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Exploring the social metabolism of urban wastewater reuse: analysis framework and a case study in South-Central Chile

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Abstract: Although wastewater reuse is a vital strategy for mitigating water scarcity, its implementation is complex and faces several challenges. To effectively inform decision-makers, comprehensive evaluations are essential, considering the strategy's benefits and socio-ecological constraints in a case-specific manner. This study employs the social metabolism concept to assess the sustainability of wastewater reuse, through the joint application of the Material Flow Analysis (MFA) and Multiscale Integrated Assessment of Societal and Ecological Metabolism (MuSIASEM) tools. We analyze key aspects of wastewater reuse, including its potential as a water source, its technical challenges, and main social constraints.

The results of our analysis highlight the potential of wastewater reuse to improve urban self-sufficiency, replace water in relevant economic activities at the regional level, and avoid the environmental impacts of wastewater discharge. Nevertheless, the viability of wastewater reuse is constrained by variations in wastewater flow and effluent quality. This limitation is further compounded by social barriers, which become more pronounced with increased contact with reclaimed water. Overall, the proposed framework serves as a valuable tool for evaluating wastewater reuse alternatives. It can be enriched by in-depth assessments of critical problems, providing a comprehensive approach to address the multifaceted aspects of sustainable wastewater reuse.

Keywords: water metabolism, wastewater reuse, MuSIASEM, material flow analysis.

1. Introduction.

1.1 Challenges of water management and the role of wastewater reuse.

Achieving a sustainable and equitable management of water resources is one of the most relevant issues currently faced by society. Factors such as the increase in water consumption due to population and economic growth (Boretti & Rosa, 2019; Okello et al., 2015), the modifications in the hydrological cycle caused by agriculture, forestry and other human activities (Abbott et al., 2019), and the observed and projected effects of climate change over the water cycle (Douville et al., 2021), characterize a highly uncertain scenario for water availability in the future, one that pushes for a significant change in water management towards a more holistic and comprehensive paradigm.

In Chile, water management is constrained by the spatial and temporal variability of water resources. At a national level, the country shows a high variability in climate and water resources distribution. According to the National Water Directorate (Dirección General de Aguas; DGA), the average precipitation in Chile is 1,525 mm/year, with a total runoff of 29,245 m^3/s (DGA, 2016). However, there is a high variability between the arid northern region and the sub-Antarctic conditions of the southern regions: the average runoff in the northernmost region of Arica y Parinacota averages 5.5 m^3/s, compared with 10,134 m^3/s in the southern region of Aysén. Long-term temporal variations associated with climatological phenomena (such as the El Niño-Southern Oscillation (ENSO)) also conditions the availability of water resources, and phenomena such as the Pacific *warm blobs* and anthropogenic climate change can significantly disrupt normal climate patterns and lead to phenomena such as heatwaves and droughts (Amaya et al., 2020; Garreaud et al., 2021). The severity and longevity of the phenomenon has led to its denomination as a "megadrought" by scientists and policymakers, resulting in a generalized concern for water resources (Fuentealba et al., 2021). Consequently, several guidelines and strategic roadmaps have been developed by private and public organizations to help confront this issue (e.g., EH2030, 2019; MOP, 2012).

One of the most discussed strategies to confront water scarcity is the implementation of *new water supplies* (NWS). NWS include technology-related sources such as desalinated water (Darre & Toor, 2018), harvested rainwater (Pala et al., 2020), water transferred from other basins (Rollason et al., 2022), or reclaimed wastewater (Angelakis & Snyder, 2015). The reuse of wastewater presents several advantages over the other alternatives, such as its potential viability in zones that are distant from the sea (Crutchik & Campos, 2021), its relatively

lower energy cost compared to water desalination (Tow et al., 2021), the potential for nutrients recovery through fertigation (Mainardis et al., 2022), and the potentially low investment necessary for retrofitting the existing wastewater infrastructure (Mavhungu et al., 2020). Consequently, several full-scale applications of wastewater reclamation are currently in operation for different uses (such as crop and green space irrigation, industrial reuse, and direct or indirect potable reuse), including the Goreangab Reclamation Plant in Namibia, the NEWater project in Singapore, the Rouse Hill Water Resource Recovery Facility in Australia, and the Dan Region Wastewater Treatment Plant in Israel (Brenner et al., 2000; du Pisani, 2006; Radcliffe & Page, 2020).

The situation of water reuse is highly variable across the world. On one hand, countries like Spain started their first wastewater reuse projects in the 1970s, and others like Israel have reached wastewater reuse rates of up to 80% (Jodar-Abellan et al., 2019; Kesari et al., 2021). On the other hand, Chile is only recently starting to implement this strategy in pilot projects, even though the country presents one of the highest sewage treatment coverages in Latin America (up to 100% in urban areas) (SISS, 2022; Villamar et al., 2018).

Despite its advantages, wastewater reuse it is not free from challenges that complicate its widespread implementation. These include social, technical, economic, and environmental issues, such as the social acceptance of reuse; the costs and environmental impacts of water treatment, conveyance and distribution; the potential abandonment of infrastructure when climatic conditions change; and the potential pollution of water and food caused by non-regulated pollutants and antibiotic-resistance organisms (Guo et al., 2014; Holloway et al., 2016; Leiva et al., 2021; Radcliffe, 2015; Smith et al., 2018). Therefore, holistic and case-specific assessments of water reuse are necessary in order to provide a wide perspective on the potential benefits and issues related to its implementation. As can be observed in studies published in this and other journals, the social metabolism concept has been widely employed to evaluate the material functioning of urban systems and its environmental and social implications (e.g., González-García et al., 2021; Kissinger & Stossel, 2021). Furthermore, several studies recognize the relevance of social metabolism for developing urban sustainability policies (Dijst et al., 2018; Elliot et al., 2020; Ulgiati & Zucaro, 2019). In this study, we propose that this concept could form the basis for analyzing the various questions arising from the implementation of wastewater reuse strategies.

1.2 Wastewater reuse from a social metabolism perspective.

Borrowing Wassenaar's (2015) definition of social metabolism as the *phenomena of human-mediated matter change for sustaining the functioning of society,* we define the use of reclaimed wastewater as a modification of the metabolic pattern of water inside society. In doing so, wastewater reuse has the potential of decreasing the need of surface and ground water extraction, increasing the compatibility of societal water needs with the environmental contains associated with water scarcity. An approach to water management based on social metabolism provides an explicit link between water users, economic activities, and ecosystems; it serves for the representation of water use across different spatial and functional dimensions; and it has the potential to integrate water use with other relevant aspects of sustainability assessment, such as energy or food (Taghdisian et al., 2022).

Two methodologies have been most widely used to analyze and quantify social metabolism: Material Flow Analysis (MFA) and Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Gerber & Scheidel, 2018). MFA provides detailed accounting and analysis of specific goods and substances at different levels (city, industry, region, etc.), allowing the calculation of efficiency/performance indicators and the identification of missing flows (Brunner & Rechberger, 2017). MFA and its principles are useful to assess current and proposed water management practices in cities (Farooqui et al., 2016), including the implementation of wastewater reuse strategies (Hong & Park, 2023; Jeong & Park, 2020). It also represents one of the main approaches that has been used for the construction of urban water metabolism models (Nezami et al., 2022).

MuSIASEM is an analytical framework that brings a hierarchic conceptualization to the analysis of the metabolism of socio-ecological systems (Giampietro & Mayumi, 2000). One of its main strengths is the capacity to integrate different analytical scales, and to relate societal functions to its material and energy requirements. Since Madrid et al. (2013) and Madrid-López & Giampietro (2015) laid down the conceptual and methodological basis for the analysis of water through the lenses of MuSIASEM, this framework has not been used to assess wastewater reuse issues.

