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Evolution of water environmental regulations in Chile since 1900

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ABSTRACT

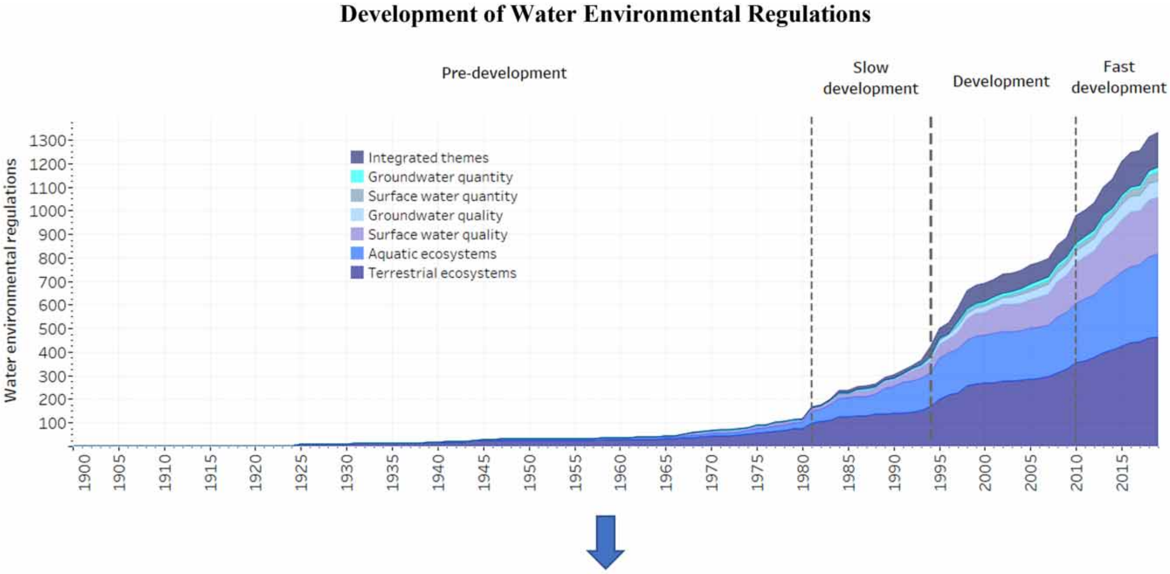
Understanding the development of water environmental regulations over time and its response to external stress is crucial to enhance its performance, but there are few studies on it. This study aims to unfold the evolution of water environmental regulations in Chile and its response to changing water resources management, socio-economic, climate, and environmental conditions from 1900 to 2019. Content analysis was used to code the water environmental regulations, whereas trend analysis was carried out to identify the development stages, and both qualitative and quantitative co-evolutionary approaches were used to analyze the response of water environmental regulations to external changes. Results show that the development of water environmental regulations experienced the following four stages: the pre-development (1900–1980), slow development (1981–1993), development (1994–2009), and fast development (2010–2019). The development of water environmental regulations seriously lagged from water resources management and linearly responded to economic development and population growth. However, it presented a weak response to climate change and had a limited impact on environmental degradation. Development of water environment regulations should be integrated and synchronized with water resources management in future.

Key words: Chile, Co-evolutionary system, Environmental regulations, Water resources management

HIGHLIGHTS

- Development of water environmental regulations in Chile since 1990 and its response to changing factors with both qualitative and quantitative approaches.
- Development of water environmental regulations was not synchronized with water resources management and presented a strong relationship with the economic and population growth.

GRAPHICAL ABSTRACT



Effects of Economic and Population Growth in Development of Water Environmental Regulations

	Coefficient Correlation Analysis	P-value Two-way ANOVA Analysis
GDP per Capita	+ 0.99	$2 \cdot 10^{-16}$
Population	+ 0.95	$3.35 \cdot 10^{-7}$

INTRODUCTION

Natural environments are globally degraded due to population growth and economic development. Ineffective and uncoordinated regulations on human activities (e.g. agriculture intensification, industry development, infrastructure construction, energy production, and deforestation) are considered as one of the main causes of environmental crisis (Pahl-Wostl *et al.*, 2008; Pahl-Wostl, 2009, 2017; Biermann *et al.*, 2010).

Water environmental governance is often separated from water resources management in most countries. Water resources management agencies (e.g. the Ministry of Water Recourses) have the primary objective to achieve an efficient water resources allocation to maximize the total economic benefits without compromising the sustainability of the riverine ecological system, which is the recent goal for some river basins. Environmental protection agencies (e.g. the Ministry of Environmental Protection) often revise existing or issue new environmental regulations for reaching desired ecological outcomes based on information (data) from their monitoring systems. In addition, the change in the ecological system is an accumulated consequence which often occurs over decades or even a hundred years (Sivapalan & Blöschl, 2015). Therefore, ineffective and uncoordinated management between water resources management and water environmental governance could result in unintended or undesired ecological outcomes (Genova, 2022).

There is rich literature on water resources management involving the soft path (water resources regulations) and the hard path (construction of hydraulic works). There are also increasing studies on formal (laws and regulations) and informal (participatory management and social learning) environmental governance. Most of these studies used various indicators (e.g. corruption, political stability, government effectiveness, resource availability, democracy status) to assess the adaptive capacity of governance to various environmental issues in a qualitative way and often a short timeframe (years or a couple of decades) (Bryant *et al.*, 2000; Adger *et al.*, 2005; Brooks *et al.*, 2005; Hooper, 2006; Engle & Lemos, 2010; Clarvis & Allan, 2014). Thus, they cannot identify the responses of the environmental governance to socio-economic, climate, and ecological conditions in a quantitative way, nor reveal its adaptive characteristics over the long term. In addition, to our knowledge, no studies are found on how water environmental governance co-evolves with water resources management. Without this knowledge, our capacity for developing effective water environmental governance will be seriously compromised.

Chile is an interesting example of water environmental governance during the last century. It has been regarded by the World Resource Institute as a country in 'High water stress'. The country's economy is strongly dependent on the use of water resources. Changes in water governance moving from a centralized system (managed by the State) to a free-market water system since the 1980s have led to an intensive economic growth but resulted in serious environmental issues (Donoso, 2018b). Moreover, Chile moved from a democratic regime to a military regime and finally back again to democracy in 1990, influencing the national governance objectives (Reyes-Mendy *et al.*, 2014). While the impact of water resources management reforms on water resources allocation and water use has been highly recognized and intensively studied (Donoso, 2015; Hearne, 2018; Vergara & Rivera, 2018), lack of understanding remains on how water environmental regulations has been developed over time and its ability to cope with the environmental degradation caused by changes in water resources allocation, water use, and other socio-economic and climatic drivers.

