdisciplinary river science approach is required to understand complex interactions between social and ecological systems as well as the response of aquatic communities to human induced disturbances (Thoms et al., 2018). This is essential for securing the long-term sustainability of water and other natural resources such as biodiversity in Chile. Key information gaps for Chilean riverine landscapes include the generation of ecological data on the spatial distribution and critical habitats of organisms, their functional traits, and how they interact with other species; information on the natural physical character of Chilean river systems and how this influences aquatic communities; and, knowledge of social systems, and their attitudes and values to free flowing river landscapes and the ecosystems they contain (Vörösmarty et al., 2010). This implies stronger support towards a new and effective strategic planning of Chilean river systems, where all stakeholders should be involved in the decision-making process of incorporating a dam (or other activity) within the basin (cf. Te Aho, in press).

Increasingly, the Chilean people are becoming aware of the social effects of dams and hydropower. This awareness is at a local scale, but effects on the broader environment, and on other industries that rely on riverine landscapes (e.g. tourism) is increasing. Conflicts and differences in opinion over water development in Chile occur. As an example, lobbyists for electric companies include populist arguments focused on investment and return; with common benefits including the generation of jobs, improvement of roads, hospitals, schools, all of which are used as levers to get political and social support. This was estimated at US$ 3.2 billion for the life of PHA project in Patagonia (Bauer, 2009). By comparison, Ponce et al. (2011) estimated the economic loss of building one of the five dams of the PHA project (Baker 1), to be approximately US$ 205 million per year. In any cost-benefit analysis of national and global importance, all stakeholders must have the opportunity to consider arguments with as much information as possible, as well as have the opportunity to contribute to the decision making process.

Integrated, sustainable water resource management is a crucial challenge for the 21st century. Water is a finite resource that needs to be managed to ensure sufficient water availability to satisfy key environmental assets and functions of entire riverine landscapes, while seeking to optimize social and economic outcomes. Planning processes must be underpinned by excellent science; science that covers entire river basins. Evaluations and tradeoffs must be made for single human activities, and the synergistic effects that will result from combined effects. As river scientists, one of the main emphases must be to contribute to fundamental research concerned with the resilience of riverine landscapes of this important ecoregion. Beyond establishing baseline studies for future monitoring programs, models of the resilience of Chilean riverine landscapes in the face of different scenarios (e.g. changes of land and water use, climate change) must be constructed and then communicated to Chilean society and to policy makers in order to have a real effect in the country.

Acknowledgements

Much of the work presented in this manuscript was funded by several sources: FONDECYT 1110441 and 1150154 to EH and OL; fellowship CONICYT to AG and GD and COLBÚN S.A. Comments on early drafts by Dr Melissa Parsons and those of two anonymous reviewers are gratefully acknowledged.

6. References

Aigo, J. and Ladio, A. 2016. Tradicional Mapuche ecological knowledge in Patagonia, Argentina: fishes and other living beings inhabiting continental waters, as a reflection of processes of change. *J Ethnobiol Ethnomed* 12 – 56. doi: 10.1186/s13002-016-0130-y

Arratia, G., Quezada-Romegialli, C., 2017. Understanding morphological variability in a taxonomic context in Chilean diplomystids (Teleostei: Siluriformes), including the description of a new species. *PeerJ.* 5: doi.org/10.7717/peerj.2991

Bartle, A., 2002. Hydropower potential and development activities. *Energy Policy* 30: 1231-1239.

Bauer, C.J., 2009. Dams and markets: Rivers and electric power in Chile. *Natural Resources Journal* 49: 583-651.

CEDEC-SIC, 2015. Estudio de Previsión de Demanda 2015-2035 (2050). Centro de Despacho Económico de Carga del Sistema Interconectado Central. Technical Report. 138 pp.

Cussac, V., Ortubay, S., Iglesias, G., Milano, D., Lattuca, M., Barriga, J., Battini, M., Gross, M., 2004. The distribution of South American galaxiid fishes: the role of biological traits and post-glacial history. *Journal of Biogeography* 31: 103-121.

Dollar, E.S.J., James, C.S., Rogers, K.H., Thoms, M.C., 2007. A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology* 89: 147-162.

Edenhofer, O., Pichs, R., Madruga, Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C.E., 2011. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press,Cambridge, United Kingdom and New York, NY, USA.

Elgueta, A., Habit, E. M., Górski, K., Thoms M. C. In Press. Hydrogeomorphology governs fish assemblages across a river network influenced by different water resource development levels. *Ecohydrology*

Esguícero, A.L., Arcifa, M.S., 2010. Fragmentation of a Neotropical migratory fish population by a century-old dam. *Hydrobiologia* 638: 41-53. DOI 10.1007/s10750-009-0008-2.

García, A., Jorde, K., Habit, E., Caamaño, D., Parra O., 2011. Downstream environmental effects of dam operations: changes in habitat quality for native fish species. *River Research and Applications* 27: 312-327.

Habit, E., Victoriano P., Parra O., 2002. Translocación de peces nativos en la cuenca del río Laja (Región del Biobío, Chile). *Gayana (Concepcion)* 66: 181-190.

Habit, E., Dyer, B., Vila I., 2006. Estado de conocimiento de los peces dulceacuícolas de Chile. *Gayana* 70: 100-113.

Habit, E., Belk, M., Parra, O., 2007. Response of the riverine fish community to the construction and operation of a diversion hydropower plant in central Chile. *Aquatic Conservation: Marine and Freshwater Ecosystems* 17: 37-49.

Habit, E., Piedra, P., Ruzzante, D.E,, Walde, S.J., Belk, M.C., Cussac, V.E., Gonzalez, J., Colin, N., 2010. Changes in the distribution of native fishes in response to introduced species and other anthropogenic effects. *Global Ecology and Biogeography* 19: 697-710.

Hall, S.F., Román, R., Cuevas, F., Sánchez, P., 2009. Se necesitan represas en La Patagonia? Un análisis del futuro energético chileno. *Ocholibros,* Universidad de Chile.

Hall, C.J., Jordaan, A., Frisk M.G., 2011. The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. *Landscape Ecology* 26: 95–107.

Hermoso, V., 2017. Freshwater ecosystems could become the biggest losers of the Paris Agreement. *Global Change Biology* 23: 3433-3436.

Jaramillo, A., Sapianins, R., Salamanca, F., Castillo, E., 2008. Impacto de los proyectos de represas en Aysén en el desarrollo del turismo de la región. Universidad de Chile, Santiago, Chile.

Koch, F.H., 2002. Hydropower – the politics of water and energy: Introduction and overview. *Energy Policy* 30: 1207-1213.

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, Habit, E., Link, O., 2016. Hydropower development, riverine connectivity and nonsport fish species: Criteria for hydraulic design of fishways. *River Research and Applications* 32: 1949-1957.

Lacy, S.N., Meza, F.J. and Marquet, P.A., 2017. Can environmental impact assessments alone conserve freshwater fish biota? Review of the Chilean experience. *Environmental Impact Assessment Review* 63: 87-94.

Link, O., E. Habit. 2012. Informe de medidas de manejo especie-específicas 1: Estructuras para generación de hábitat para *Galaxias platei*. Informe Técnico preparado para Colbún S.A. Oficina de Asistencia Técnica, Centro de Ciencias Ambientales EULA, Universidad de Concepción. 70 págs + 1 Anexo.

Link, O., Habit, E., 2015. Requirements and boundary conditions for fish passes of non-sport fish species based on Chilean experiences. *Reviews in Environmental Science and Bio/Technology* 14: 9–21.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A., Kents, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853-858.

Neraas, L.P., Spruell, P., 2001. Fragmentation of riverine systems: the genetic effects of dams on bull trout (*Salvelinus confluentus*) in the Clark Fork River system. *Molecular Ecology* 10: 1153-1164.

Pelicice, F. M., Azevedo-Santos, V. M., Vitule, J. R., Orsi, M. L., Lima Junior, D. P., Magalhães, A. L., Pompeu, P. S., Petrere, M., Agostinho, A. A. 2017. Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries* 18: 1119-1133.

Petts, G.E. 1984. *Impounded Rivers*. Wiley, Chichester.

Poff, N.L., Schmidt, J.C. 2016. How dams can go with the flow. *Science* 353, 1099-1100.

Ponce, R.D., Vásquez, F., Stehr, A. Debels, P., Orihuela, C., 2011. Estimating the economic value of landscape losses due to flooding by hydropower plants in the Chilean Patagonia

Water Resources Management 25: 2449.

Pringle, C.M., Freeman, M.C., Freeman, B.J., 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. *Bioscience* 50: 807-823.

Ruzzante, D., Walde, S.J., Cussac, V.E., Macchi, P.J., Alonso, M.F., Battini, M.A., 2003. Resource polymorphism in a Patagonian fish *Percichthys trucha* (Percichthyidae): phenotypic evidence for interlake pattern variation. *Biological Journal of the Linnean Society* 78: 497-515.

Te Aho, L. (in press). Te Mana o te Wai: A tangata whenua perspective on rivers and river management. *River Research and Applications*

Thoms, M.C., Gilvear, D.A., Greenwood, M.W., Wood, P.A., 2016. An introduction to river science: research and applications. In Gilvear, D.A., Greenwood, M.W., Thoms, M.C., Wood, P.A., (Eds.). *River Science, Management and Policy for 21st Century*. Wiley, 1-11.