In this work, we analyze the potential of wastewater reuse from a social metabolism perspective that joints the MFA and MuSIASEM methodologies. The contribution of our paper to the field of study is twofold. First, it provides a practical integration of different water metabolism tools and perspectives, in order to leverage their main strengths and to generate an overarching assessment of water reuse through a case study. Secondly, it integrates specific issues related to wastewater reuse in the framework of metabolism studies, such as

wastewater quality and quantity, and potential barriers to its implementation due to social acceptance. To do so, we adapt the idea of the *feasibility, viability* and *desirability* analysis described by Giampietro et al. (2014) to the specific issues of wastewater reuse, focusing on the potential environmental benefits of wastewater reuse (feasibility), the characteristics of wastewater and its potential for reuse in the current conditions (viability), and the social acceptance of reuse for different applications (desirability).

2. Methodology.

To meet our objective, we use MFA to generate a diagnosis of water flows at the city and sub-city level, identifying missing flows and quantifying relevant indicators of performance. We then use the MuSIASEM tool to systematize relevant water data across multiple levels of analysis, and to relate the urban water reuse strategies with the broader water basin context. Through the application of this tool, an explicit link between the main level of analysis (cities) with the overall context of the water basin and region is obtained, which is important giving that wastewater reuse can be focused on different applications and users (agriculture, industry, etc.) that are outside the spatial limits of cities. Finally, we approach the feasibility, viability and desirability concepts used in the MuSIASEM literature from a perspective that is specific to the issues of wastewater reuse. This allows us to include technical and social aspects that are normally outside of the scope of most socio-metabolic studies. Fig. 1 shows the overall conceptual framework used in the study.

Fig. 1

2.1. Area of study: Ñuble region

Ñuble is an historical and administrative region in south-central Chile. With an area of 13,179 km^2, it is the smallest and most rural region in the country (30.6% of the population lives in rural areas). Most of the population is concentrated in the capital city of Chillán, which represents about 45% of the total population of the region. The most important economic activity of the region is agriculture, with a limited industrial development. Forestry is also relevant, with a total of 277,590 hectares destined to this activity, and the presence of one of the biggest pulp mills in the country. Just like the rest of the country, the Ñuble region is characterized by almost 100% coverage of sanitation services in urban areas, including provision of drinking water, sewage, and wastewater treatment services (SISS, 2022). Additionally, the quality of both surface and groundwater sources for drinking water reflects good water quality, complying with most international guidelines (Barriga et al., 2022). However, the situation significantly diverges in rural areas, where currently over 20,000 people

rely on water supply via tanker trucks, as well as deep deficiencies in terms of sewage infrastructure and wastewater treatment.

Hydrologically, the Itata basin is the main watershed of the region, with a total area of 11,294 km^2. The average annual precipitation in normal years accounts to 1,200 mm in the coastal zone and 2,000 to 2,500 mm in the Andes Mountain range, with a Mediterranean climate with warm summers according to the Köppen-Geiger climate classification (Csb; Sarricolea et al., 2017). Precipitations are concentrated in the winter months, with around 65 – 70% of the annual precipitation occurring between May and August, and only 5 – 6% in the warm period between December and February (Acuña et al., 2015). In 2020 the precipitation deficit was around 34%, and in 2019 several rivers and water reservoirs of the Itata basin showed historically low average flows and levels (Dirección Meteorológica de Chile, 2020). Facing the drought and the projected hydrological threats has become one of the main challenges for the region, more so considering the serious deficiencies in infrastructure and access to water observed in rural areas. Fig. 2 shows the area of study, including the most important sub-basins and the location of the studied urban centers. We included the following cities in the MFA assessment: Bulnes, Chillán, Coihueco, Quirihue, and San Carlos. The land cover classification of the 5 cities is shown in the Supplementary Material accompanying this paper (SM1).

Fig. 2

2.2. Calculation of urban water flows.

A water analysis based on the principles of Material Flow Analysis (MFA) was performed in 5 of the main urban centers of the Ñuble region. We integrated *natural* and *anthropic* flows in the same conceptual framework, as proposed in the urban water model of Renouf et al. (2017). A detailed description of the steps and data sources used for the construction of the models is presented in the Supplementary Material (SM2).

Based on the results, several indicators were quantified for the 5 cities under study. These include indicators of urban hydrological performance, water consumption, water use intensity, and the potential self-sufficiency of cities.

Hydrological performance indicators are defined as the ratio between the natural flows estimated in the urbanized state and the same flows in a referential state without urbanization (Renouf et al., 2018), as shown in Equation 1.

$$HP_{E,R,I} = \frac{UF_{E,R,I}}{RNF_{E,R.I}} \qquad \text{Equation 1}$$

Where HP represents the Hydrological Performance for Evapotranspiration (E), Runoff (R), or Infiltration (I); UF are the Urban water Flows for Evapotranspiration (E), Runoff (R), or Infiltration (I) (in mm), and RNF are the Reference Natural Flows for Evapotranspiration (E), Runoff (R), or Infiltration (I) (in mm).

Two indicators of water consumption were calculated: total water consumption per capita (L/inhab-day), and domestic water consumption per capita (L/inhab-day). An indicator of water use intensity was also calculated, defined as the ratio between the total water consumption of the city and its surface area (m^3/m^2-year) (Ghosh et al., 2019).

Finally, the potential self-sufficiency of the studied cities was estimated, defined as the ratio between the potentially usable internal water flows of the city and water consumption (Fragkou et al., 2015). Potential self-sufficiency was estimated for runoff and wastewater, as shown in Equation 2.

$$PSS_{R,w} = \frac{UF_{R,W}}{TWC} \qquad \text{Equation 2}$$

Where PSS represents the Potential Self-Sufficiency of the city based on the Runoff (R) or Wastewater (W) flow; UF are the Urban water Flows for Runoff (R) or Wastewater (W) (in m^3/year), and TWC represents the Total Water Consumption inside the city (in m^3/year).

2.2 Regional water metabolism analysis.

In MuSIASEM, wastewater reuse is a means of decreasing the *external* requirements of water by means of closing the *internal* flows of water, resulting in a reduced dependency from ecosystems. Under this view, reuse represents a modification of the *metabolic pattern* of water use, as the water demands for the maintenance and reproduction of the structural elements of society can be supplied in a new, cascading configuration that links different users inside society. The Water Metabolic Rate (WMR) (Equation 3) was calculated to understand water use dynamics at the basin level.

$$WMR_i \left({}^{m^3}/_{hours} \right) = \frac{WU_i(m^3)}{HA_i(hours)} \qquad \text{Equation 3}$$

Where WMR_i represents the water metabolic rate of households or economic sector i, WU_i represents the water use of sector i (or consumption in households), and HA_i represents the hours of human activity allocated to economic sector (paid work) or to household activities in the given basin. Details about the data used for the calculation of the WMR can be found in the Supplementary Material (SM3).

2.3 Analysis of techno-economic and ecological constrains.

As previously mentioned, a successful implementation of wastewater reuse is complex due to the interaction of technical, environmental, and social constrains. In this work, we loosely adapt the feasibility, viability and desirability framework proposed by Giampietro et al. (2014) to analyze constrains of socio-metabolic patterns, in order to study some of the most important issues of wastewater reuse.

In terms of **feasibility,** or the compatibility of the proposed scenarios with the local environmental conditions and boundaries, we focus on the potential avoidance of nutrient pollution in the receiving waters that can be achieved due to water reuse. To assess the **viability**, understood as the congruence of wastewater reuse alternatives with the requirements of water users, an analysis of wastewater characteristics and its compliance with international water reuse guidelines was performed. Details about the data used for this assessment can be consulted in the Supplementary Material (SM 4).