This study aims to unfold the history of water environmental regulations (formal governance) in Chile and its responses to changes in external conditions since 1900. Specifically, it has the following objectives: (1) describe the temporal and spatial development of water environmental regulations; (2) identify the development stages of these environmental regulations; (3) analyze the co-evolution of water environmental regulations with water resources management, climatic change, socio-economic development and environmental degradation in a qualitative way; and (4) analyze the responses of water environmental regulations to key socio-economic and climatic factors in a quantitative way. It is expected that findings from this study will generate valuable learning from the past for improving water environmental regulations in future.

METHODS

Case study description

Chile is a country located in South America which extends for 4,300 km in the north–south direction. It is divided into the following four macro-regions: North, Central, South, and Austral, each with different climate characteristics. Temperature decreases and precipitation increases from North to South. The natural environmental systems vary across the country (Donoso, 2018a; McPhee, 2018). These four macro-regions are composed of 101 river basins, including 1,250 rivers and more than 12,700 lakes. The Chilean economy has rapidly grown since the 1990s with GDP more than double during the last decades. It heavily relies on water consumption (Anríquez & Melo, 2018; Donoso, 2018b) with surface water and groundwater consumption increasing by 1,083 and 633%, respectively, in the same period (Donoso, 2018b).

The environmental conditions in Chile are highly degraded. First, there was a significant reduction of water availability in several catchments during the last 60 years, and this reduction rate has dramatically increased during the last decades. This situation arose as a result of high demand pressures also due to the most prolonged drought in the last decade (Universidad de Chile, 2019). Then, water quality in Chile was also a big challenge characterized by elevated concentrations of metals, metalloids, salinity, decrease in dissolved oxygen, and eutrophication in several reservoirs and lakes in the North and Central region of Chile (Vega *et al.*, 2018; Universidad de Chile, 2019). Third, there emerged rapidly decreasing rates of native forest during the last decades (CONAF, 2016; Miranda *et al.*, 2017; Universidad de Chile, 2019). Nearly 50% of terrestrial ecosystems were classified as threatened according to the IUCN Red list (Pliscoff, 2015). Finally, continental aquatic ecosystems in Chile were considered fragile (Universidad de Chile, 2019). For example, 50% of freshwater fish species were at risk of extinction, and 90% in danger (Riestra, 2018). Therefore, strengthening environmental governance in Chile is urgently needed.

Mining water environmental regulations

Environmental governance contains, in a broad sense, formal and informal rules that are set up to steer societies preventing from, mitigating, or adapting to environmental change for sustainable development (Biermann *et al.* (2010). The formal rules often refer to the legislations and regulatory frameworks which arguably are principally responsible for improving environmental conditions for desired outcomes (Plummer & Armitage, 2010; Wandel & Marchildon, 2010; Kandasamy *et al.*, 2014). Therefore, the formal rules were considered in this study. Specifically, the formal rules in Chile included the set of regulations (articles) contained in the Laws, Decree-Law (DL), Decree with force of Law (DFL), Decrees, and Resolutions (here after, in a general sense, we used the term *legal frameworks* to refer to the Laws, DL, DFL, Decrees, and Resolutions and *regulations* to the regulations (articles) contained in these legal frameworks).

To track the long-term development of water environmental regulations, we chose *Ley Chile* as our data source. *Ley Chile* is a database of the National Library of Congress containing all Chile's legal frameworks (Laws, DL, DFL, Decrees, and Resolutions) and could be freely accessed online (www.LeyChile.cl). We considered a study period from 1900 to 2019 as no water environmental regulation were found before this date. We retrieved all legal frameworks using keywords 'water' and 'environment' and the derived words (in Spanish), and relevant theme filters in the search portal of the web. Additionally, we reviewed official documents of main water and environmental policies applied in Chile throughout history. We eliminated duplicates and removed those which were not freshwater environment protection-oriented (e.g. maritime, air pollution, ozone, noise pollution, luminism pollution). After these processes, we obtained the final datasets of Laws, DL, DFL, Decrees, and Resolutions to be further analyzed.

We used the manual content analysis approach to extract information from the retrieved datasets. Content analysis has been largely used in different fields for text mining of extensive and unstructured data to obtain trends or patterns in data (Sirmakessis, 2012; Xiong *et al.*, 2016). The coding variables were designed to describe the main characteristics of each regulation (Table 1). Information obtained from these coding variables allowed answering 'where' and 'when' 'which policy instrument' was applied for 'which environmental theme'. Specifically, we classified the coding variables into three categories based on Wei *et al.* (2015) and Xiong *et al.* (2016). The first category details general information about the legal framework (publication date, validity status). The second category defines the administrative area (the geographic locations where the regulations were applicable). The third category describes the thematic information, including the environmental theme(s) each regulation was applied to and the policy instrument used in each regulation. The environmental themes were categorized based on the widely recognized environmental topics.

Identifying the development stages of water environmental regulations

We measured the trajectory of water environmental regulations over time through the number of regulations that were in force in each year of the study period. This was complemented by more detailed qualitative analysis of the

Table 1 | Coding variables to describe the content of water environmental regulations.

Category	Variable	Description
General information	Publication date	Year when the regulation was promulgated
	Validity status	Repealed or in-force; repealed year
Context information	River basin	Basin(s) where it was applied
	Administrative area	Where the regulation was applicable: all national territory, or specific region/local area.
Thematic information	Themes	The regulations were categorized into the following seven themes: (a) Surface water quality (b) Surface water quantity (c) Groundwater quality (d) Groundwater quantity (e) Terrestrial ecosystem and biodiversity (f) Aquatic ecosystem and biodiversity (g) Integrated themes (included all the themes mentioned above).
	Policy instrument	The regulations were categorized into nine types: Prohibition restrictions and obligations (PRO); funds; information; inspections; plans to protect or restore; environmental impact assessment and mitigation plans (EIA); sanctions; protected areas; and plans for protected areas (characteristics of each policy instrument are detailed in the Supplementary Material)

main regulations. Firstly, we identified development stages of water environmental regulations with the method proposed by Bernaola-Galván *et al.* (2001), which localizes tipping points. This method is applicable for non-stationarity and non-linear systems where tipping points are challenging to identify. The approach calculates the statistic t value as defined in Equation (1), for each point along with the entire timeframe (1900–2019), which measures the difference between the mean values of the left (previous) and right (next) time series.