Thoms, M.C., Delong, M.A., Collins, S.E., Flotemersch, J.H., 2017. Physical heterogeneity and aquatic community function in river networks: A case study of the Kanawha River, USA. *Geomorphology* 290: 277-287.

Thoms, M.C., Piegay, H., Parsons, M., 2018. What do you mean, 'resilient Geomorphic Systems'? *Geomorphology* 305: 8-19.

Vaux, P.D., Goldman, C.R., 1990. Dams and development in the tropics: the role of applied ecology. In Goodland, R., (Ed.) *Race to save the tropics. Ecology and economics for a sustainable future*, Washington, D.C., Island Press: 101-23.

Vera-Escalona, I., Habit, E., Ruzzante, D., 2015. Echoes of a distant time: effects of historical processes on contemporary genetic patterns in *Galaxias platei* in Patagonia. *Molecular Ecology* 24: 4112–4128.

Vila, I., Habit, E., 2015. Current situation of the fish fauna in the Mediterranean region of Andean river systems in Chile. *Fishes in Mediterranean Environments* 2: 19-29.

Vila, I., Fuentes, L., Contreras, M., 1999. Peces Límnicos de Chile. *Boletín del Museo Nacional de Historia Natural Chile* 48: 61-75.

Villagrán, C., Hinojosa, L.F., 1997. Historia de los bosques del sur de Sudamérica, II: Análisis fitogeográfico de la flora. *Revista Chilena de Historia Natural* 70: 241-267.

Vince, G., 2010. Dams for Patagonia. *Science* 329: 382-385.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555-561. DOI 10.1038/nature09440.

Winemiller, K.O., McIntyre, P.M., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I. G., Darwall, W. , Lujan, N. K., Harrison, I., Stiassny, M. L. J., Silvano, R. A. M., Fitzgerald, D. B., Pelicice, F. M., Agostinho, A. A., Gomes, L. C., Albert, J. S., Baran, E., Petrere Jr., M., Zarfl, C., Mulligan, M., Sullivan, J. P., Arantes, C. C., Sousa, L. M., Koning, A. A., Hoeinghaus, D. J., Sabaj, M., Lundberg, J. G., Armbruster, J., Thieme, M. L., Petry, P., Zuanon, J., Torrente Vilara, G. , Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C. S., Akama, A., van Soesbergen, A., Sáenz, L., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong: Basin-scale planning is needed to minimize impacts in mega-diverse rivers. *Science* 6269: 128-129.

Yeakley, J.A., Ervin, D., Chang, H., Granek, E.F., Dujon, V., Shandas, V., Brown, D., 2016. Ecosystem services of streams and rivers. In Gilvear, D.A., Greenwood, M.W., Thoms, M.C., Wood, P.A., (Eds.). *River Science, Management and Policy for 21st Century*. Wiley, 335-371.

Zarfl, C., Lumdson, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. *Aquatic Sciences* 77: 161-170.

VII. Anexo 2. Fragmentation of Chilean Andean rivers: expected effects of hydropower development

Gustavo Díaz[1], Pedro Arriagada[2], Konrad Górski[3], Oscar Link[4], Bruno Karelovic[5], Jorge Gonzalez[1] & Evelyn Habit[1, 6]

[1] Departamento de Sistemas Acuáticos, Facultad de Ciencias Ambientales, Universidad de Concepción, Concepción, Chile.
[2] Departamento de Ingeniería Ambiental, Facultad de Ciencias Ambientales, Universidad de Concepción, Concepción, Chile
[3] Departamento de Ecología, Facultad de Ciencias y Centro de Investigación en Biodiversidad y Ambientes Sustentables (CIBAS), Universidad Católica de la Santísima Concepción, Concepción, Chile
[4] Departamento de Ingeniería Civil, Facultad de Ingeniería, Universidad de Concepción, Concepción, Chile
[5] Departamento de Ingeniería Matemática, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción, Chile
[6] Centro de Ciencias Ambientales EULA, Universidad de Concepción, Concepción, Chile
Correspondence author: Gustavo Díaz.

Publicado en: Revista Chilena de Historia Natural

Abstract

Background: Fragmentation (establishment of barriers e.g., hydropower dams, reservoirs for irrigation) is considered one of the greatest threats to conservation of river systems worldwide. In this paper we determine the fragmentation status of central Chilean river networks using two indices, namely Fragmentation Index (FI) and Longest Fragment (LF). These are based on the number of barriers and their placement as well as river length available for fish movement. FI and LF were applied to eight Andean river basins of central Chile in order to assess their natural, current (2018) and future (2050) fragmentation at the doorstep of a hydropower boom. Subsequently, we exemplify the use of these indices to evaluate different placement scenarios of new hydropower dams in order to maximize hydropower use and at the same time minimize impact on fish communities.

Results: In the natural scenario 4 barriers (waterfalls) were present. To these 4 barriers, 80 new ones of anthropogenic origin were added in the current (2018) scenario, whereas 377 new barriers are expected in near future (2050). Therefore, compared to the ´natural´ scenario, in 2050 we expect 115-fold increase in fragmentation in analysed river systems, which is clearly reflected by the increase of the FI values in time. At the same time, the LF diminished by 12 % on average in the future scenario. The fastest increase of fragmentation will occur in small and medium rivers that correspond to 1st, 2nd and 3rd Strahler orders. Finally, case study on configuration of potential hydropower plants in the Biobío basin showed that hydropower output would be maximized and negative effects on fish communities minimised if new hydropower plants would be located in tributaries of the upper basin.

Conclusions: Fragmentation of Chilean Andean river systems is expected to severely increase in near future, affecting their connectivity and ecological function as well as resilience to other anthropogenic stressors. Indices proposed here allowed quantification of this fragmentation and evaluation of different planning scenarios. Our results suggest that in order to minimise their environmental impact, new barriers should be placed in tributaries in the upper basin and river reaches above existing barriers.

Keywords: Connectivity, Dams, Hydroelectricity, Fragmentation Index, Native fish

1. Background

River systems are hierarchical dendritic networks and their functioning strongly depends on physical connectivity (Campbell Grant, Lowe & Fagan, 2007; Fuller, Doyle, & Strayer, 2015; Fullerton et al., 2010). Fragmentation (establishment of any type of barriers e.g., dams, reservoirs for irrigation) and consequent loss of connectivity are considered one of the greatest threats to conservation of river systems worldwide (Lehner et al., 2011). It impedes fundamental eco-hydrological processes in river systems affecting the hydrologic, sediment, and temperature regimes; channel morphology, nutrient cycling, interactions with floodplains and consequently impacts riverine biota (Bunn & Arthington, 2002; Elosegui & Sabater, 2013; McCluney et al., 2014; Olden & Naiman, 2010). For example, fragmentation has been documented to affect the structure of biotic communities, alter migrations, and limit dispersion of riverine organisms (Arthington, Dulvy, Gladstone & Winfield, 2016; Tonkin & Death, 2013). Therefore, fragmentation is expected to be detrimental to the ecological functioning of river systems and conservation of biota that inhabits them (Flotemersch et al., 2016; McCluney et al., 2014; Vörösmarty et al., 2010). Still, in recent decades there has been an explosive increase in the number of barriers in river systems worldwide, mostly in relation to hydropower development (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). At the same time, new conceptual frameworks to advance understanding of physical, hydrologic, and ecological aspects of connectivity have been proposed and new metrics and indices to quantify fragmentation have been developed (Cote, Kehler, Bourne, & Wiersma, 2009; Diebel, Fedora, Cogswell, & O'Hanley, 2015; Grill, Ouellet Dallaire, Fluet Chouinard, Sindorf, & Lehner, 2014). Indices to quantify fragmentation need to be based on theoretical principles of connectivity and hierarchical nature of river networks (Delong & Thoms, 2016). Often, fragmentation of the river network is represented through indices of longitudinal connectivity of the physical habitat of fish species, because fishes are the most vagile aquatic organisms, and their movements are crucial to complete their life cycle and maintenance of populations (Arthington et al., 2016; Liermann, Nilsson, Robertson & Ng, 2012). In this way, Cote et al. (2009) proposed Dendritic Connectivity Index (DCI) to assess habitat connectivity for fish with different life-histories (potadromous; DCI_P and diadromous; DCI_D) on a scale of a river network (basin). This index incorporated three variables: number of barriers, placement (location within the network) and passability (probability to cross a barrier). Thus, for resident or potamodromous fish, connectivity is expected to depend more on the "largest fragment", whereas for diadromous fish it depends on the position of the barrier in relation to the river mouth (Cote et al., 2009). This index has been successfully used to assess effects of fragmentation on diversity, abundance and distribution patterns of riverine fish in some river systems (Mahlum, Kehler, Cote, Wiersma & Stanfield, 2014; Perkin, Shattuck, Gerken & Bonner, 2013; Perkin & Gido, 2012). Some limitations of DCI have also been recognised, most importantly the consideration of the barrier placement only as a theoretical approximation expressed as the distance to the lowest point of the network (Grill et al., 2014). Grill et al., 2014 included an additional metric for placement of barriers within the river network, namely the river volume related to discharge and channel dimensions. This approach, however, strongly relies on data availability and may not be suitable for river basins where detailed hydrologic data are not available.