2.4 Analysis of social desirability.

The **desirability** or the level of social pressure resulting from the proposed scenarios, was assessed at the regional level in terms of the social acceptance of different wastewater reuse applications. To do so, a survey was developed, validated, and applied to the population of the region, and the acceptance declared by the respondents concerning 14 potential applications of reclaimed water is presented. This survey was part of a wider study whose main objective was to identify the main determinants of the acceptance of wastewater reuse in Chile, including exposure to water scarcity, perception of wastewater reuse risks, emotional responses, pro-environmental behavior, and other potential explaining factors. The survey was self-applied by respondents from an internet panel, which were probabilistically sampled by clusters according to region and city. The target population included adult men and women from all socioeconomic strata., and the total sample for the Ñuble region was 403 persons, representing an estimated 4.9% error with a 95% confidence level. Details about the questions presented to the respondents can be consulted in the Supplementary Material (SM 4).

3. Results and discussion.

3.1 Urban water balances and potential of municipal wastewater reuse.

Fig. 3 presents a visual representation of the water balance for the city of Chillán. Approximately 18.8 million cubic meters per year of water enter the city's system through precipitation. This inflow is approximately 1.6 and 5.1 times greater than the combined outflows from surface and subsurface water sources, which total 15.5 million cubic meters per year. Of this total, roughly 30.3% is lost in the distribution system, a volume

comparable to the average urban water distribution losses in Chile (33.2%) (SISS, 2022). The main users of water at the urban level are households, with 8.7 $10^6 m^3$/year. A combined 8.6 $10^6 m^3$/year of wastewater are generated from households, commercial, institutional, and industrial activities, but the estimated flow based on Wastewater Treatment Plant (WWTP) records shows a discharge of about 18.6 $10^6 m^3$/year. Although this important difference is most likely related to the intrusion of rainwater in the sewerage system, even assuming that 100% of runoff enters the sewerage system there is at least 3.1 $10^6 m^3$/year of unregistered discharges to the system, most likely associated with households, industries and other activities that extract water from unregistered wells and other sources, as has been reported in previous studies (Zúñiga et al., 2023).

Fig. 3

Table 1 shows the hydrological performance and water metabolism indicators of all the assessed cities. In terms of hydrological performance, the evapotranspiration and infiltration of most cities decreased compared to the pre-urbanized state, with reductions that ranged between 18 – 86% and 24 – 59%, respectively. Conversely, urbanization led to higher runoff in all case studies, with increases ranging between of 74 – 192%. These results are consistent with previous studies (Farooqui et al., 2016; Renouf et al., 2018), showing the significant influence that urbanization presents over the natural flows of water.

In relation to water consumption, total per capita use ranged between 135 – 171 L/inhab-day. A consumption of about 33 – 40 L/inhab-day is attributable to non-household activities (industries, institutions, and commerce), revealing the importance of these activities in urban water use. The observed per capita values are the in same range, but slightly lower, than the average values reported for Chile (172 L/inhab-day; SISS, 2018).

The average water use intensity per area was 0.25 – 0.35 m^3/m^2-year, with variations mainly associated with the population density of the different urban areas (15.1 – 388.9 inhab/km^2), similar to previous studies (Ghosh et al., 2019). In terms of the potential self-sufficiency, the results show that in most cities the total consumption of water could be theoretically supplied through rainwater harvesting or wastewater reuse (Table 1), similar to the results of Fragkou et al. (2015). Overall, the results highlight the relevance of wastewater reuse and rainwater harvesting as alternatives to decrease the dependence of water supply from sources outside the city limits.

Table 1

Table 2 shows the water demands per economic activity and sub-basin. Depending on the conditions of the sub-basin, reuse of wastewater can achieve significant reductions of water extraction for human activities. The estimated overall demand of blue water (water extracted from superficial and underground sources) in the Ñuble region is approximately 356 10^6m^3 per year, 7.5% of which could be satisfied if all the wastewater generated in the region is reused. Agriculture is by far the activity that requires the greatest volume of water per year (up to 87.5% of total requirements per sub-basin). According to data from SISS (2022), the annual generation of urban wastewater is estimated at 22.2 10^6m^3 in the Lower Ñuble basin, 0.6 10^6m^3 in the Higher Itata basin, 2.6 10^6m^3 in the Middle Itata basin, 0.8 10^6m^3 in the Lower Itata basin, and 0.7 10^6m^3 in the coastal basins, representing about 11%, 8%, 4%, 17%, and 77% of the corresponding sub-basin water demands for irrigation. Furthermore, reuse of municipal wastewater could fully meet the demand of the industrial sector in the Lower Ñuble basin, or the total water demand required by the service sector, grazing activities, or rural households in several basins (e.g., Lower Ñuble, Higher Itata, or Middle Itata). Reclaimed wastewater could also cover 29.9 – 100% of the urban household demand in the Lower Ñuble, Middle Itata, Lower Itata, and Higher Itata basin, highlighting the high potential of wastewater reuse. The study conducted by Villamar et al. (2018) has previously highlighted the potential of livestock and municipal wastewater reuse on a national scale. Nevertheless, they also identified that one of the primary challenges for reuse is the current quality of treated wastewater, which does not guarantee its safe use in applications such as food crop irrigation.

Table 2

3.2 Regional water metabolism and its relationship with urban areas.

Fig. 4 shows the regional water metabolism and its relationship with urban areas, taking as an example the city of Chillán and the Lower Ñuble basin. The water-cycle level includes the most relevant hydrological processes, determining the availability of water in aquatic ecosystems (lakes, rivers, subsurface reservoirs) that are in turn one of the main sources of water for human activities. It also determines the availability of water as soil moisture (green water), whose use represents the most important socially mediated water flow in the Lower Ñuble basin: a total of 1558.9 10^6m^3/year used in agricultural (~45%) and forestry (~55%) activities. In turn, the total appropriation of blue water in the watershed represents 227.9 10^6m^3/year, with the main users being agriculture (204.8 10^6m^3/year) and urban consumption (15.5 10^6m^3/year in Chillán). Industrial and rural users represent the remaining 4.9 10^6m^3/year and 2.7 10^6m^3/year of water demand, respectively.

Fig. 4

Cities interact with the water cycle through the direct capture of water from ecosystems, hydrological processes such as precipitation, runoff, and evapotranspiration, and the discharge of wastewater. Precipitation in Chillán is comparable in magnitude to water extracted from aquatic ecosystems, with approximately 34% of this flow being retained or infiltrated. The remaining portion exits the city limits either as runoff (37%) or water vapor (29%). These findings contrast with those of Hong & Park (2023), who calculated a greater significance of runoff flow (54% of precipitation) in the water balance of Paju city (Korea). This difference can be primarily attributed to the notable prevalence of unpaved surfaces and vegetation in our case study area (comprising 36% of the total urban area), a characteristic typical of smaller-sized cities. Wastewater discharge represents about 54% of the total input of water to the city, mainly coming from households, economic activities, and a significant contribution from urban runoff and unregistered discharges, estimated at 54% of the total wastewater flow. In the current scenario, wastewater is treated though a conventional activated sludge process and discharged to the Chillán River, without any recovery or reutilization. This situation is analogous to most cities in Chile, as even though the country presents one of the highest wastewater treatment coverages in Latin America (~99% compared to the 30 – 40% reported for Latin America (World Bank, 2020)), municipal wastewater reuse has not been widely implemented, with only a 5.8% of wastewater currently being reused, mainly in the most arid regions of the country (SISS, 2022).