$$t = \left| \frac{\mu_{left} - \mu_{right}}{S_D} \right| \tag{1}$$

where

$$S_D = \left(\frac{S_{left}^2 (N_{left} - 1) + S_{right}^2 (N_{right} - 1)}{N_{left} + N_{right} - 2} \right)^{\frac{1}{2}} \times \left(\frac{1}{N_{left}} + \frac{1}{N_{right}} \right)^{\frac{1}{2}}$$

S_D is the pooled variance. μ_{left}, μ_{right} are the mean values of the data to the left and right of the point, respectively. S_{left}, S_{right} are the standard deviations of the data to the left and right of the pointer, respectively. N_{left}, N_{right} are the number of points to the left and right of the pointer, respectively. The maximum value of t within the evaluated time series indicates the maximum difference between the mean values of the left and right time series of the evaluated point. Therefore, it represents a potential tipping point or transition. Then, the statistical significance $P(t_{\max})$ is calculated using Equation (2). If $P(t_{\max}) \geq 95\%$ means that t is statistically significant, consequently t_{max} represents a changing point.

$$P(t_{\max}) \approx \{1 - I_{[v/(v+t^2)]}(\delta v, \delta)\}^{\gamma} \tag{2}$$

where $\gamma = 4.19 lnN - 11.54$, $\delta = 0.4$, N is the size of the sequence, $v = N - 2$, and $I_X(a, b)$ is the incomplete beta function. Additional changing points were identified within the time periods at the right and left of the t_{max} by following the same process.

Then, we used the societal transition theory to explain these identified development stages. It is conceptually recognized that a successful societal transition includes an initial stage characterized by slow or absence of change, followed by a period of rapid changes and finalizing with a stabilization period where the speed of change starts decreasing until reaching a new equilibrium (Rotmans *et al.*, 2001; Rotmans, 2005; Tàbara & Ilhan, 2008).

Analyzing the co-evolution of water environmental regulations with external changes with both qualitative and quantitative approaches

We first analyzed how the development of water environmental regulations co-evolved with water resources management, climatic, socio-economic, and environmental conditions in different development stages with the qualitative approach. The indicators for representing water resources management, climate, socio-economic, and environmental conditions were chosen according to the recent literature on this field, the site-specific characteristics in Chile and data availability (Table 2). We used key water resources Laws and Reforms (focused on water administration and management), water storage capacity and irrigated areas to represent water resources management. We used the drought events in Central Chile, the standardized precipitation index (SPI) and the standardized temperature anomalies (STA) as proxy indicators of climate change. Social-economic factors included GDP per capita of the country and national population growth. The mean annual runoff to the sea indicating the amount of instream flow maintained in rivers for ecological uses was considered for representing the environmental conditions. Due to the lack of data for the whole country, the mean annual runoff to the sea in the

Table 2 | External factors for development of water environmental regulations.

	External factors	**Available data**
Water resources management	Main water resources regulations[a]	1900–2019
	Water storage capacity, irrigated areas[b]	1900–2010
Climatic	Drought events in Central Chile[c]	1900–2019
	[d]Standardized precipitation index Central Chile (SPI)[e,f]	1962–2019
	[d]Standardized temperature anomalies Central Chile (STA)[e]	1962–2019
Socio-economic	[d]GDP per capita[g]	1960–2019
	[d]Population growth[h]	1900–2019
Environmental	Mean annual runoff flow to sea on Maipo River Basin, Central Chile (Cabimbao station)[f]	1980–2019
	Number of depleted rivers[i]	1950–2019
	Natural vegetation loss[j]	1970–2010

[a]Data obtained from the National Library of the Congress of Chile (www.LeyChile.cl).
[b]Data obtained from (MOP, 2010; OCDE, 2016).
[c]Data obtained from (Garreaud *et al.*, 2020).
[d]Data used on statistical analysis.
[e]Data obtained from the National Service of Environmental Information SINIA (https://sinia.mma.gob.cl).
[f]Data obtained from the Centre for Climate and Resilience Research Climate Explorer (https://explorador.cr2.cl/).
[g]Data obtained from the World Bank (https://data.worldbank.org).
[h]Data obtained from census available at the National Statistical Institute INE (https://www.ine.cl).
[i]Data obtained from the DGA (DGA, 2018a).
[j]Data obtained from (Miranda *et al.*, 2017).

Maipo river basin was used, where the capital city of Santiago is located, and it is the most important river of the country in terms of economy. The number of depleted rivers in the country was another indicator related to river health. Natural vegetation loss was considered as a proxy for loss of terrestrial ecosystems and biodiversity.

Then we conducted correlation analysis and two-way ANOVA between water environmental regulations and the external factors to analyze the effect of these factors on the development of water environmental regulations. As some indicators were either qualitative or only had a few data points without the continuous coverage of the study period, GDP, population growth, SPI, and STA were used for the quantitative analysis, which we argue as the key external factors.

RESULTS

Temporal and spatial development of water environmental regulations

We found 295 legal frameworks (Laws, DL, DFL, Decrees, and Resolutions) related to water environment protection. Each one included one or several regulations, thus over 1,400 regulations were coded (Figure 1(a)). The most covered environmental themes within the large set of regulations were terrestrial ecosystem followed by aquatic ecosystem with a total of 189 and 130 legal frameworks, respectively, including 504 and 361 regulations (Figure 1(a)). The most common policy instruments used within these two topics were prohibition/restrictions/obligations (PRO). This kind of instrument was applied 193 times in terrestrial ecosystem regulations and 140 times in aquatic ecosystem regulations (Figure 1(b)). Protected areas were also highly applied, 127 times in terrestrial ecosystem regulations and 73 in aquatic ecosystem regulations (Figure 1(b)). These protected areas include national reserves, national parks, natural monuments, nature sanctuaries, forestry reserves, and Ramsar