Worldwide, rapid population growth and energy demand combined with increased consciousness about climate change and need of reduction of the emissions of greenhouse gases have led to hydropower boom with various projects of hydropower plants under construction or planned (Zarlf et al., 2015). These projects are unequally distributed across the globe with most of them concentrated in South America, South-

East Asia and the Balkans in Europe (Zarlf et al., 2015, Winemiller et al., 2016). In South America hydropower plant projects concentrate in Andean regions of various countries including Chile (Habit et al., 2018). Currently, in the Chilean energy matrix hydroelectricity accounts for 35 % and this percentage is expected to grow due to policies promoting the reduction of greenhouse gases and the exploitable hydropower potential estimated at 11 GW spread in approximately 1500 sites (Chilean Ministry of Energy, 2016). These new projected barriers are expected to increase the current fragmentation status of Chilean river systems. Thus, there is a strong need to quantify fragmentation and evaluate different planning scenarios of hydropower plant placement (Jagger et al., 2015). To support decision making processes towards the conservation of the unique Andean river systems that are inhabited by fauna of extremely high level of endemism (e.g., 82 % of fish species in Chilean freshwater systems are endemic to Chile; Vila & Habit, 2015). In addition, for majority of the river systems in Chile, detailed hydrological data are not available, and therefore, calculation of hydrological variables needed in order to use recently proposed indices that consider placement of barriers is difficult (Grill et al., 2014).

This study aims to compare the physical fragmentation level of Andean Chilean rivers among three different scenarios: 'natural' (before anthropogenic intervention), current (2018), and scenario expected in near future (2050) based on present hydropower development plans. To do this, we quantify fragmentation status of eight Andean rivers of central Chile in each of the scenarios using two newly developed indices that consider placement of barriers and are suitable for river basins with poor hydrological data availability: Fragmentation index (FI) and Longest fragment index (LF). We use Strahler order as an easy to obtain metric that represents placement of the barrier within the basin. Subsequently, on the example of one of the analysed basins with the highest hydropower potential (the Biobío basin), we evaluate a range of configurations of hydropower plants using our indices and compare them to distribution of native fish within the basin. Finally, we discuss implications of temporal changes in level of fragmentation of these systems for their ecological function.

2. Methods

2.1 Study area

The study area is located in central Chile, and comprises eight river basins (river networks) namely: Aconcagua, Maipo, Rapel, Mataquito, Itata, Biobío, and Imperial (32°S - 38°S; Table 9 and Fig. 37). From Aconcagua to Biobío the rivers are characterised by discharge regimes dominated by rainfall and snowmelt, and rapid flows, because of their steep slopes. Imperial River originates at a lower altitude in the piedmont of the Andes and thus, it lacks torrential flows (Niemeyer & Cereceda, 1984; Vila, Fuentes & Contreras, 1999). In addition, these river basins show differences in their catchment area, total length of river network and maximal Strahler order, where Biobío river basin is the largest among all assessed basins (Table 9). All basins of the study area belong to the same ichthyogeographic province (Dyer, 2000). This province is the most diverse in Chile and accommodates a total of 21 native and 15 non-native fish species (Vila & Habit, 2015). Native freshwater fish present a high endemism and primitivism level, and are of high conservation interest (Habit, Vila & Dyer, 2006). Most of native species are characterised by small body sizes and therefore are expected to have limited swimming capacities (Vila, Fuentes & Contreras, 1999).

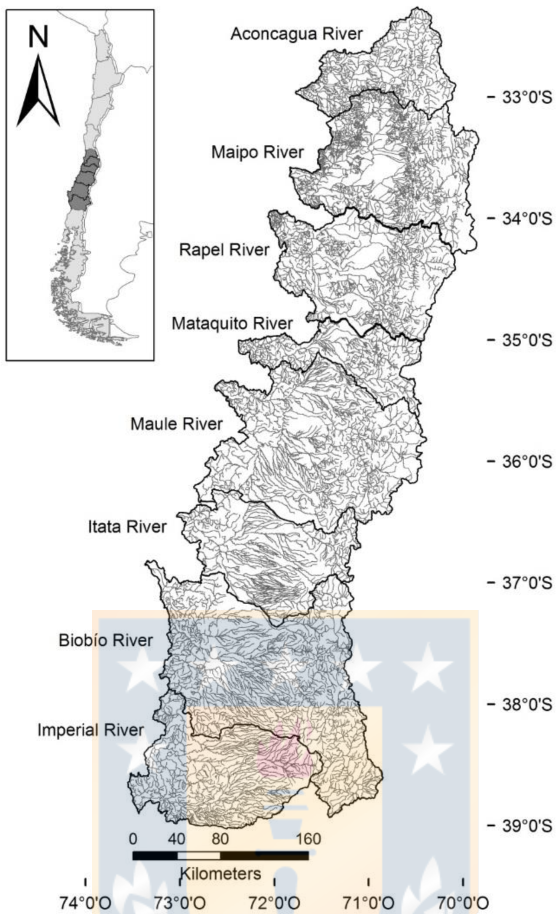

Figura 37. Location the study area which comprises eight river network of central Chile.

Tabla 9. Geographical and physical features of eight studied river networks. Latitude indicates the northern and southern boundaries, whereas Longitude indicates eastern and western boundaries of each river network.

Basin	**Latitude** (°′)	**Longitude** (°′)	**Area** (km^2)	**Length** (km)	**Maximum Strahler order**
Aconcagua	32°15′-33°11′ S	69°59′-71°33′ W	7.334	3.671	5
Maipo	32°56′-34°18′ S	69°48'-71°38' W	15.274	8.216	7
Rapel	33°54'-35°00' S	70°01'-71°51' W	13.766	5.915	6
Mataquito	34°48'-35°38' S	70°24'-72°11' W	6.332	2.879	5
Maule	35°06'-36°35' S	70°21'-72°27' W	21.053	8.532	6
Itata	36°12'-37°20' S	71°02'-72°52' W	11.327	4.887	6
Biobío	36°52'-38°54' S	70°50'-73°12' W	24.370	10.789	7
Imperial	37°49'-38°58' S	71°27'-73°30' W	12.668	6.370	6

2.2 Assessment of fish distribution in the Biobío basin

Current distribution of native fish in the Biobío basin was assessed by field sampling in low-flow conditions in January of 2017 (austral summer). We sampled a total of 25 sites across the basin, using backpack electrofishing equipment (Halltech HT-2000, Ontario, Canada). At each site, riffle and pool habitats were sampled to capture the majority of fish species. Specimens collected from different local communities were identified to species level according to available identification keys and returned to their original habitats (Dyer, 2000; Ruiz & Marchant, 2004; Salas, Véliz, & Scott, 2012). A total of 9 native fish species were captured in both habitat types, and most representative order was Siluriformes with three species (Table 10). Furthermore, *Percilia irwini* Eigenmann, 1928 and *Trichomycterus areolatus* (Valenciennes, 1840) were the most abundant species across sampling sites respectively.

Tabla 10. Native fish species found in Biobio river basin and their ecological and conservation features. Native fish species considered on planning optimization case are symbolized by an asterisk.

Specie	Habitat use	Conservation category	Endemic
Cheirodon galusdae Eigenmann, 1928	Pelagic	Vulnerable	Yes
Bullockia maldonadoi (Eigenmann, 1928)*	Benthic	Endangered	Yes
Trichomycterus areolatus (Valenciennes, 1840)	Benthic	Vulnerable	No
Diplomystes nahuelbutaensis Arratia, 1987*	Benthic	Endangered	Yes
Galaxias maculatus (Jenyns, 1842)*	Pelagic	Less concern	No
Basilichthys microlepidotus (Jenyns, 1841)*	Pelagic	Vulnerable	Yes
Ondontesthes mauleanum (Steindachner, 1836)	Pelagic	Vulnerable	Yes
Percichthys trucha (Valenciennes, 1833)*	Pelagic	Less concern	No
Percilia irwini Eigenmann, 1928	Pelagic	Endangered	Yes

2.3 River networks and barriers

We used the official river hydrographic network data from the Chilean Ministry of Social Development (MIDEPLAN; Ministerio de Desarrollo Social) to assess river networks of analysed basins. This dataset is based on cartographic data from the Military Geographic Institute of Chile (IGM, 1:250.000) and is verified since 2005 by national agencies via field observations to contain only perennial rivers.

To determine the fragmentation status in the study area we overlaped these river networks with shapefile containing georeferenced barriers. Data in this shapefile were obtained from different available data bases from governmental entities related to energy policies, energy production and the use of natural resources (see below). Based on these the final dataset was compiled that contained location and type of barriers. These data were used to create three scenarios:

1) Natural scenario: impassable waterfalls higher than 20 m, since these have certainly involved a historical interruption of free movement upstream. They were identified in Google Earth photographic database and verified in the field (during 2017).