Table 3 resumes the Water Metabolic Rates (WMR) results for the different economic activities at sub-basin level. Middle Itata was the basin with the highest overall WMR, with a value of 151.5 L per hour of human activity, while the Lower Itata and coastal basins reported values fourteen times lower. The results for the Middle Itata basin are highly influenced by its industrial sector, which includes some of the most important pulp mills facilities and agro-industrial processing plants of the region, leading to the highest industrial consumptive demand (about 30.7 $10^3 m^3$/year according to (DGA, 2017). In most basins, the highest WMR were those of the agricultural sector. The Lower Ñuble basin showed the highest agricultural WMR of 7,229.5 L/h, while the coastal basins registered values twenty times lower. This difference is associated with the significant agricultural activity in the Lower Ñuble region, which includes three of the most important agricultural communes of the region: San Carlos, Coihueco, and Chillán. Comparatively, the most important activities in the coastal basins are forestry, tourism, and fishing (Acuña et al., 2015). As expected, the WMR of households

showed the lowest values across all basins, even though the values are higher than previous studies (Rodríguez-Huerta et al., 2019; Taghdisian et al., 2022). The results for the household WMR ranged between 5.1 and 16.4 L/h, with the Higher Itata basin reaching the highest value. The service sector reached its maximum WMR of 27.7 L/h in the Lower Itata and Coastal basins, while the other basins registered rates 22.0 – 41.2% lower.

Table 3

Overall, the results of the WMR reflect the relative importance of the different activities in the assessed basins. Most of the agricultural and industrial activities are located in the central valley, while tourism and activities that do not demand the extraction of water are more predominant in the coastal and Andes regions. It is important to mention that the results are highly related to the significant differences observed in the distribution of population between the water basins, as can be observed in the Supplementary Material (SM3). The relative differences between the WMR of economic sectors reveal similar patterns of flow/fund ratios for water resources compared to previous studies (Rodríguez-Huerta et al., 2019), such as agricultural WMRs about two orders of magnitude higher than the service sector, and around two to ten times higher than the overall paid work sector.

3.3 Feasibility and potential nutrient recovery through wastewater reuse.

Besides the decreased pressure over water availability, one of the most important environmental benefits of wastewater reuse is the potential reduction on the discharge of pollutants to receiving aquatic bodies. This reduction in wastewater discharges is an important enabler of the *feasibility* (i.e., compatibility with environmental constrains) of wastewater reuse scenarios. Even though the environmental impacts associated with wastewater reuse are complex and merit more specific evaluations by means of Life Cycle Assessment (LCA) or other tools, focusing on the pollutant load in wastewater allows an analysis of the most fundamental material interaction between wastewater reuse and the state of water funds.

Fig. 5 shows the estimated phosphorous and nitrogen loads in the wastewater of all WWTP of the Ñuble region. From all basins, the Lower Ñuble was the one with the highest pollutant load in its effluent, with about 304.2 ton of nitrogen and 33.5 ton of phosphorous generated by year. As expected, the biggest contribution came from the most populated cities, as Chillán represented 91.7% of the N load and 85.7% of the P load, and San Carlos represented 6.2% of the N load and 9.7% of the P load. The Middle Itata basin presented the second highest pollutant load, reaching considerably lower values of about of 28.2 t N/year and 4.5 t P/year. Bulnes (42.6% of

N and 46.4% of P) and Quillón (32.6% of N and 16.1) were the cities with the highest contribution inside the basin.

Besides the expected relationship between city population and pollutant load, Fig. 5 also shows a direct relation between the nitrogen and phosphorous loads of the assessed WWTP, shown in logarithmic scale. As expected, water consumption, WMR, and pollutant load are all correlated to population. As the most consuming activities are also present in the basins with the highest wastewater generation and pollutant load, focusing reuse on the most populated areas could led to significant reductions in the environmental impacts of wastewater management in the region.

Fig. 5

3.4 Internal constrains and viability of wastewater reuse.

One of the most relevant constraints of wastewater reuse is related to the water quality standards necessary to guarantee the safe utilization of water by society. This represents an important limitation of the possible metabolic patterns of water utilization, and it is one of the main sources of social tension regarding its implementation (Smith et al., 2018). Furthermore, and even though reclaimed wastewater can be considered a stable supply of water compared with strategies such as rainwater harvest, there are temporal variations in wastewater flows that can affect its availability due to factors such as floating population or climatic variations. Table 4 shows the seasonal flow variations of wastewater in all the WWTP of the Ñuble region. Overall, average monthly flows during the period of December to May showed significant reductions compared with the average annual flows, with values up to 48% lower. This trend was observed for almost all WWTP, with the exceptions being observed mainly is small-scale treatment plants, and in areas where tourism is an important economic activity during the summer season. Comparatively, during the period of June to November, a significant increase was observed, with values up to 73% higher than the baseline flow. These results are consistent with the observed influence of rainwater over wastewater flow, as estimated based on the water balances. Flow variability could represent one of the main barriers to implement wastewater reuse in activities such as agriculture, as irrigation is mostly demanded in months in which the maximum flow reductions were observed. However, it is important to note that the most significant variations in flows were observed for the WWTP with lower average wastewater flows (Ninhue, El Carmen, Yungay), highlighting that this issue is more relevant for smaller cities ($\leq$1,500 m^3/day).

Table 4

Table 5 shows the overall classification of the effluent quality for reuse according to the categories stablished in international technical guidelines. The maximum observed values of parameters such as BOD_5 and TSS results in the classification of treated wastewater in categories with a limited range of applications. In fact, around 70.4% of the total wastewater flow in the region (consisting of the effluents of Chillán and Quirihue), were outside of the suggested category limits for reuse stablished in ISO 16,075, specifically due to the maximum observed values of BOD_5. One of the main limitations for the feasibility of wastewater reuse in the Ñuble region lies in the inconsistency of current WWTPs for generating a stable quality in their effluents, even if the average quality parameters are within the recommended limits. Moreover, it is important to note that this study only considered the parameters that are currently reported by the WWTP, with important quality parameters such as turbidity and conductivity not included in the assessment. In this scenario, the implementation of advanced and more reliable wastewater treatment methods is necessary to promote wastewater reuse in the region, a requirement that is exacerbated by other potential issues, such as the presence of emerging pollutants, pathogens, and antibiotic-resistant microorganisms in wastewater (Leiva et al., 2021; Riquelme et al., 2022).

Table 5

3.5 Social acceptance of wastewater reuse.

Fig. 6 shows the level of social acceptance of different wastewater reuse alternatives. Overall, the applications that showed levels of acceptance over 50% (including the responses *strongly agree* plus *agree*) were mainly those classified in low and medium contact. This includes strategies such as firefighting, toilet flushing, irrigation of crops for industrial use and animal feed, and cleaning of exterior surfaces. Exceptions of applications with higher level of contact than showed better acceptance include domestic laundry and cleaning of interior surfaces, with the later observed only for greywater reuse.

As can been seen in Figure 6, an inverse trend between acceptance and level of contact was observed both for domestic wastewater reuse and greywater reuse, which is in accordance with previous studies (Al-Khatib et al., 2022; Dolnicar et al., 2011). No major differences between the perception of domestic wastewater reuse and greywater reuse were observed, suggesting that the most relevant factor determining the social acceptance of reuse is the activity where water will be used, and not its origin. Considering that some of the most important

water consuming activities inside and outside cities involve either direct or indirect contact with water, the result of this assessment shows that social acceptance can be a limiting factor for leveraging the potential of wastewater reuse.

Indeed, only firefighting exhibited acceptance levels exceeding 80%. Considering these results, it is foreseeable that the reuse of wastewater in more essential water-consuming activities like laundry and toilet flushing (Zúñiga et al., 2023) or irrigation (DGA, 2017) could potentially lead to notable social tensions. Recent studies suggests that communication and the level of knowledge and trust of the population regarding this strategy can greatly influence its social sustainability (Chfadi et al., 2021; Scruggs et al., 2020), implying that public participation and engagement would be fundamentals to validate its social pertinence and ensure a successful implementation.