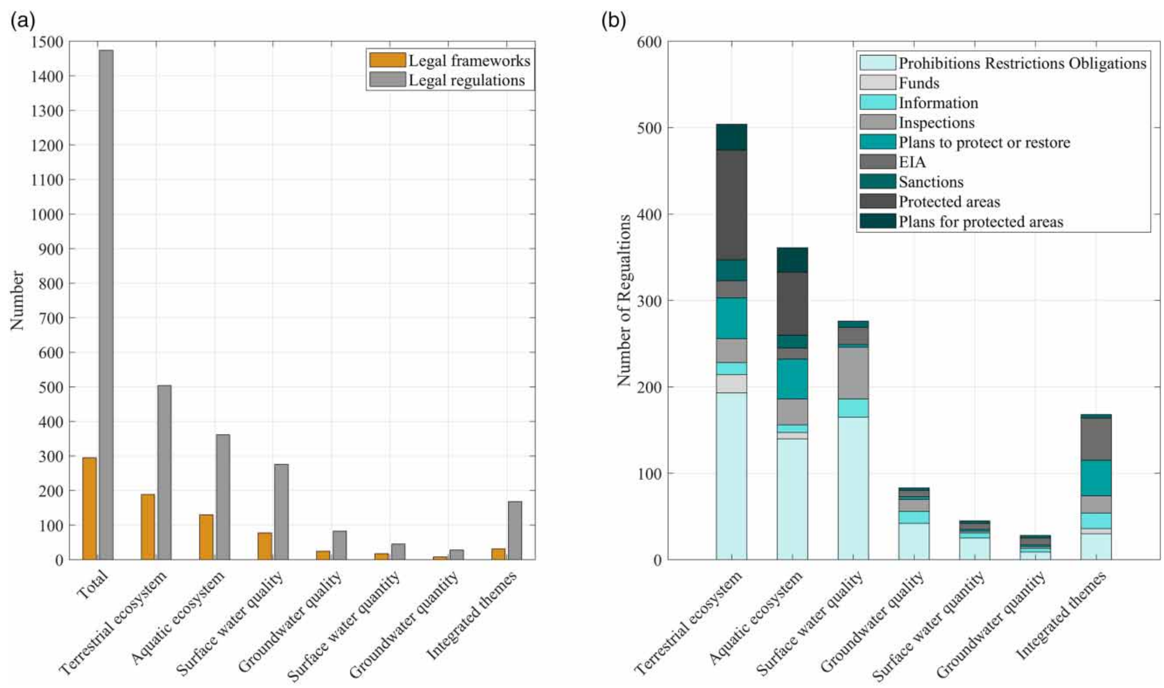


Fig. 1 | (a) Number of Laws, DL, DFL, Decrees, and Resolutions (legal frameworks) and regulations involving each environmental theme. (b) Number of regulations and number of policy instruments applicable to each environmental theme.

wetlands. Water quality was also a recurrent theme, as it was included in 78 legal frameworks involving 276 regulations (Figure 1(a)). Surface water quantity and groundwater quantity topics were only included in very few regulations compared with the other themes (45 and 28, respectively) (Figure 1(a)).

As shown in Figure 2, environmental regulations on water were distributed throughout the entire country. Among the 295 legal frameworks, 123 were applicable nation-wide, whereas the other 173 legal frameworks applied in certain regions/locations and in the 101 river basins of the entire country. The central region of

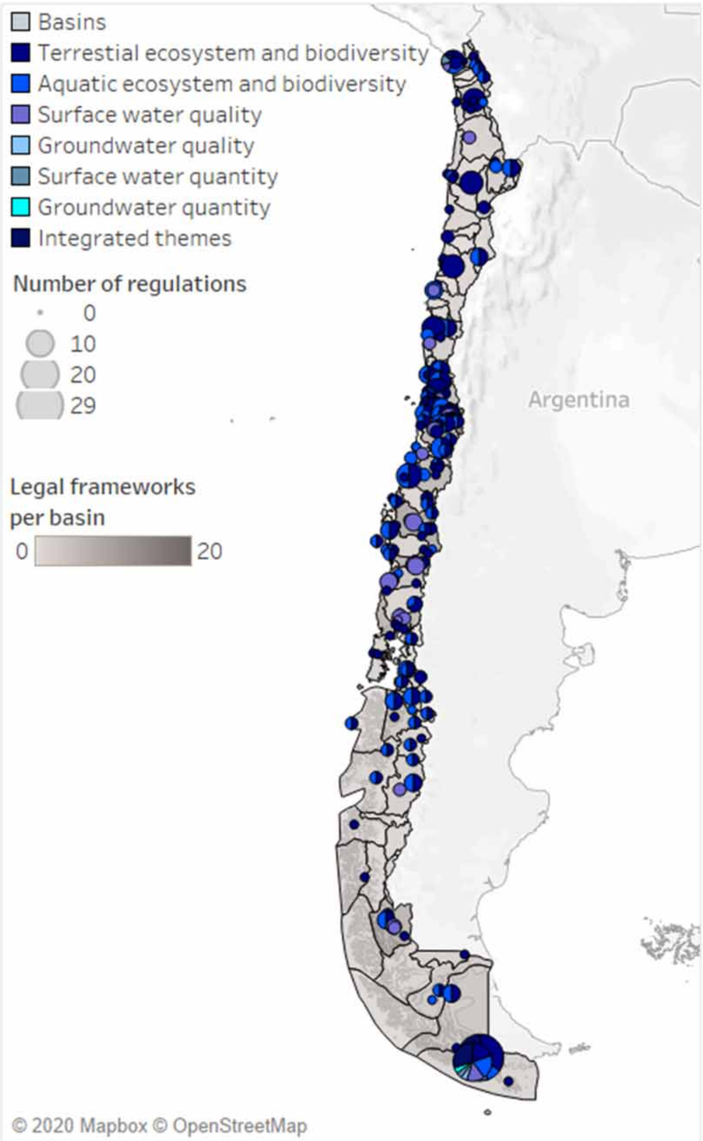


Fig. 2 | Spatial distribution of water environmental regulations in Chile (*note*: this map includes only those regulations that are applied to the regional or local scale).

Chile presented the highest number of regulations, where the major focus of the national population, economy and also environmental degradation took place (OCDE, 2016). Furthermore, the Maipo River Basin, which is in the central region, was the river basin with the biggest number of legal frameworks applied. About 80% of legal frameworks applied in the different regions covered the topics associated with terrestrial ecosystem (123) and aquatic ecosystem (73) through protected areas. Surface water quality regulations were mostly covered in the central and south region of Chile, in big rivers and lakes (the Maipo River, Biobio River, Villarrica Lake, Valdivia River, Llanquihue Lake, and Serrano River). The policy instruments applied to these water quality regulations corresponded to inspections, PRO, and information.