2) Current (2018) scenario: physical barriers that completely obstructed the cross-section of the river, i.e. the barrier width was equal to the width of the active channel, as well as hydroelectric barriers with generation capacity higher than 3 MW. These data were obtained for operating hydropower plants, tailings dams, and water diverting structures and reservoirs for irrigation registered in the databases of the Chilean Ministry of National Assets (Ministerio de Bienes Nacionales; http://www.geoportal.cl/visorgeoportal/) and the Chilean Ministry of Energy (Ministerio de Energía; http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/).

3) Future (2050) scenario: barriers in this scenario included those of the current (2018) scenario, and potential barriers based on analyses of hydropower potential of the rivers performed by the Chilean Ministry of Energy. Sites with hydropower potential higher than 3MW were included to allow comparisons with the current (2018) scenario. These data were obtained from the database of the Chilean Ministry of public works (Ministerio de Obras Públicas; http://walker.dgf.uchile.cl/Explorador/DAANC/). We are aware that this future scenario is an approximation as it depends on whether hydropower development plans will not change in the future and it excludes probable barriers unrelated to hydroelectricity.

2.4 Assessment of fragmentation level

Fragmentation level was evaluated for these three scenarios using two indices: Fragmentation index (*FI*) and Longest fragment (*LF*) that were formulated based on principles proposed by *DCI* (Cote et al. 2009).

The functioning of *FI* is explained in Fig. 38 that shows how a barrier fragments the river network generating disconnected stretches up and downstream (L_1 to L_5 in Fig. 38). A fragment is composed of 1) river stretches upstream of a barrier, 2) the river network located between two barriers, or, 3) the river network located downstream of the barrier closest to the mouth of the river. Fragments upstream of several barriers are considered more impacted/disconnected. The way a barier affects river network strongly depends on its location (Kanno, Russ, Sutherland, & Cook, 2012; McCluney et al., 2014; Rolls, 2011) and, therefore, barrier placement in the network needs to be considered in the fragmentation index. Herein it was considered through the Strahler order of river stretch where the barrier is located (Fig. 38). Thus we calculate the impact of each barrier *i* on the fragmentation index following (Equation 1):

$$(1) \quad IFI(i) = \frac{\sum_{j=1}^{M} L_j S_j}{T}$$

Where *M* is the number of stretches in the river network upstream of the barrier, whereas L_j and S_j are the length and the Strahler order, respectively, of each stretch in the river network upstream of the barrier. In order to normalise this value, it is divided by *T* that is the maximum value that numerator of *IFI(i)* could reach, therefore, $T = \sum_{j=1}^{N} L_j S_j$, where L_j and S_j are defied as above and *N* is the number of stretches in all the river network. In other words, if the river network has a single barrier *i* located in the mouth of the river, *IFI(i)= 1*.

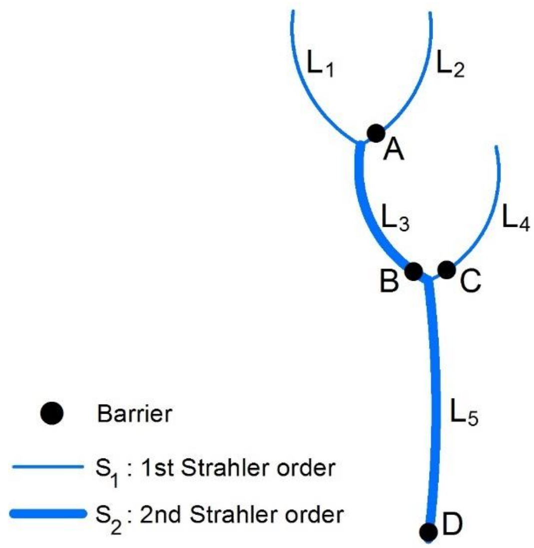

Figura 38. River network with five stretches such that $L_1 = L_2 = L_3 = L_4 = 1$, $L_5 = 2$, and $S_1 = S_2 = S_4 = 1$, $S_3 = S_5 = 2$. Then T= $\sum_{j=1}^{5} L_j S_j$ = 9. For barriers A, B, C and D we can calculate IFI (A) = 1/9, IFI (B) = 4/9, IFI (C) = 1/9 and IFI (D) = 1 respectively. Hence, $\sum_{i\in\{A,B,C,D\}} IFI(i)$ = 15/9. Then FI (A) = 0.044, FI (B) = 0.164, FI (C) = 0.044, and FI (D) = 0.333 (See text for more details).

As such that the sum of *IFI(i)* over all the barriers in the river, i.e., $\sum_{i=1}^{N} IFI(i)$ where *N* is the number of barriers, could reach values higher than 1 (Fig. 38). Hence, we apply a function over $\sum_{i=1}^{N} IFI(i)$ that maps this sum into values between 0 and 1. A direct candidate is an exponential function (Equation 2):

$$(2) \quad FI = 1 - 1.5^{-\sum_{i=1}^{N} IFI(i)}$$

Therefore, *FI* takes values between 0 and 1. The level of fragmentation increase with the number and length of fragments that are disconnected within the river network, and with the Strahler order of the fragment (Fig. 39). Thus, values close to 0 indicate little or no fragmentation, while values close to 1 indicate strong fragmentation of the network. The impact of barriers in reaches with high Strahler order (i.e., lower reaches of the network) was considered to be greater because the specific richness of native fish fauna increases in lower reaches of the network and therefore the potential number of species affected increases, and because the accessibility of most of the river network for diadromous species is affected more strongly by these barriers.

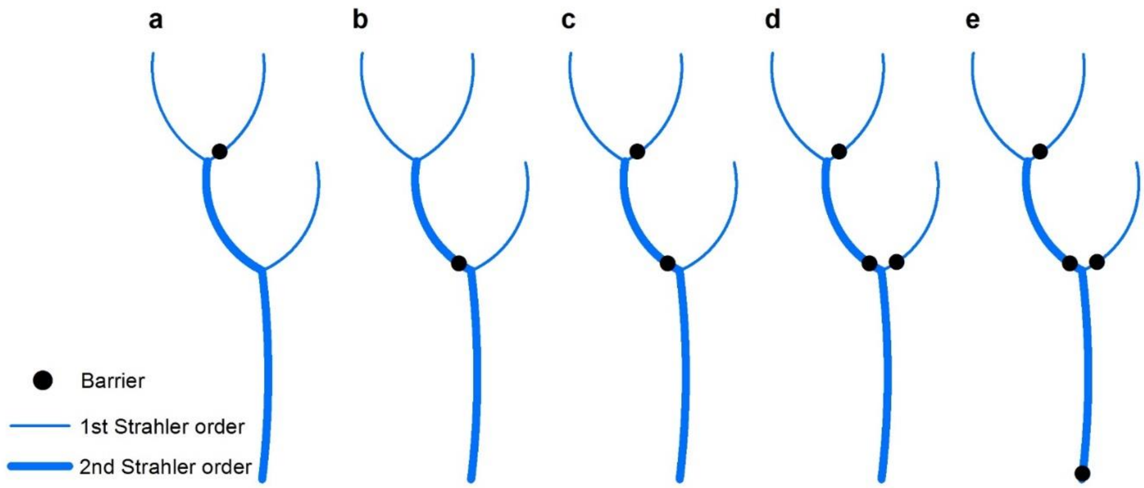

Figura 39. Examples of different levels of fragmentation for river network. For case a we have $\sum_i IFI(i) = 1/9 = 0.111$, then FI=1−1.5$^{-0.111}$=0.04; Likewise for cases b, c, d and e and we have respectively $FI = 0.16, FI = 0.20, FI = 0.24, FI = 0.49$.

Cote et al. (2009) recognised passability as an important variable to estimate habitat connectivity. Passability, however, is difficult to approximate due to specificity of design of each barrier as well as physiology, morphometric of fish and environmental conditions (Bourne, Kehler, Wiersma & Cote, 2011).

Quantification of passability remains a challenge and necessitates specific barrier design and fish characteristics data. Furthermore, probability to pass different barriers is not necessarily independent. We are not able to make quantification, but based on small body size and low swimming capacity of most of the fish species in our study area we assumed passability of all these barriers is very low or null (Laborde et al., 2016).

To estimate the available river section for fish movement, we calculate the Longest fragment of the basin (*LF*). *LF* quantifies the maximum length available for fish to move within the river network. This length can be found between two barriers or one barrier and a river network boundary (headwaters or river mouth) and, thus was calculated as the ratio of the length of the longest fragment to the total length of the network in each basin. *LF* was calculated based on (Equation 3):

$$(3) \quad LF = \frac{L_M}{L_T}$$

where, L_M is the length of the longest fragment in the river network and L_T is the total length of this network.

LF represents a basic but different index to assess the river fragmentation level than *FI*. Its values are close to 0 when the available network to fish movement is very small in comparison to total network length and close to 1 when available network is similar to total length of the network. *FI* and *LF* have a negative relationship, and *FI* increase when a barrier is added to the network in any fragment, whereas *LF* decreases only when a barrier is added in the longest fragment.