Fig. 6

3.6. Main limitations and future work

It is important to note that a primary limitation of this study arises from its very strength: the extensive scope of the analysis. This breadth has resulted in the predominantly exploratory nature of our assessment. For instance, the technical, environmental, and social issues related to wastewater reuse are themselves very complex, as suggested by previous literature on these topics. (e.g., Holloway et al., 2016; Leiva et al., 2021; Opher et al., 2017; Scruggs et al., 2020; Smith et al., 2018). Furthermore, our approach may require a significant amount of data, some of which may not be necessarily available in all study cases.

Although our analysis provides a handful of selected indicators that could form the basis for designing sustainable policies for water reuse, the results should be further supplemented by specific tools that are more suitable to deal with these complexities, such as LCA for environmental issues. Due to the various facets involved in wastewater reuse, the implementation of multicriteria analysis tools can also significantly enhance this study through the analysis and prioritization of reuse strategies (e.g., Azbari et al., 2021), provided that the selection of criteria to be analyzed and their quantification is conducted within a framework that enables a transparent and informed decision-making process. Finally, another limitation of the study is related to the absence of an analysis of the effect that water reuse has on the metabolic pattern at the city and regional levels, as well as on related indicators such as WMR. These aspects will be addressed in future research.

4. Conclusions

Wastewater reuse is one of the most prominent strategies to confront the growing water scarcity experimented worldwide. Our study proposed a method to provide a comprehensive assessment of wastewater reuse from a social metabolism perspective and applied it to a case study in south-central Chile. Overall, the consumption of green water (soil moisture) is the most relevant socially mediated water flow in the assessed basins, while agricultural and industrial activities stand out as the most relevant users of blue water (water extracted from superficial and underground sources).

The assessment highlights the significant role that wastewater reuse could play to improve the self-sufficiency of urban centers and to replace water consumption in economic activities. Wastewater reuse also has the potential to recover significant amounts of nutrients for activities such as agriculture, avoiding their discharge to superficial water bodies. As expected, indicators such as blue water consumption, WMR, and pollutant load were all correlated to population and the presence of the most demanding activities, highlighting the relevance of wastewater reuse in the corresponding basins. Nonetheless, the quality of effluent and the fluctuations observed in wastewater flow constrain the feasibility of certain alternatives, necessitating the utilization of additional treatment technologies and/or storage systems in order to ensure a reliable supply of reclaimed water. Furthermore, the result of the social analysis shows that the desirability of wastewater reuse is mainly limited to applications where the contact with reclaimed water is reduced, limiting its applicability in the most relevant water consuming activities and highlighting the necessity of public engagement to make reuse a socially accepted strategy. It is important to mention that the results are contingent to our case study, and that more studies are necessary to assess the influence that relevant social and environmental conditions can have over the most important recommendations for wastewater reuse implementation.

Overall, the proposed framework allowed for the integration of some of the most important aspects of wastewater reuse metabolism and sustainability. MuSIASEM presents significant advantages for the analysis of wastewater reuse, given the complexity of the issue and the numerous potential interactions between the different functional levels of society associated with water reuse strategies. As MuSIASEM's strengths can led to very data-demanding analyses, the flexibility and capacity of the approach to focus in the most critical aspects of the assessment is also important for its practical feasibility. Besides the analysis of the water flows and its relationship to human activities and funds, water metabolism is a useful tool that could be used to integrate specific issues of wastewater reuse into a cohesive, science-based narrative. The proposed method can be

adapted and applied to other cases studies for the diagnosis of current systems and the assessment of prospective scenarios, allowing the integration of case-specific considerations and its complementation with specific tools for the analysis of environmental, social, economic and/or technical issues.

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Figures and tables

Scale		Metabolism tool	Metabolism focus	Complementary focus
Region		MuSIASEM	Water demand per economic sector	Social acceptance (desirability)
Watershed		MuSIASEM	Relationship between cities, users and hydrological processes	Wastewater nutrient loading (feasibility)
City		MuSIASEM MFA	Internal water flows and socio-hydrological performance	Wastewater characteristics (viability)

Figure 1. Conceptual framework proposed in this work. MuSIASEM: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism; MFA: Material Flow Analysis.

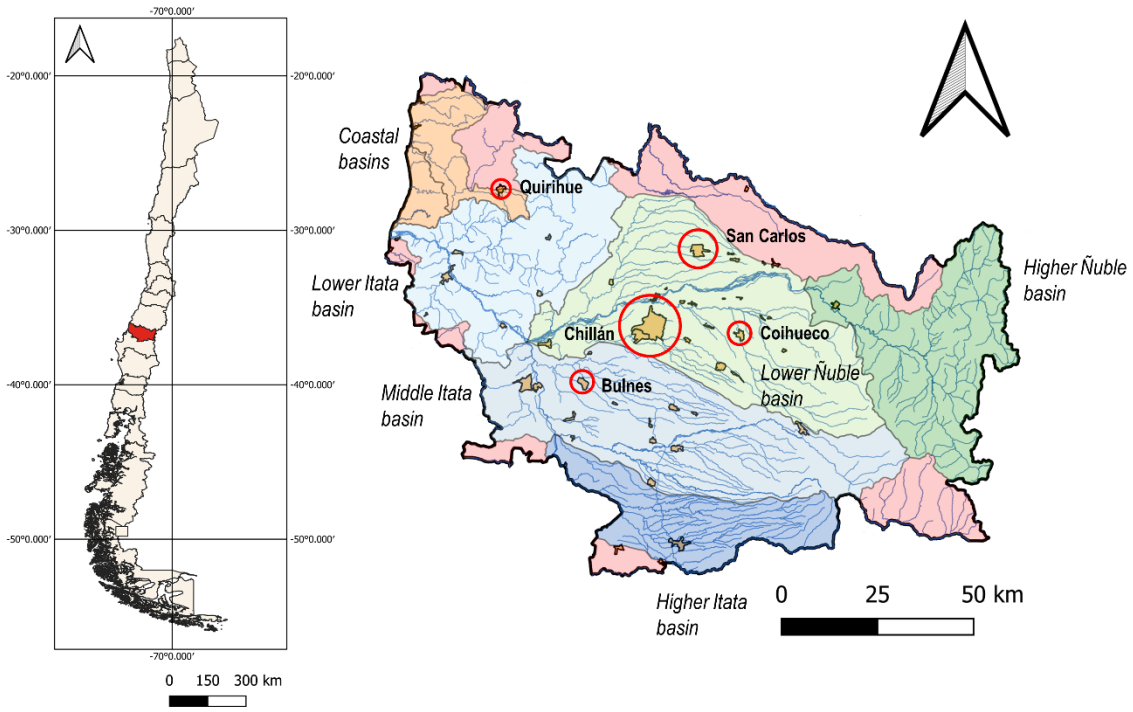


Figure 2. Area of study. Red circles highlight the cities selected for the MFA assessment. Water basins: Higher Ñuble river, Lower Ñuble river, Higher Itata river, Middle Itata river, Lower Itata river, Coastal rivers, Other basins.