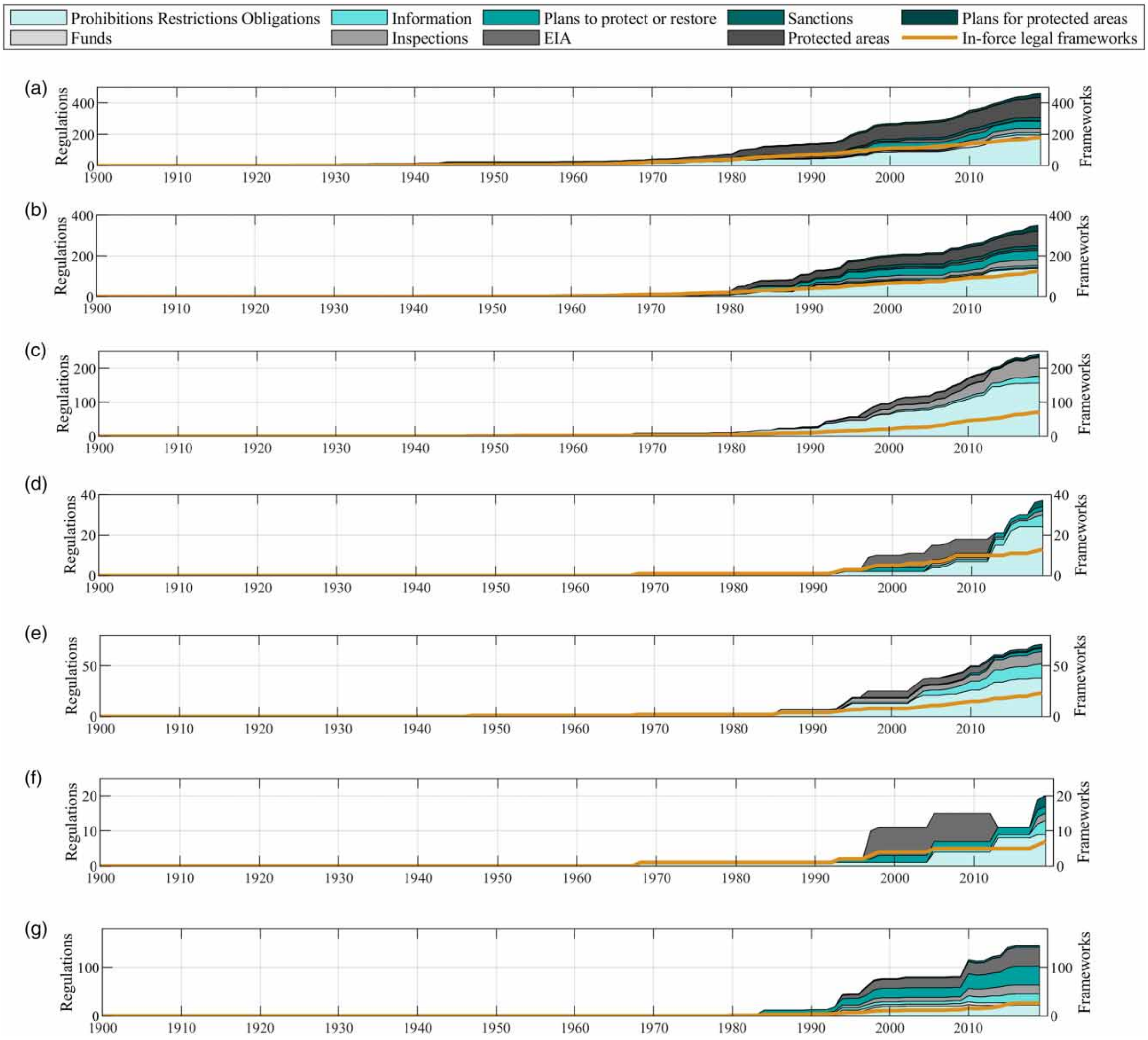
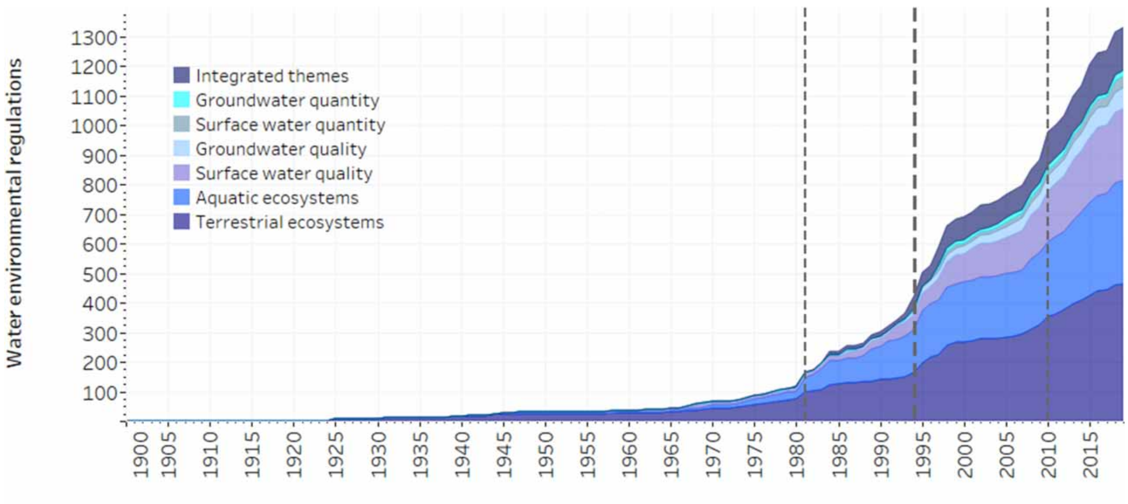


Fig. 3 | Evolution of in-force Laws, DL, DFL, Decrees, and Resolutions (legal frameworks) and regulations on each environmental theme. (a) Terrestrial ecosystem and biodiversity; (b) aquatic ecosystem and biodiversity; (c) surface water quality; (d) surface water quantity; (e) groundwater quality; (f) groundwater quantity; and (g) integrated themes.

The development stages of water environmental regulations

The evolution of water environmental regulations has been a slow process. Figure 3 shows the evolution in the number of in-force legal frameworks (Laws, DL, DFL, Decrees, and Resolutions) and regulations covering each environmental theme. Only after the mid-1990s were significant changes observed on all environmental themes. More specifically, terrestrial ecosystem regulations have been increasing since the 1970s or so and aquatic ecosystem since the 1980s or so. Water quality regulations were also highly covered after the 1990s. A small number of regulations covered groundwater quality, and surface and groundwater quantity, with more attention during the last two decades. Integrated themes appeared after the mid-1990s, which included those regulations covering all environmental themes. Additionally, it was observed that protected areas have been a recurrent policy instrument to protect aquatic and terrestrial ecosystems since the 1980s, and gradually increasing over time; PRO has also been highly used since 1980, being the dominant instrument in almost all environmental topics. EIA, inspections and plans to protect or restore the environment emerged only after the mid-1990s, and information after 2000 (Figure 3).