2.5 Planning optimisation: case study of the Biobío basin

To inform planning of potential hydropower plants in the Biobío basin, we evaluate a range of configurations of hydropower plants using our indices and compare them to distribution of native fish within the basin. These planning scenarios were built by adding potential future dams to current scenario, and resulted in four potential scenarios (in the parentheses a total expected production, including existing hydropower plants): new barriers only in the mainstem (4001 MW), new barriers only in tributaries in the lower basin (3512 MW), new barriers only in tributaries in the upper basin (3943 MW), all potential new barriers (5696 MW). Subsequently, field-assessed distribution (based on presence /absence data) of five native fish species of the highest conservation value (Table 10) was projected on these scenarios.

3. Results

Only three out of eight analysed river networks were characterised by natural barriers (waterfalls): Maule with two waterfalls, Itata and Biobío with one waterfall each. In the natural scenario, IF was close to 0 in all study basins (Fig. 40, Table 11). For current scenario the basin with the highest number of barriers is Maule (24 barriers) followed by Biobío (19 barriers). Itata and Imperial basins are characterised by one barrier each in the current scenario. Rapel and Biobio basins showed the highest FI values (0.463 and 0.436, respectively), whereas the lowest values of the FI were found for the Imperial (0.002) and Itata (0.044) basins (Table 11). In the future (2050) scenario a total of 461 barriers is expected in all analysed basins. There is an increase in the total number of barriers in all basins (Fig. 40, Table 11). The Biobío basin showed the highest increase in number of barriers between the current (19 barriers) and future (158 barriers) scenarios and the highest FI in the future scenario (0.936). Also, Maule basin is expected to accommodate 65 new barriers in the future scenario in comparison to 24 in the current scenario. Itata and Imperial basin are also expected to accommodate, 38 and 47 barriers, respectively (Table 11). The basin with the lowest increase of the value of FI between the current (2018) and the future (2050) scenario was the Aconcagua (~0.16-fold increase caused by four new barriers), whereas Imperial showed the highest increase in the FI value (~190-fold caused by 46 new barriers, Table 11). Despite this, Imperial showed the lowest FI value (0.381) in the future scenario.

The longest fragment (LF) in the ‘natural’ scenario was 1 for most of the basins, with exception of Maule, Itata and Biobío (due to the presence of waterfalls). Despite of having two natural barriers, the Maule showed the highest LF among all fragmented basins in this scenario (0.995), because both waterfalls are located in the upper reaches of the basin. In the current (2018) scenario the highest LF value was observed for the Imperial and Itata basins (Table 11). The lowest LF value was found for the Rapel (0.651), and Biobío (0.706). In all basins except Rapel, the longest fragments correspond to those that are downstream of all barriers (Fig. 40). In the future (2050) scenario LF value decreased in all basins except Aconcagua and Maule (Table 11). Maipo basin was characterised by the highest decrease that resulted in the lowest LF value among all basins (0.410).

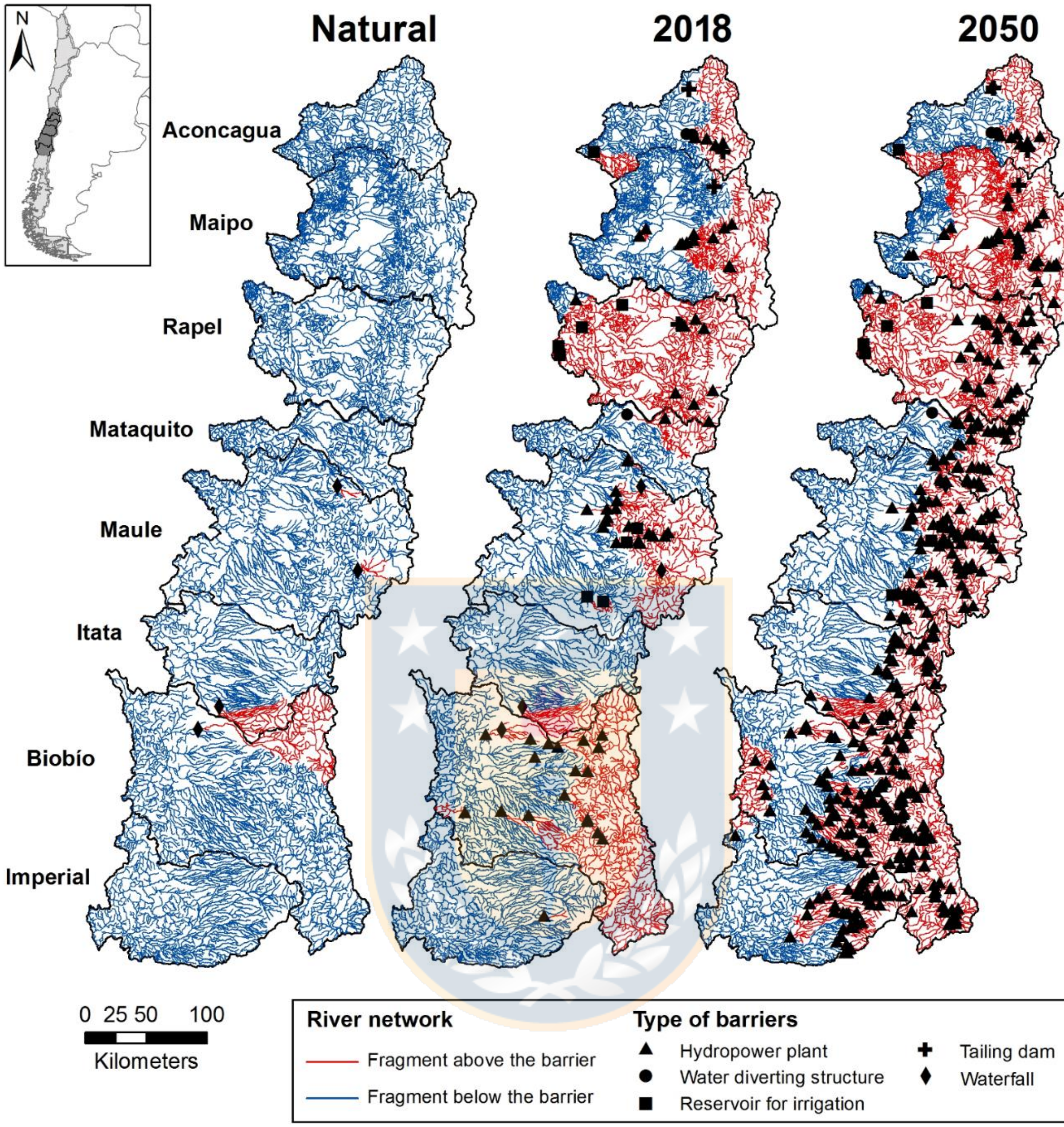

Figura 40. Natural, current (2018) and future (2050) fragmentation scenarios of analysed river basins.

Tabla 11. Metrics of fragmentation for each of the studied river network in the three analysed scenarios.

	Number of barriers (N)			Fragmentation index (FI)			Longest Fragment (LF)		
Basin	**Natural**	**2018**	**2050**	**Natural**	**2018**	**2050**	**Natural**	**2018**	**2050**
Aconcagua	0	10	14	0	0.350	0.406	1	0.768	0.768
Maipo	0	13	33	0	0.393	0.786	1	0.729	0.410
Rapel	0	14	46	0	0.463	0.752	1	0.651	0.540
Mataquito	0	2	36	0	0.080	0.548	1	0.782	0.773
Maule	2	24	89	0.006	0.361	0.681	0.995	0.750	0.750
Itata	1	1	38	0.077	0.044	0.481	0.872	0.872	0.805
Biobío	1	19	158	0.050	0.436	0.936	0.776	0.706	0.668
Imperial	0	1	47	0	0.002	0.381	1	0.995	0.781

A total of 80 barriers of anthropogenic origin are present in the current (2018) scenario. Of these, 64 correspond to hydroepower plants, 9 to reservoirs for irrigation, 4 to tailing dams, and 3 to irrigation water diverting structures. The majority of barriers in the current (2018) scenario are hydropower plants (76%; Fig. 41), that are concentrated in the upper reaches of each basin at the piedmont of the Andes (Fig. 40). This pattern is consistent in all basins with the exception of Rapel which is characterised by an old barrier in its lower reaches (Rapel hydroelectric power station constructed in 1968). In the future (2050) scenario, similar pattern is observed, but the number of barriers fragmenting the upper Itata, Imperial, Mataquito, and Biobío increases. Furthermore, the number of barriers in the middle and lower reaches of the Biobío and Maipo are also expected to increase substantially by 2050 (Fig. 40).