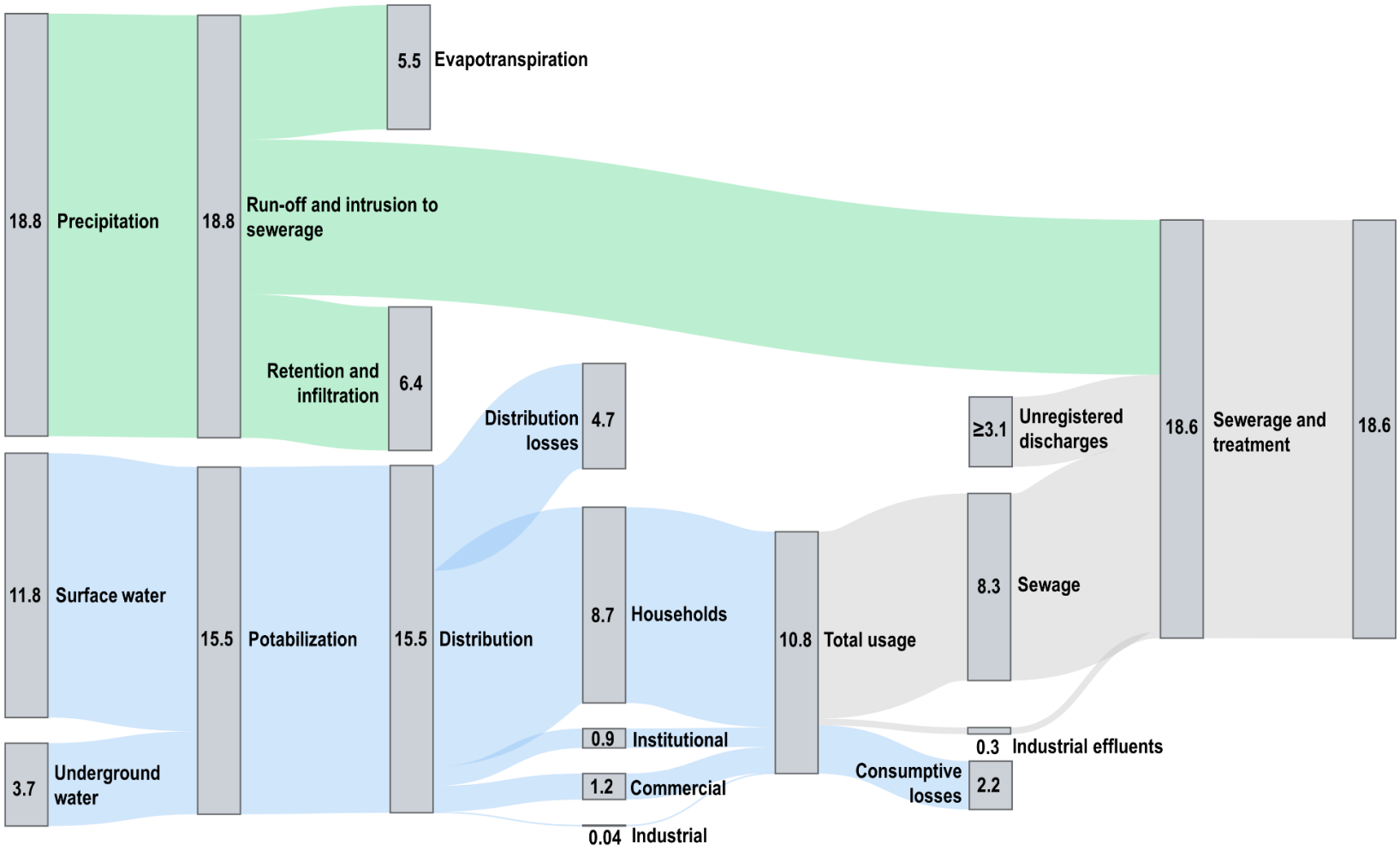


Figure 3. Urban water balance for the city of Chillán ($10^6 m^3$/year), year 2019. ▫ Green water flows (derived from precipitation), ▫ Blue water flows (water sourced from superficial and groundwater sources), ▫ Grey water flows (wastewater). Rainwater intrusion was assumed to be equal to runoff (6.9 Mm^3/year), in order to estimate the unregistered wastewater discharges that occur within the city.

Table 1. Summary of the indicators calculated for the 5 assessed urban centers, year 2019.

Hydrological performance	Unit	Bulnes	Chillán	Coihueco	San Carlos	Quirihue
Evapotranspiration	-	0.18	0.82	1.13	0.23	0.14
Runoff	-	1.93	1.85	2.92	2.76	1.74
Infiltration/retention	-	0.41	0.76	0.62	0.59	0.47
Water consumption						
Total per capita	L/inhab-d	135	175	153	171	164
Domiciliary per capita	L/inhab-d	101	142	118	133	124
Intensity per surface	m^3/m^2	0.25	0.35	0.26	0.32	0.27
Self-sufficiency						
Runoff	-	2.61	0.64	1.47	1.15	1.83
Wastewater	-	0.95	1.73	1.21	1.34	1.07

Table 2. Blue water demands in the studied region, disaggregated per water basin and activity (Based on data from DGA, 2017 and SISS, 2022).

Basin	Higher Ñuble		Lower Ñuble		Higher Itata		Middle Itata		Lower Itata		Coastal	
	10^3m^3/year	%	10^3m^3/year	%	10^3m^3/year	%	10^3m^3/year	%	10^3m^3/year	%	10^3m^3/year	%
Urban households	0.0	-	19,104.0	8.2%	2,010.0	15.1%	3,138.0	3.2%	1,227.0	18.0%	534.0	30.4%
Rural households	317.0	19.5%	2,711.0	1.2%	304.0	2.3%	1,097.0	1.1%	809.0	11.8%	138.0	7.8%
Livestock	0.0	-	0.0	-	34.9	0.3%	4.0	-	6.0	0.1%	0.1	0.0%
Agriculture	1,310.7	80.5%	204,846.1	87.5%	8,051.2	60.4%	63,285.5	64.1%	4,624.3	67.7%	900.9	51.2%
Industry	0.0	-	4,921.0	2.1%	2,776.0	20.8%	30,720.0	31.1%	0.0	-	0.0	-
Services	0.0	-	2,621.9	1.1%	143.6	1.1%	504.2	0.5%	169.3	2.5%	185.2	10.5%
Total	1,627.7	100.0%	234,204.0	100.0%	13,319.7	100.0%	98,748.6	100.0%	6,835.6	100.0%	1,758.1	100.0%