The stage division of total environmental regulations is presented in Figure 4. The total regulations per year was best adjusted to a logistic curve (or S-shape curve) $f(t) = 1819 \times (1/(1 + exp^{7+0.08\cdot(X-1925)}))$, with an R^2 of 0.9. This agrees with Rotmans *et al.* (2001), Rotmans (2005) and Tàbara & Ilhan (2008) who claim that S-shape curves are good representations of social systems. Based on the identification of transitional stages, environmental regulation evolution was divided into four stages (Figure 4). These stages were named considering the growth rate of environmental regulations. The pre-development stage (1900–1980) exhibited very few changes (growth rate of 1.5 regulations per year). The slow development stage (1981–1993) represented a transition from pre-



Development stages of water environmental regulations

1900-1980	1981-1993	1994-2009	2010-2019
Pre-development	Slow development	Development	Fast development

Fig. 4 | Evolution of water environmental regulations and their development stages.

development to a period of change, where some changes were observed (16.6 regulations per year). The development stage (1994–2009) corresponded to a period where the speed of change increases (30.6 regulations per year). And in the fast development stage (2010–2019), changes increased even faster (39 regulations per year).

Co-evolution of water environmental regulations with water resources management, socio-economic, climatic, and environmental conditions in different development stages

The co-evolutionary process of water environmental regulations with the major water resources policies/reforms in Chile, economic growth, population growth, climate change indicators, major drought events in Central Chile, depleted rivers, and instream flow on the Maipo River for the period 1900–2019 was depicted in Figure 5.

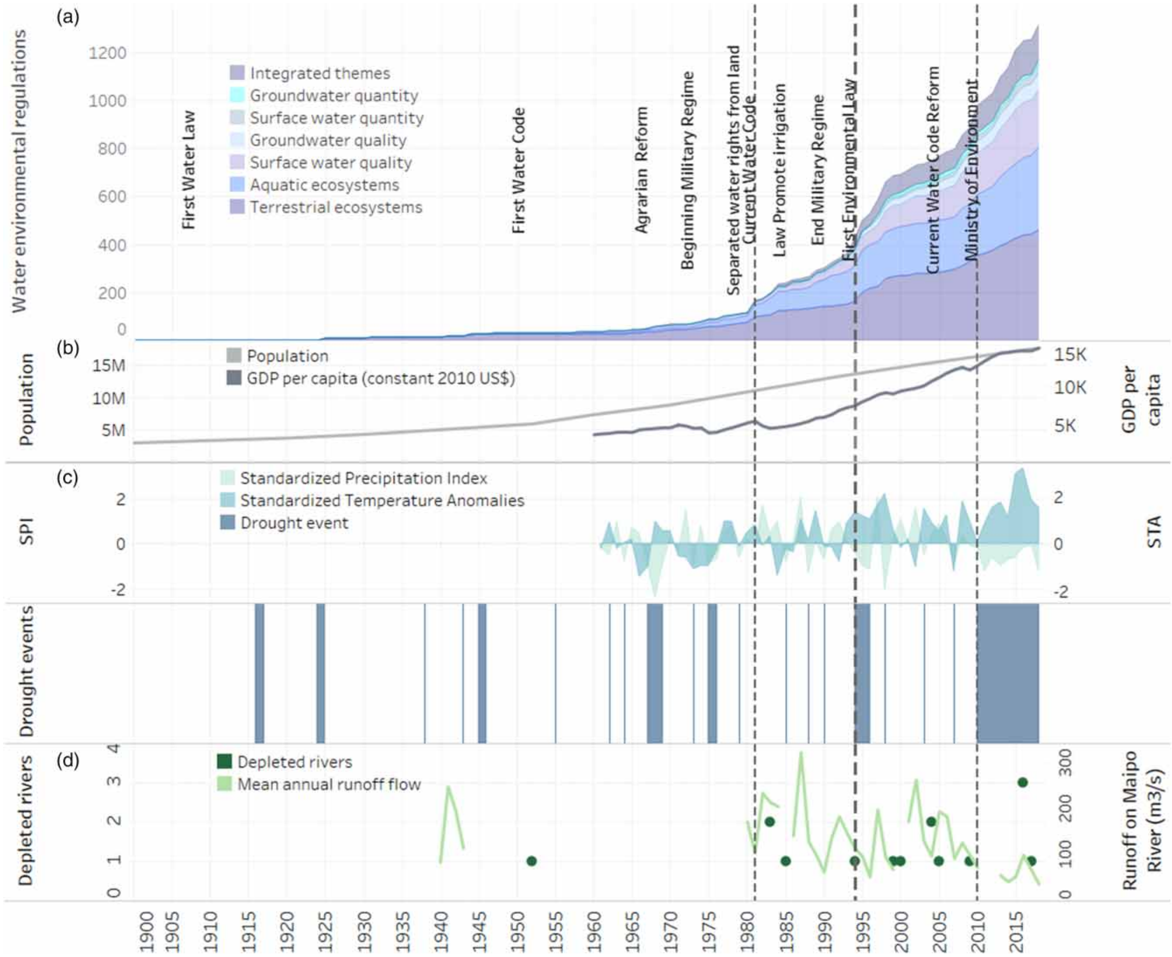


Fig. 5 | Co-evolution of water environmental regulations and water resources management, socio-economic, climatic, and environmental conditions (*note*: SPI goes from −2 to 2, which represents extreme dry and extreme rainy years, respectively, and zero represents a normal year. STA: positive values present a higher temperature and negative values a lower temperature than average, zero represents average).

The pre-development stage (1900–1980)

The pre-development stage was characterized by very few environmental regulations (Figure 5(a)), most of which were associated with protected areas. Some important regulations during this period included forest regulations (Decree No. 4363, DL No. 701 and subsequent modifications); the Sanitary Code (DFL No. 725) established in 1968; and regulations to protect flora and fauna at risk (Decree No. 141). Then, the protection of terrestrial ecosystems was by far the most covered theme during this period.