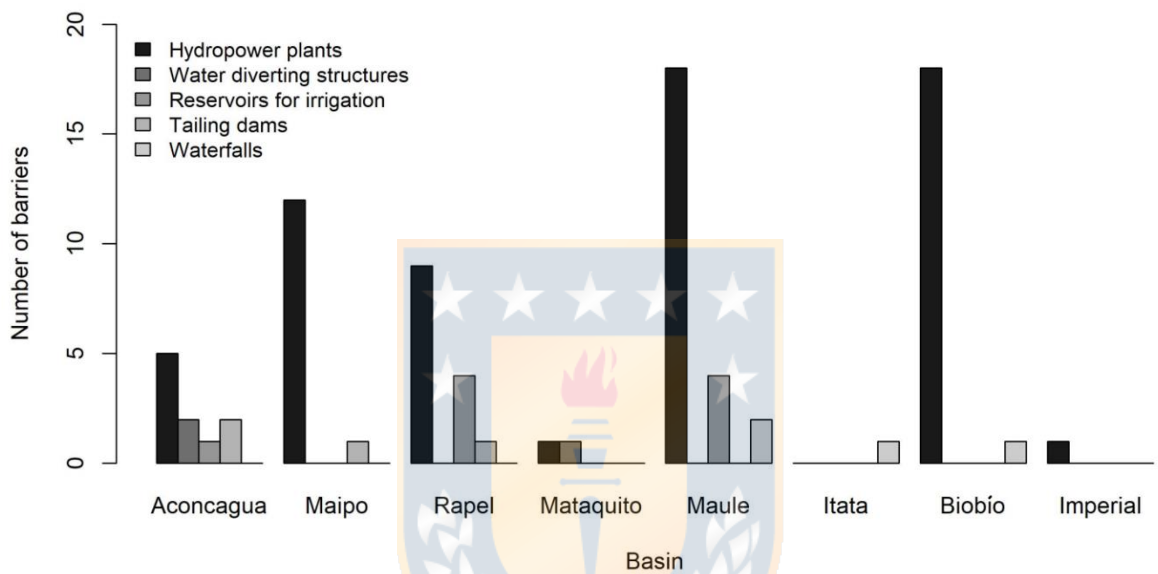

Figura 41. Distribution of different types of barriers across basins in the current fragmentation scenario (2018).

Most of the barriers in the current (2018) scenario are placed in river reaches with Strahler order 4 (26 cases, of which 19 correspond to hydropower plants; Fig. 42). Furthermore, rivers with Strahler orders 6 and 7 are characterised by the lowest number of barriers (Fig. 42). In the future (2050) scenario, the number of barriers increased in all orders, with the exception of order 6. The highest increase was observed for reaches with Strahler orders 1 and 2 with 88 and 116 barriers, respectively (Fig. 42).

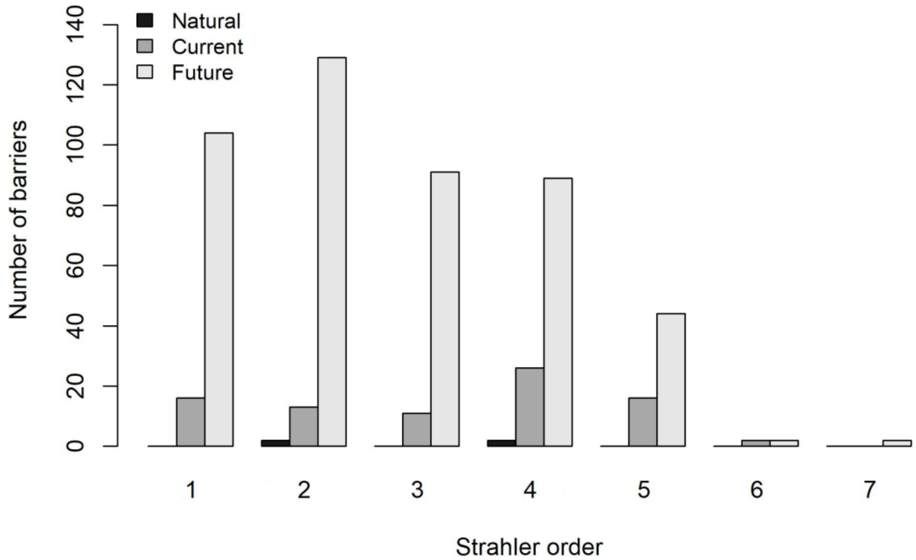

Figura 42. Total number of barriers in the natural, current (2018) and future (2050) fragmentation scenarios across Strahler orders.

Rapel and Maipo basins have undergone the greatest change from the natural to the current (2018) scenario (Fig. 43). Biobío and Maipo are expected to undergo the greatest changes from the current (2018) to the future (2050) scenario, followed by Itata, and Mataquito (Fig. 43). Aconcagua and Imperial basins are expected to undergo less changes (Fig. 43).

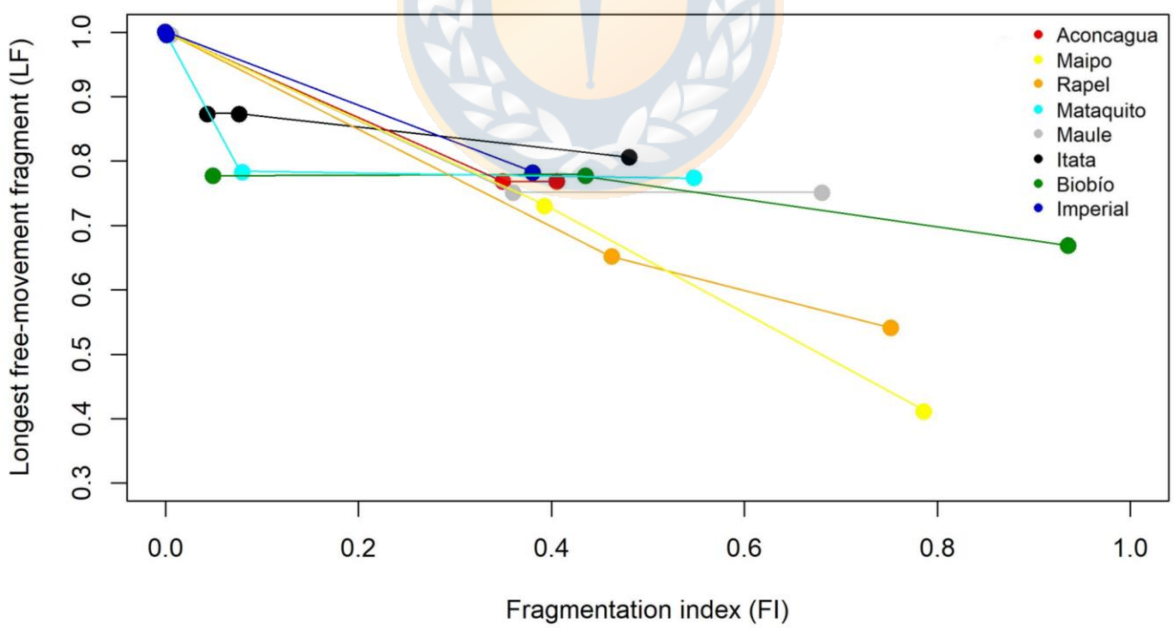

Figura 43. Changes in fragmentation of analysed basins from the 'natural' to current (2018) and from current (2018) to future (2050) scenarios.

Case study on configuration of potential hydropower plants in the Biobío basin showed that placement of new barriers in tributaries of the upper basin and upper part of the river mainstem caused the lowest increase of the FI and maintained the highest values of LF (Fig. 44d). Furthermore, compared to other scenarios, these configurations maximise the use of hydropower potential and at the same time are expected to maintain connectivity among populations of native fish (Fig. 44). In contrary, placement of new barriers in tributaries of the lower basins is expected to generate less hydropower and directly affect native fish populations of all analysed species (Fig. 44c).

4. Discussion

Already high current level of fragmentation of Chilean Andean rivers is expected to substantially increase in near future. As an effect of governmental strategy of encouragement of development of small hydropower dams as non-conventional renewable energy sources (Chilean Ministry of Energy, 2016), the fastest increase of fragmentation is expected to occur in small and medium rivers (Strahler order 1, 2 and 3). This pattern also follows international trends of establishment of barrier in smaller basins (Zarfl et al., 2015). Even though hydropower development in Chile has its origins at the end of the 18th century, national electricity development plan started only in 1943 giving the beginning of construction of large hydropower plants. In line with this plan the number of large dams started to increase with 64 dams constructed up to 2018. Compared to the ´current´ scenario (2018), in near future (2050) we expect rapid acceleration of construction of new hydropower plants with 437 projects with generation capacity higher than 3 MW in central Chilean basins. This implies 6.8-fold increase in number of barriers and corresponds to reduction of on average 12 % of the longest fragments. The future scenario evaluated here, contemplates only hydropower dams. Other anthropogenic water resource related developments such as irrigation structures and tailing dams, may cause further increase of fragmentation. For example, new irrigation reservoirs are needed for growing agriculture and an increase of 57 % (to reach 1.7 million hectares) in irrigated area in central Chile is already expected by 2022 (Valdés-Pineda et al., 2014). Establishment of these new barriers is expected to have impact on functioning of Andean rivers of central Chile. We expect disturbance of sediment and woody debris transport at the basin scale and in multiple basins (Bunn & Arthington, 2002; FitzHugh & Vogel, 2011) as well as significant changes in flow and thermal regimes (Poff et al., 1997; Poff, Olden, Merritt, & Pepin, 2007). Therefore, barriers may affect the integrity of these river systems and alter their environmental conditions, and as a consequence impact their biodiversity and resistance to other environmental stressors (Erös & Campbell Grant, 2015; Fullerton et al., 2010; McCluney et al., 2014).