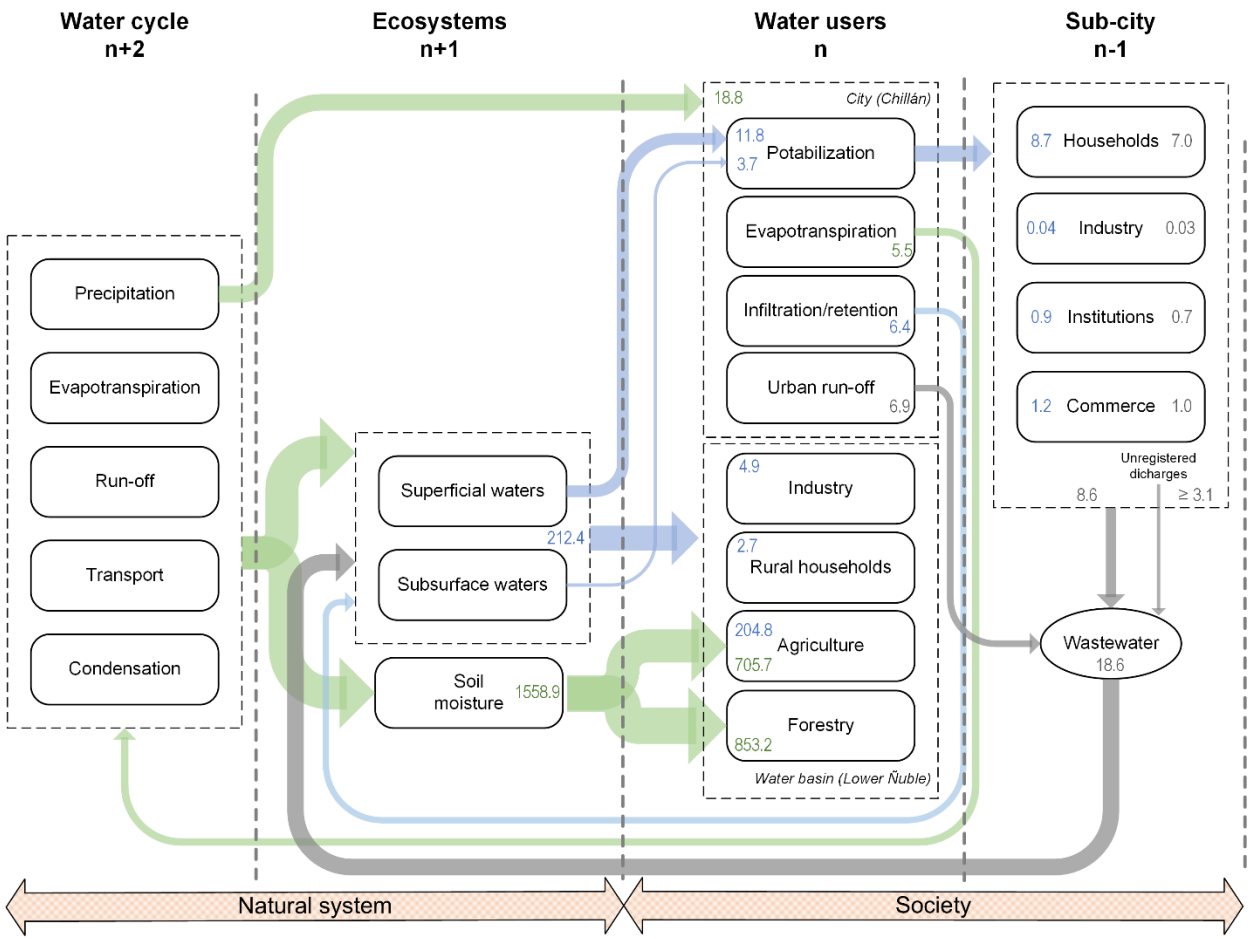
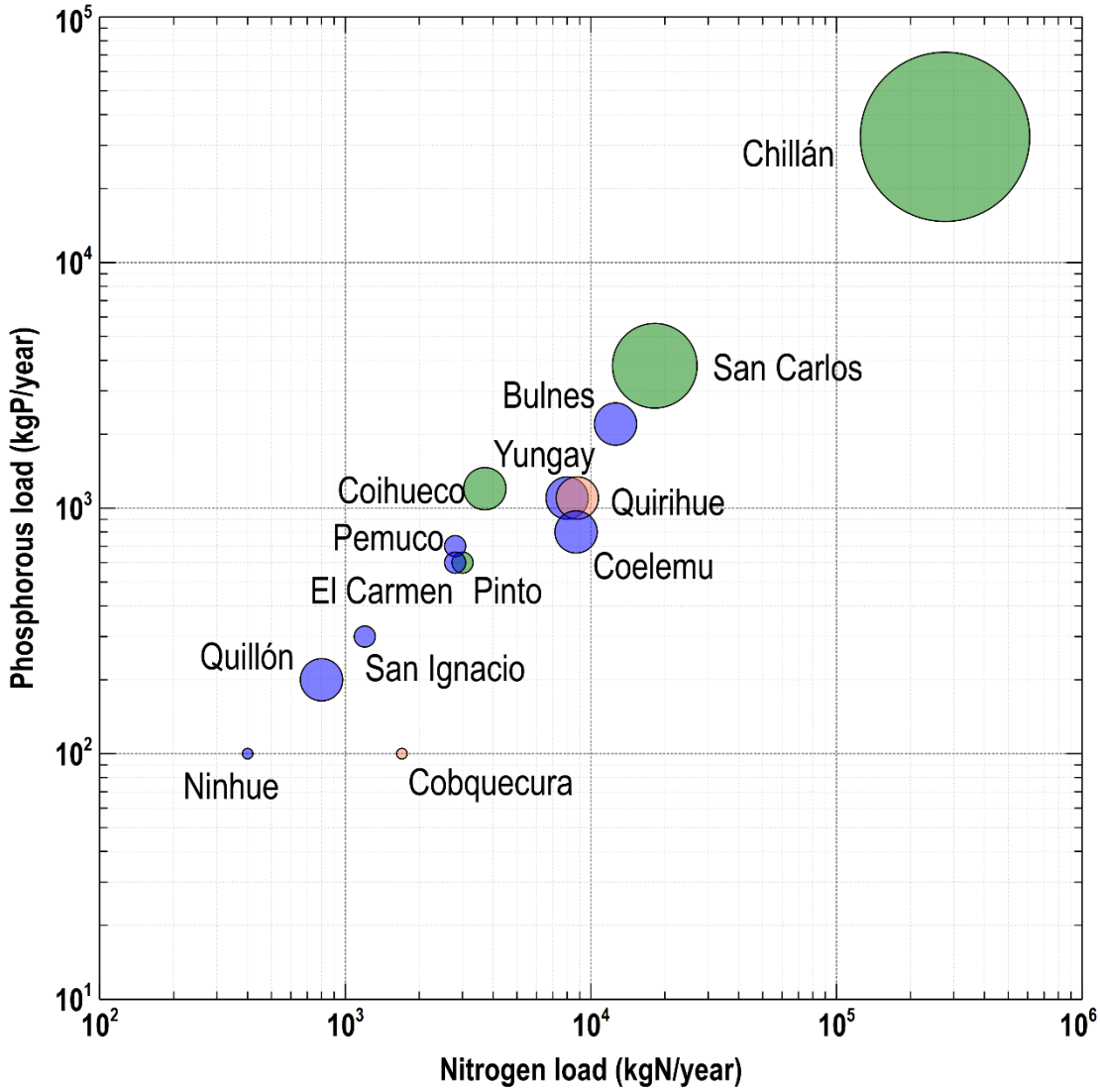


Figure 4. Main flows of the city-watershed water metabolism, using as an example the city of Chillán and its basin. ▫ Green water flows, ▫ Blue water flows, ▫ Grey water flows. All values are in million cubic meters per year (2019).

Table 3. Estimated Water Metabolic Rates (WMR) in the water basins of the Ñuble region. WMR results represent the blue water metabolic rate (water extracted from superficial and subsurface water bodies).

Basin	Higher Ñuble		Lower Ñuble		Higher Itata		Middle Itata		Lower Itata		Coastal	
	Activity	WMR (L/h)	Activity	WMR (L/h)	Activity	WMR (L/h)	Activity	WMR (L/h)	Activity	WMR (L/h)	Activity	WMR (L/h)
Total	100%	44.6	100%	85.1	100%	86.9	100%	151.5	100%	21.5	100%	11.1
Households	93.9%	9.2	92.5%	8.7	93.3%	16.4	93.2%	7.0	93.6%	6.8	93.1%	5.1
Paid Work	6.1%	588.0	7.5%	1,036.6	6.7%	1,081.2	6.8%	2,144.8	6.4%	236.7	6.9%	110.5
Agricultural*	24.2%	2,430.3	13.8%	7,229.5	13.5%	5,874.6	34.7%	4,142.6	29.2%	781.7	25.8%	301.8
Industry*	6.6%	-	7.8%	306.0	13.5%	1,279.3	8.3%	8,386.2	10.9%	-	6.1%	-
Services*	69.2%	-	78.3%	16.3	65.2%	21.6	57.0%	20.1	59.9%	13.9	68.1%	27.7

*Percentages of paid work.



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2 **Figure 5.** Wastewater nitrogen and phosphorous flows in the communes of the Ñuble region, classified per
3 water basin: ▫ Ñuble sub-basin, ▫ Itata sub-basin, and ▫ Coastal basins. The size of the circles is proportional
4 to the population of the communes.