During this stage, essential water reforms oriented to water resource administration took place (Figure 5(a)). The first Water Law (Law No. 2139) and Water Code (Law No. 9909) were established in 1908 and 1951, respectively, and linked water rights to land ownership. Later in 1967, the second Water Law and Agrarian Reform (Law No. 16640) was passed, which strengthened the State responsibilities on water resource administration, as well as expropriation and land redistribution (Bauer, 2015). At the end of this period, in 1979, the DL No. 2603 separated water rights from land ownership for the first time, and the transition to a decentralized water system started when water resources management shifted from the State to the private users, making possible water rights markets and other kind of transactions. The economy of Chile did not present significant advances during this period, and population started to increase only after the 1950s (Figure 5(b)). Almost four thousand million cubic meters of water storage capacity were constructed during the 1950s and 1960s (MOP, 2010; OCDE, 2016). Most of these reservoirs were developed for irrigation purposes. Consequently, irrigation areas showed a substantial increase, from 500,000 ha at the beginning of the 1900s to more than 1 million hectares near to the 1970s (OCDE, 2016). However, few regulations (especially on water quality and quantity) for preventing potential consequences of these developments were issued during this period (Figure 5(a)).

The slow development stage (1981–1993)

The slow development witnessed an increase of water environmental regulations, from 116 to 364 by the end of 1993 (Figure 5(a)), corresponding to 52 legal frameworks. Most of these regulations focused on aquatic and terrestrial ecosystem protection, particularly by the creation of protected areas. Other regulations included the agreement of species conservation (Decree No. 868); fishing and aquiculture Laws (DFL No. 5, Law No. 18892 and subsequent modifications); creation of CONAF (National Forest Corporation) to protect forests and natural resources (Law No. 18348); creation of a national system to protect wild areas (Law No. 18362); creation of National Ecology Commission (Decree No. 680); and the regulation for aquatic pollution control (Decree No. 1).

This stage also had the creation of the current Water Code in 1981. This code was characterized by water rights granted permanently and treated as commodities, freely transferable for efficient water allocation after initial allocation by the State. Consequently, since 1981 the State has reduced its intervention on water resources management to a minimum (Hearne & Donoso, 2014). This Water Code also stimulated private investment and paid very little attention to environmental protection (Peña, 2018). In 1985, Law No. 18450 was passed (Figure 5(a)), which aimed to promote investment in irrigation, resulting in a significant improvement of technologies to enhance irrigation efficiency (Anríquez & Melo, 2018). This period was characterized by a significant increase in water demand for economic activities, without a relevant increase in water storage (MOP, 2010; OCDE, 2016). It should be noted that during this period, Chile was under a military regime (between 1973 and 1990), and environmental protection was not a priority (Hearne & Donoso, 2005). Natural environmental degradation during this period was reflected in a significant loss of natural forest areas. Between 1970 and 1990, Chile presented its highest rate of deforestation (Miranda *et al.*, 2017). By the end of this period, significant accumulated environmental issues arose, including water pollution in North and Central Chile (Camus & Hajek, 1998; Tecklin *et al*., 2011). The Chilean society and media started to show more concern about these issues (Camus & Hajek, 1998).

The development stage (1994–2009)

During this development stage regulations increased from 364 to 882 by the end of 2009, corresponding to 90 legal frameworks with all environmental themes getting more attention (Figure 5(a)). This period started with the creation of the National Environmental Framework Law (Law No. 19300) in 1994, being the core of environmental-oriented reforms up to the present, targeting all environmental topics. Other important regulations were the agreement of biologic diversity (Decree No. 1963); the environmental quality and emission norms (Decree No. 93); emission standards for pollutants discharging on surface water (Decree No. 609 and Decree No. 90) and on groundwater (Decree No. 46); regulations of the EIA (Decree No. 30 and modifications); the Water Code Reform (Law No. 20017) issued in 2005, which established for the first time the minimum ecological flows (MEFs); fishing norms (Law No. 20256); and the conservation and restoration of native forest Law (Law No. 20283). Consequently, during this period, more attention was given to all environmental issues, especially to the protection of water quality, including surface water and groundwater (Figure 5(a)).

The GDP of the country has increased very fast since the 1990s (Figure 5(b)), presenting a clear correlation with water consumption (Donoso, 2018b). In the 1990s, after Chile recovered democracy, the export-based model was reinforced, resulting in a significant economic growth that depended in part on water use. The agricultural sector, with the highest water consumption, presented a transition from producing import-competing crops (mostly cereals) to higher-value crops (fruits, wine, and nuts), allowing an increase in agriculture economic outcomes without significant expansion of irrigation lands (Anríquez & Melo, 2018; Donoso, 2018b). Also, irrigation efficiency raised from 48.6% in 1997 to 56.9% by 2007 (Martin & Saavedra, 2018). However, this economic growth resulted in an aggressive impact on the natural environment (Donoso, 2018b; Peña, 2018). Seven river basins were depleted (i.e. when natural sources of water do not have enough water to grant new water rights) (Figure 5(d)). Additionally, a significant number of hydraulic works were constructed during this period, including 447 million cubic meters of water storage (MOP, 2010). Also, hydropower production increased sharply with newly granted water rights (World Bank, 2011; Donoso, 2018b; DGA, 2019). Despite a non-consumptive water use, several environmental issues arose from hydropower generation (World Bank, 2011). In addition, the mining industry in the north region of Chile grew rapidly, which made negative impacts on wetlands and riparian areas and also surface water and groundwater availability (Acosta, 2018).

The fast development stage (2010–2019)

The fast development stage was characterized by a faster increase in water environmental regulations (Figure 5(a)). This stage started with the creation of the Ministry of the Environment (Law No. 20417). Many other critical regulations were issued: the regulation of soil, water, and wetland (Decree No. 82); treatment of industrial effluents (Decree No. 3); environmental quality and emission norms (Decree No. 38); regulations of the EIA (Decree No. 40); modification to the fishing and aquaculture law (Law No. 20657); new organic regulations of the Environmental Ministry (Decree No. 62); first programs of environmental regulations (Resolution No. 177); a new approach to determine MEFs (Decree No. 14, Decree No. 71); the right of environmental conservation Law (Law No. 20930); and a regulatory framework governing water regarding inspections and sanctions (Law No. 21064). During this period, all environmental topics were highly covered compared with prior periods, and especially more attention was paid to water quantity (near 50% of total surface water quantity regulations were issued during this period) (Figure 5(a)).