Future changes in connectivity (increase of fragmentation) are expected to occur in parallel with other anthropogenic stressors. According to climate change predictions, higher temperatures, reduced precipitation and increased evaporation is expected in central Chile within upcoming decades (IPCC, 2014). For example, Pino et al. (2015) estimated reduction of precipitation in central Chile by 20-30 % in 2070; this reduction is expected to augment direct changes in connectivity on ecological function of these river systems. Furthermore, fragmentation and climate change in central Chile will work in concert with other anthropogenic stressors such as land-use changes and pollution as well as increasing demand of water for irrigation as well as industrial and domestic uses (Valdes-Pineda et al., 2014). As such, two river basins that have the highest drinking and industry water demands, Maipo and Biobío (Figueroa et al., 2013), are also expected to undergo the highest connectivity loss due to hydropower development. Therefore, cumulative effects of multiple stressors are expected in these basins that require informed management actions in order to mitigate effects of these stressors on their ecological function and provision of ecosystem services.

Fragmentation assessment tool proposed here may be useful to monitor changes in connectivity as the main driver of riverine ecosystem function (Gilvear, Greenwood, Thoms, & Wood, 2016). The FI incorporates explicitly the location of barriers trough Strahler orders and allows assessment of cumulative effects of barriers. Higher Strahler order reflects higher impact on basin level due to dendritic structure of river networks (Campbell Grant et al., 2007). Furthermore, FI and LF can be used to assess the potential effects of fragmentation on fish communities of the entire basin independently of their life histories. This is different form indices proposed by Cote et al., 2009 that require calculations of separate indices for diadromous and potamodromous fish species.

Addition or removal of hydropower plants in order to minimise the ecological effects of hydropower and restore or maintain connectivity of river networks is currently a major concern of river management and science (e.g., Erös, O'Hanley & Czeglédi, 2018; King, O´Hanley, Newbold, Kemp & Diebel, 2017; O´Hanley, Wright, Diebel, Fedora & Soucy, 2013). We show with our study case that similar hydropower potential could be harnessed with different hydropower plant configurations that can result in different effects on connectivity and ecology of river ecosystem. Fragmentation indices calculated for different scenarios showed severe changes in fragmentation level depending on configuration of hydropower plants within the basin (Jager et al., 2015). Specifically for the Biobío River, hydropower output would be maximised and negative effects on fish communities minimised if new hydropower plants would be located in tributaries of the upper basin. This configuration maintains the connectivity of mainstem of the network that favours fish dispersal among non-impacted tributaries and therefore allows maintenance of fish metapopulations and metacommunities (Erös et al., 2015; Wilkes et al., 2018). Furthermore, it maximises the connectivity of tributaries in the lower basin that is inhabited by majority of native fish species and allows connection with marine habitats for diadromous species (Górski, Habit, Pingram & Manosalva, 2018; Habit, Belk, Tuckfield & Parra, 2006).

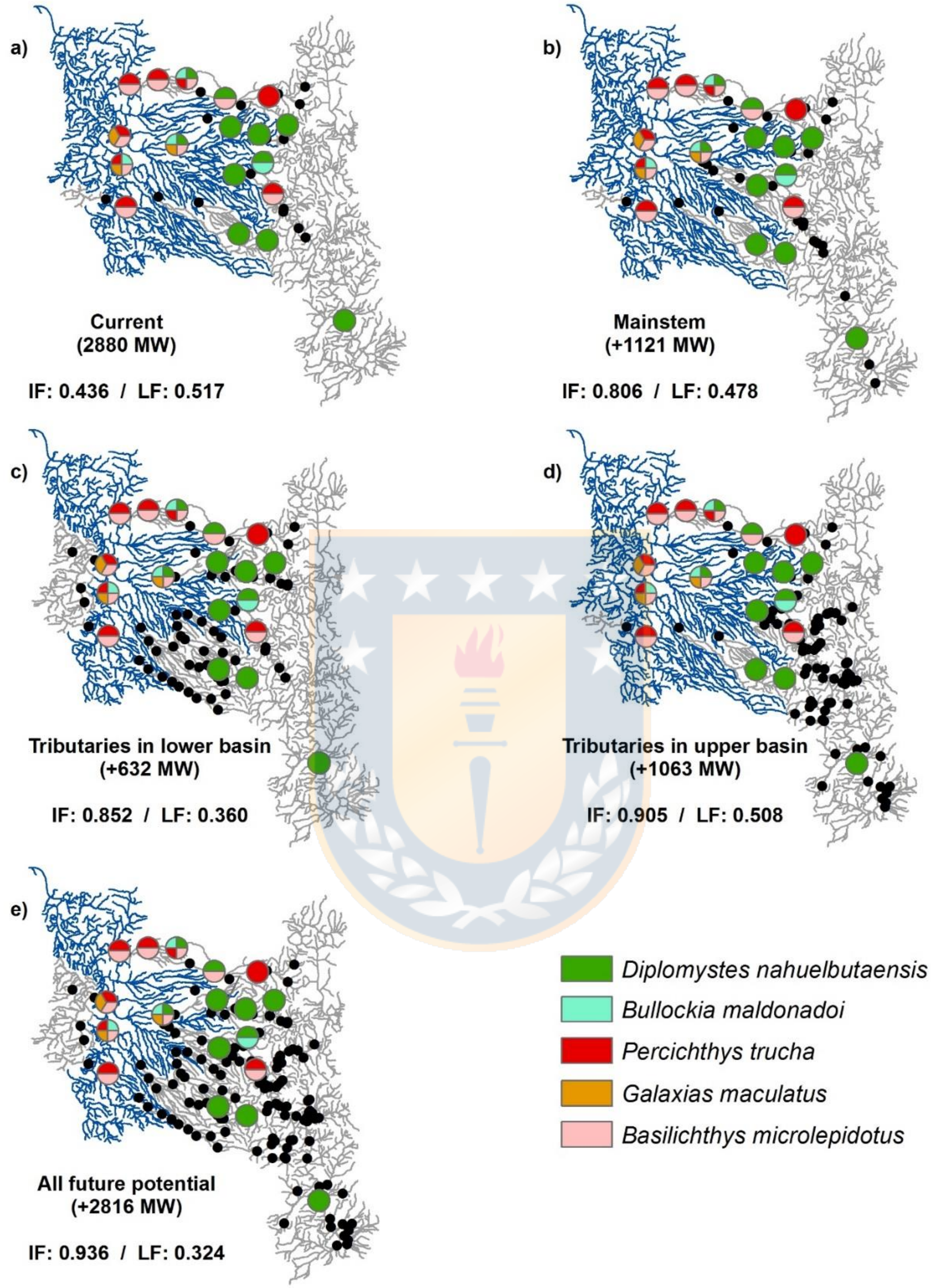

Figura 44. Configurations of planning optimization for future hydropower plants on Biobío river network and distribution the five native fish species of high conservation value. Each configuration (a - e) show impacted (gray) and non-impacted (blue) fragments of the basin according to current and future hydropower plants locations (black dots). Furthermore the hydropower potential and values of corresponding fragmentation indices are indicated. The current distribution (based on presence /absence data) of native freshwater fishes was described using pie charts.

5. Conclusions

Fragmentation of Chilean Andean river systems is expected to severely increase in near future, affecting their connectivity and ecological function as well as resilience to anthropogenic stressors. Indices proposed here allow quantification of this fragmentation and evaluation of different planning scenarios. Subsequently, as shown for the Biobío basin study case similar hydropower potential could be harnessed with different hydropower plant configurations that can have different impact on fish communities. As such, our results suggest that in Chilean Andean rivers new barriers should be prioritised in tributaries in the upper basin and already impacted fragments above existing barriers.

List of abreviations
FI: Fragmentation index
LF: Longest fragment

Authors contributions
GD, EH, KG, OL and JG designed the study and wrote the bases of manuscript; PA, BK, and OL contributed to design the indices; GD, PA and BK performed data analyses to modelled the fragmentation status of river basins in the study area; GD, KG and JG conducted the fieldwork to obtain fish data; GD, KG and EH contributed ideas and wrote the paper. All authors discussed the results and gave a final approval for publication

Acknowledgements
GD is funded by Beca Doctorado Nacional, CONICYT. Also, the authors wish to express their gratitude to Jorge Félez Bernal for his help with the GIS software.

6. References

Campbell Grant, E. H., Lowe, W. H., & Fagan, W. F. (2007). Living in the branches: population dynamics and ecological processes in dendritic networks. *Ecology letters*, *10*(2), 165-175.

Fuller, M. R., Doyle, M. W., & Strayer, D. L. (2015). Causes and consequences of habitat fragmentation in river networks. *Annals of the New York Academy of Sciences*, *1355*(1), 31-51.

Fullerton, A. H., Burnett, K. M., Steel, E. A., Flitcroft, R. L., Pess, G. R., Feist, B. E., ... & Sanderson, B. L. (2010). Hydrological connectivity for riverine fish: measurement challenges and research opportunities. *Freshwater biology*, *55*(11), 2215-2237.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., ... & Nilsson, C. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494-502.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental management*, *30*(4), 492-507.

Elosegi, A., & Sabater, S. (2013). Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. *Hydrobiologia*, *712*(1), 129-143.

McCluney, K. E., Poff, N. L., Palmer, M. A., Thorp, J. H., Poole, G. C., Williams, B. S., ... & Baron, J. S. (2014). Riverine macrosystems ecology: sensitivity, resistance, and resilience of whole river basins with human alterations. *Frontiers in Ecology and the Environment*, *12*(1), 48-58.