Table 4. Monthly variability of daily wastewater flows compared with the annual average, for a period of 6 years (2014 – 2019). Based on data from SISS (2021).

WWTP	Average flow (m^3/day)	January	February	March	April	May	June	July	August	September	October	November	December
		%											
Bulnes	1,664	-21	-11	-11	-4	-1	11	28	13	5	3	-4	-6
Chillán	47,954	-25	-29	-31	-14	-6	6	21	27	22	13	6	-5
Cobquecura	184	-16	19	-30	-16	-15	1	24	38	38	6	-21	-9
Coelemu	1,512	-33	-20	-20	-7	2	39	4	41	5	6	0	-2
Coihueco	1,592	-12	-12	-20	-12	-10	0	14	16	10	3	7	10
El Carmen	1,265	-31	-31	-48	-40	-35	-4	48	73	27	11	10	5
Las Mariposas	893	-27	-32	1	38	-6	2	-8	22	16	-4	-5	-4
Ninhue	255	-50	-46	-43	-20	-8	28	44	42	31	0	7	-34
Ñipas	229	-19	-14	-21	-10	-9	26	25	12	17	11	-3	-13
Pemuco	1,494	-18	-25	-38	-33	-10	10	25	28	17	11	28	1
Pinto	836	-18	-34	-32	-21	-26	3	41	38	22	7	7	12
Quillón	1,089	-19	-10	-18	-2	-1	-3	-7	38	21	5	-1	7
Quirihue	1,565	-29	-22	-19	-13	-10	9	27	36	7	17	9	-10
San Carlos	7,202	-14	-27	-26	-18	-10	8	18	22	7	17	11	5
San Ignacio	745	-20	-32	-32	-14	-16	-2	14	7	18	9	27	27
Santa Clara	503	-27	-38	-35	-7	-12	19	42	39	16	16	-5	-9
Yungay	1,382	-38	-31	-39	-20	-20	7	45	46	42	18	15	-11

Table 5. Classification of the effluent quality for reuse according to the categories stablished in ISO 16,075.

WWTP	BOD_5 (mg/L)		TSS (mg/L)		Coliforms (MPN/100 mL)		Overall category	Average flow (m^3/day)
	Max.	Average	Max.	Average	Max.	95th percentile		
Coelemu	34.5	13.9	31.8	6.4	500	8.0	C	
Las Mariposas	32.0	7.4	44.0	7.6	500	30.6	C	3,241
Pinto	34.7	10.6	21.9	5.7	800	17.0	C	
Bulnes	38.9	13.4	54.5	7.6	800	70.0	D	
Cobquecura	53.0	18.6	74.0	9.8	700	4.0	D	
Coihueco	93.7	12.0	33.6	6.0	800	50.0	D	
El Carmen	69.0	22.1	78.0	18.7	500	2.0	D	
Ninhue	70.5	24.5	64.9	19.6	300	8.0	D	
Ñipas	63.9	16.4	55.8	9.8	300	30.8	D	17,605
Pemuco	39.1	10.1	43.5	6.4	800	30.0	D	
Quillón	72.0	21.5	40.4	9.4	800	230.0	D	
San Carlos	86.7	12.8	79.0	7.2	800	22.8	D	
San Ignacio	37.7	10.1	61.7	7.7	900	129.0	D	
Santa Clara	34.5	11.9	57.0	7.8	800	170.0	D	
Yungay	55.2	20.8	52.1	12.6	500	50.0	D	
Chillán	119.7	15.3	66.0	7.2	900	130.0	NC	49,519
Quirihue	105.7	22.6	49.1	16.6	300	50.0	NC	

Treated water of very high quality (A category); Treated water of high quality (B category); Treated water of good quality (C category); Treated water of medium quality (D category); Treated water that does not comply with the quality requirements for reuse (NC). Max: Maximum value observed.

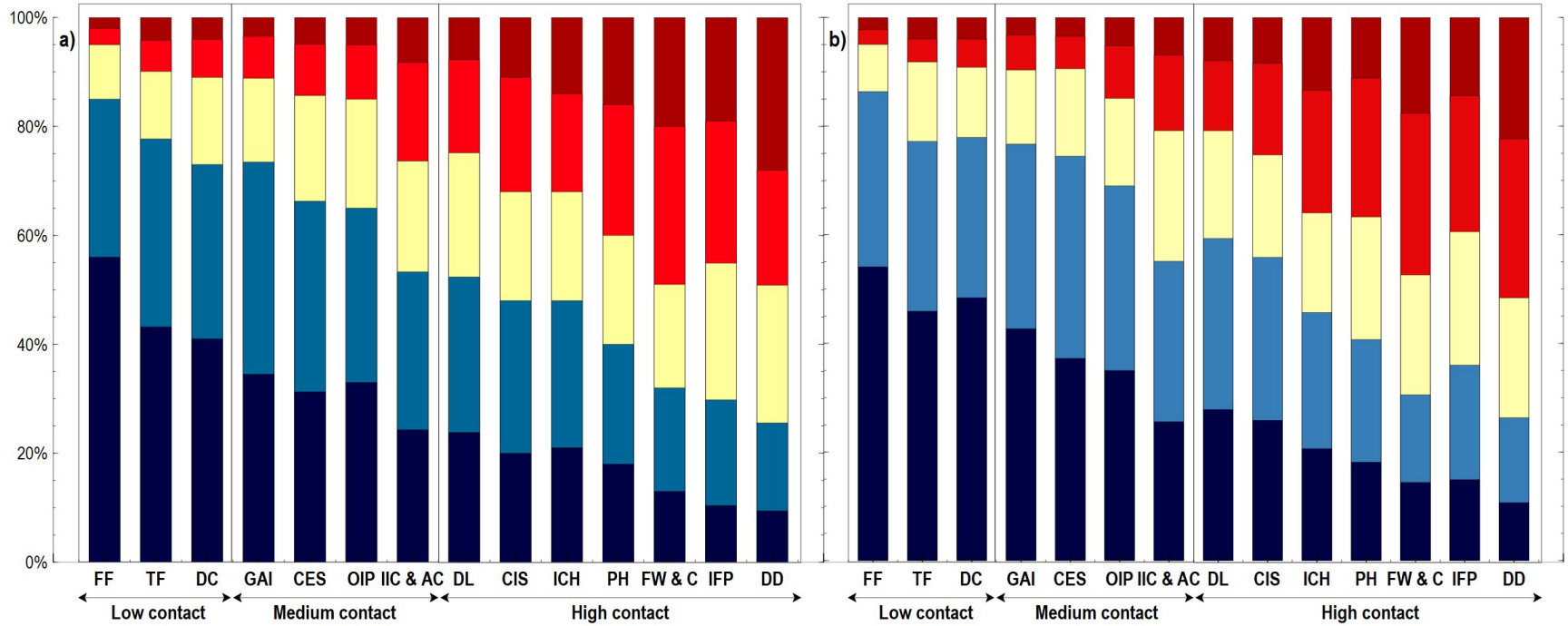

Figure 6. Social acceptance of reclaimed water applications. a) Municipal wastewater. b) Greywater. FF: Firefighting; TF: Toilet flushing; DC: Dust control on roads; GAI: Green areas irrigation; CES: Cleaning of exterior surfaces (floors, playground, vehicles, etc); OIP: Other industrial processes; IIC & AC: Irrigation of crops for industrial use and animal consumption; DL: Domestic laundry; CIS: Cleaning of interior surfaces (tables, counters, floors, and others); ICH: Irrigation of crops for human consumption; PH: Personal hygiene (e.g., shower); FW & C: Food washing and cooking; IFP: Industrial food processes; DD: Direct drinking. ■ Strongly agree, ■ Agree, □ Neither agree nor disagree, ■ Disagree, ■ Strongly disagree.