Significant development of hydraulic works continued during this stage, mostly for hydropower generation, mining, and irrigation (DGA, 2018b). The GDP of the country continued growing fast. Notably, this period was mainly marked by the most prolonged drought in Central Chile (Figure 5(c)), which exacerbated environmental issues, presenting the most extended number of consecutive years with water deficit (ODEPA, 2016). Moreover, four additional natural water sources located in Northern and Central Chile were declared depleted (Figure 5(d)). Also, the Maipo River basin presented severe issues during this period, and a drastic decrease in instream flow was observed (Figure 5(d)). It is recognized that until the present, aquatic deterioration was not yet reverted. Almost 50% of freshwater fishes species were at risk of extinction, and 90% in the category of conservation danger (Riestra, 2018).

The correlation analysis between environmental regulations, GDP per capita, population, SPI and STA shows that environmental regulations had a strong positive correlation with GDP and Population, where GDP presented the highest correlation coefficient (0.99), a medium positive correlation with the temperature anomalies (0.6) and no significant correlation with precipitation anomalies (−0.14) (Table 3). It is further verified from the two-way ANOVA that GDP and population had a statistically significant effect on the environmental regulations (p-value of 2×10^{-16} and 3.35×10^{-7}, respectively), and a significant interaction between the effects of GDP and population (p-value of 6.28×10^{-6}), that is, the effects of GDP on the environmental regulations is influenced by population and vice versa. Moreover, it is observed that GDP presented the highest effect on the environmental regulations (F-value considerably higher) (Table 4). No statistically significant effect of climatic

Table 3 | Results of Pearson correlation analysis.

	Regulations	GDP	Population	SPI	STA
Regulations	1				
GDP	0.99***	1			
Population	0.95***	0.93***	1		
SPI	−0.14	−0.16	−0.06	1	
STA	0.6***	0.59***	0.55***	−0.19	1

Statistical significance level: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'.

Table 4 | Results of two-way ANOVA.

Factors:	*df*	Sum square	Mean square	*F*-value	Pr(>*F*)
GDP	1	8,791,551	8,791,551	5,212.448	$< 2 \times 10^{-16}$ ***
Population	1	57,668	57,668	34.191	3.35×10^{-7} ***
SPI	1	71	71	0.042	0.839
STA	1	2,642	2,642	1.567	0.216
GDP: Population	1	42,613	42,613	25.265	6.28×10^{-6} ***
Residuals	52	87,706	1,687		

df, degrees of freedom.
Statistical significance level: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'.

indicators such as precipitation and temperature anomalies on the environmental regulations was found (*p*-value of 0.84 and 0.22, respectively).

DISCUSSION AND CONCLUSIONS

This paper aimed to unfold the evolution of water environmental regulations in Chile and its response to change in water resources management and changing socio-economic, climate, and environmental conditions. The water environmental regulations promulgated since early 1900 in the whole country were examined using a content analysis approach. The development stages of these environmental regulations were identified and the responses of water environmental regulations to change in water resources management, climatic change, socio-economic development and environmental degradation were analyzed in both qualitative and quantitative ways. The findings from this study and their implications on improving water environmental regulations in future are summarized as follows:

Unsurprisingly the number of in-force water environmental regulations increased over time. The regulations on quality and quantity of both surface water and groundwater only appeared in recent decades. The water environmental regulations in Chile experienced four development stages: the pre-development (1900–1980), slow development (1981–1993), development (1994–2009), and fast development (2010–2019). Similar trends have been observed in Australia and China (Zhang & Wen, 2008; Kandasamy *et al*., 2014; Wei *et al*., 2017). According to the transition theory, the stabilization stage has not been reached yet. This implies the development of water environmental regulations may stabilize, backlash, or lead to system breakdown (Wei *et al*., 2017). Therefore, maintaining and strengthening water environmental regulations is still a critical mission in Chile if the country moves towards sustainability.

The development of water environmental regulations in Chile seriously lagged water resources management. The National Environmental Framework Law, the core of Chile environmental policy reforms, which was promulgated more than a decade after the current Water Code in which water rights were treated as commodities to promote water use efficiency for economic development and several decades after a significant increase in agriculture development. Water environmental regulations were issued after water crisis (river depletion, water pollution, and natural vegetation degradation) emerged. This finding implies that water environmental regulations only made response to the evidence of environmental degradation arising from water resources management. Moreover, it is recognized that the failure of governance institutions to cope with the accelerating rate of change in other social and biophysical systems can be for several reasons, such as the non-recognition of environmental degradation until it is evidently severe or formally documented, and the non-perceived slow ecological degradation, which limits and delays the institutional willingness to respond to this (Kollmuss & Agyeman, 2002). Therefore, the development of water environment regulations is required to integrate and synchronize with water resources management.

Water environmental regulations showed a very strong relationship with the socio-economic conditions of the country. In other words, the development of water environmental regulations closely followed the pace of economic development and population growth, indicating a responsive behavior. These results are consistent with Donoso (2018b), which based on a comprehensive assessment of water policies in Chile concluded that economic development of the country has led Chilean society to be more concerned about the environment. A special effort on environmental regulations should be put into mitigating and adapting to the adverse effects of climate change as Chile is considered a country vulnerable to climate change (Universidad de Chile, 2019). The effects of environmental regulations against environmental degradation were limited. Despite the fact that the environmental regulations have notably increased, environmental conditions in Chile are still in deterioration (water pollution, river depletion, terrestrial ecosystem degradation and aquatic biodiversity loss) (Riestra, 2018; Universidad de Chile, 2019). Therefore, more effective environmental regulations are required.

Despite its contributions, several limitations of this study should be noted: (1) for the purpose of this study, we considered only the formal governance; informal institutions were not included. (2) Insufficient data on environmental conditions in Chile throughout the whole study period limited our analysis. To develop the process-based inter-disciplinary modeling to reveal the mechanistic relationships between environmental regulations and its response to changing socio-economic, climate, and ecological conditions is a future direction.

In conclusion, this study unfolded the evolution of water environmental regulations in Chile and its response to changing water resources management, socio-economic, climate, and environmental conditions since 1900. It can assist environmental policymakers in identifying regulations incapacity in environmental themes and policy instruments for future improvement. Chile is currently drafting a new Constitutional Reform. The proposed new articles related to water and environment, including the creation of the National Water Agency (an autonomous and decentralized body), may have relevant implications for the water and environmental regulations and governance system. The findings from this study may offer valuable learning from the past for formulating and improving water environmental regulations in future.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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