Olden, J. D., & Naiman, R. J. (2010). Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology*, *55*(1), 86-107.

Arthington, A. H., Dulvy, N. K., Gladstone, W., & Winfield, I. J. (2016). Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *26*(5), 838-857.

Tonkin, J. D., & Death, R. G. (2013). Macroinvertebrate drift-benthos trends in a regulated river. *Fundamental and Applied Limnology/Archiv für Hydrobiologie*, *182*(3), 231-245.

Flotemersch, J. E., Leibowitz, S. G., Hill, R. A., Stoddard, J. L., Thoms, M. C., & Tharme, R. E. (2016). A watershed integrity definition and assessment approach to support strategic management of watersheds. *River Research and Applications*, *32*(7), 1654-1671.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., ... & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161-170.

Cote, D., Kehler, D. G., Bourne, C., & Wiersma, Y. F. (2009). A new measure of longitudinal connectivity for stream networks. *Landscape Ecology*, *24*(1), 101-113.

Diebel, M. W., Fedora, M., Cogswell, S., & O'Hanley, J. R. (2015). Effects of road crossings on habitat connectivity for stream-resident fish. *River Research and Applications*, *31*(10), 1251-1261.

Grill, G., Dallaire, C. O., Chouinard, E. F., Sindorf, N., & Lehner, B. (2014). Development of new indicators to evaluate river fragmentation and flow regulation at large scales: A case study for the Mekong River Basin. *Ecological Indicators*, *45*, 148-159.

Delong, M. D., Thoms, M. C., Gilvear, D. J., Greenwood, M. T., & Wood, P. J. (2016). An ecosystem framework for river science and management. *River science: Research and management for the 21st century*, 11-36.

Liermann, C. R., Nilsson, C., Robertson, J., & Ng, R. Y. (2012). Implications of dam obstruction for global freshwater fish diversity. *BioScience*, *62*(6), 539-548.
Mahlum, S., Kehler, D., Cote, D., Wiersma, Y. F., & Stanfield, L. (2014). Assessing the biological relevance of aquatic connectivity to stream fish communities. *Canadian journal of fisheries and aquatic sciences*, *71*(12), 1852-1863.

Perkin, J. S., Shattuck, Z. R., Gerken, J. E., & Bonner, T. H. (2013). Fragmentation and drought legacy correlate with distribution of burrhead chub in subtropical streams of North America. *Transactions of the American Fisheries Society*, *142*(5), 1287-1298.

Perkin, J. S., & Gido, K. B. (2012). Fragmentation alters stream fish community structure in dendritic ecological networks. *Ecological Applications*, *22*(8), 2176-2187.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., ... & Stiassny, M. L. J. (2016). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, *351*(6269), 128-129.

Habit E, García A, Díaz G, et al. River science and management issues in Chile: Hydropower development and native fish communities. River Res Applic. 2018;1–11. https://doi.org/10.1002/rra.3374
Chilean Ministry of Energy. (2016). Estudio de Cuencas. Analisis de las condicionantes para el desarrollo hidroeléctrico en las cuencas del Maule, Biobío, Toltén, Valdivia, Bueno, Puelo, Yelcho, Palena, Cisnes, Aysén, Baker y Pascua. Chile (ed.), pp: 104 pp.

Jager, H. I., Efroymson, R. A., Opperman, J. J., & Kelly, M. R. (2015). Spatial design principles for sustainable hydropower development in river basins. *Renewable and Sustainable Energy Reviews*, *45*, 808-816.

Vila, I., & Habit, E. (2015). Current situation of the fish fauna in the Mediterranean region of Andean river systems in Chile. *Fishes in Mediterranean Environments*, *2*, 1-19.

Niemeyer, H., & Cereceda, P. (1984). Hidrografía, Geografía de Chile, Tomo VIII. Santiago: Instituto Geográfico Militar.

Vila, I., Fuentes, L., & Contreras, M. (1999). Peces límnicos de Chile. *Boletín del Museo Nacronal de Historia Natural. Chile*, *48*, 61-75.

Dyer, B. (2000). Systematic review and biogeography of the freshwater fishes of Chile. *Estudios Oceanológicos,* 19: 77-98.

Habit, E., Dyer, B., & Vila, I. (2006). Estado de conocimiento de los peces dulceacuícolas de Chile. *Gayana (Concepción)*, *70*(1), 100-113.

Ruiz, V. H., & San Martín, M. M. (2004). *Ictiofauna de aguas continentales chilenas*. Universidad de Concepción, Facultad de Ciencias Naturales y Oceanográficas.

Salas, D., Véliz, D., & Scott, S. (2012). Diferenciación morfológica en especies del género Cheirodon (Ostariophysi: Characidae) mediante morfometría tradicional y geométrica. *Gayana (Concepción)*, *76*(2), 142-152.

Ministerio de Bienes Nacionales. Visor de datos geoespaciales. http://www.geoportal.cl/visorgeoportal/. Accessed 02 April 2018.

Ministerio de Energía. Modulo cartográfico. http://sig.minenergia.cl/sig-minen/moduloCartografico/composer/. Accessed 02 April 2018.

Ministerio de Obras Públicas. Explorador de derechos de aprovechamiento de aguas no consuntivos. http://walker.dgf.uchile.cl/Explorador/DAANC/. Accessed 04 April 2018.

Kanno, Y., Russ, W. T., Sutherland, C. J., & Cook, S. B. (2012). Prioritizing aquatic conservation areas using spatial patterns and partitioning of fish community diversity in a near-natural temperate basin. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *22*(6), 799-812.

Rolls, R. J. (2011). The role of life-history and location of barriers to migration in the spatial distribution and conservation of fish assemblages in a coastal river system. *Biological Conservation*, *144*(1), 339-349.

Bourne, C. M., Kehler, D. G., Wiersma, Y. F., & Cote, D. (2011). Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity. *Aquatic Ecology*, *45*(3), 389-403.

Laborde, A., González, A., Sanhueza, C., Arriagada, P., Wilkes, M., Habit, E., & Link, O. (2016). Hydropower Development, Riverine Connectivity, and Non-sport Fish Species: criteria for Hydraulic Design of Fishways. *River Research and Applications*, *32*(9), 1949-1957.

Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J. B., Olivares, C., Vera, M., ... & Abarza, A. (2014). Water governance in Chile: Availability, management and climate change. *Journal of Hydrology*, *519*, 2538-2567.

FitzHugh, T. W., & Vogel, R. M. (2011). The impact of dams on flood flows in the United States. *River Research and Applications*, *27*(10), 1192-1215.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... & Stromberg, J. C. (1997). The natural flow regime. *BioScience*, *47*(11), 769-784.

Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences*, *104*(14), 5732-5737.

Erös, T., & Campbell Grant, E. H. (2015). Unifying research on the fragmentation of terrestrial and aquatic habitats: patches, connectivity and the matrix in riverscapes. *Freshwater biology*, *60*(8), 1487-1501.

IPCC. (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Pino, P., Iglesias, V., Garreaud, R., Cortés, S., Canals, M., Folch, W., ... & Steenland, K. (2015). Chile confronts its environmental health future after 25 years of accelerated growth. *Annals of global health*, *81*(3), 354-367.

Figueroa, R., Bonada, N., Guevara, M., Pedreros, P., Correa-Araneda, F., Díaz, M. E., & Ruiz, V. H. (2013). Freshwater biodiversity and conservation in mediterranean climate streams of Chile. *Hydrobiologia*, *719*(1), 269-289.

Gilvear, D. J., Greenwood, M. T., Thoms, M. C., & Wood, P. J. (Eds.). (2016). River science: Research and management for the 21st century. John Wiley & Sons.

Erős, T., O'Hanley, J. R., & Czeglédi, I. (2018). A unified model for optimizing riverscape conservation. *Journal of Applied Ecology*, *55*(4), 1871-1883.

King, S., O'Hanley, J. R., Newbold, L. R., Kemp, P. S., & Diebel, M. W. (2017). A toolkit for optimizing fish passage barrier mitigation actions. *Journal of applied ecology*, *54*(2), 599-611.

O'Hanley, J. R., Wright, J., Diebel, M., Fedora, M. A., & Soucy, C. L. (2013). Restoring stream habitat connectivity: a proposed method for prioritizing the removal of resident fish passage barriers. *Journal of environmental management*, *125*, 19-27.

Wilkes, M. A., Webb, J. A., Pompeu, P. S., Silva, L. G. M., Vowles, A. S., Baker, C. F., ... & Kemp, P. S. (2018). Not just a migration problem: M etapopulations, habitat shifts, and gene flow are also important for fishway science and management. *River Research and Applications*.

Habit, E., Belk, M. C., Cary Tuckfield, R., & Parra, O. (2006). Response of the fish community to human-induced changes in the Biobío River in Chile. *Freshwater Biology*, *51*(1), 1-11.
Górski, K., Habit, E. M., Pingram, M. A., & Manosalva, A. J. (2018). Variation of the use of marine resources by Galaxias maculatus in large Chilean rivers. *Hydrobiologia*, *814*(1), 61-73.