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Integrating spatial and social characteristics in the DPSIR framework for the sustainable management of river basins: case study of the Katari River Basin, Bolivia

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ABSTRACT

The drivers–pressures–state–impact–responses (DPSIR) framework has been used widely to support environmental policy developments. However, we argue that DPSIR tends to oversimplify the complexity behind socio-ecological systems. Based on the Katari River Basin in Bolivia, we explore how the incorporation of spatial and social considerations may enhance DPSIR applications. The results reveal a spatial mismatch between driving forces/pressures and policy responses, and severe impacts on the vulnerable communities. Moreover, we also show that local levels tend to be neglected. The study concludes that integrating spatial and social characteristics in the DPSIR may result in valuable implications for river basin management practitioners.

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DPSIR; sustainable development; river basin management; water management; water policy; Katari River Basin; Bolivia

Introduction

River basins represent highly complex socio-ecological systems with diverse interrelations between their physical, chemical, biological and socio-economic processes. The anthropogenic developments within these systems tend to exert environmental pressure resulting in diverse environmental effects (Elliott, 2002), which in turn can jeopardize longer term socio-economic development. Rivers connect human communities and places and play an important role in reproducing social values, cultural beliefs and forms of life (Anderson et al., 2019). Hence, the study and management of river basin systems requires information related to human and environmental links. It should also combine natural and social sciences in formulating solutions linked to the problems of socio-environmental nature (Gregory et al., 2013). A socio-ecological systems approach contributes to enhancing the understanding between water and society (Everard, 2019).

To connect the social and environmental systems, conceptual frameworks have been developed to examine, understand and visualize how both systems interact and how decision-making will influence these links and the outcomes. In early 1990s, the drivers–pressures–state–impact–responses (DPSIR) framework was developed to organize

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essential information in a set of indicators to support decision-making processes and policy developments in a meaningful sense (OECD, 2003). Since 1995, the European Environmental Agency (EEA) and Eurostat have largely applied this framework to organize environmental indicators and statistics (Smeets & Weterings, 1999). In 2003, DPSIR was also incorporated in the Water Framework Directive as part of the Common Implementation Strategy promoted by the European Commission (EC-EEA, 2003) in order to evaluate and design river basin management plans following the integrated water resource management approach. The introduction of DPSIR and its explicit connection between society and ecosystems in water management mirrored a broader and ongoing paradigm shift in water management: away from water as a production factor in a system to be developed and towards water as a fundamental component of ecosystems and their services to society and economy.

As shown in Figure 1, the EEA presents the DPSIR framework as a causal model in which the driving forces, which may be of social and/or economic nature, exert pressures on the environmental system. These pressures translate into changes in the natural state leading to environmental impacts which may cause societal responses (Smeets & Weterings, 1999, p. 8).

The DPSIR was advertised as a causal framework that facilitates the understanding of relations between society and the environment (Smaling & Dixon, 2006). Two main features allowed its widespread use. First, the framework facilitates the organization of environmental indicators based on the political objectives targeting environmental challenges. Second, the framework focuses its attention on the assumed causal relationships. This is helpful for decision-makers designing policies to tackle the environmental issues they encounter (Smeets & Weterings, 1999).

The DPSIR framework has been applied to diverse environmental research studies such as environmental degradation (Agyemang et al., 2007), reef fisheries (Mangi et al., 2007) and management of marine environments (Atkins et al., 2011; Sundblad et al., 2014). However, despite its wide application by practitioners and acceptance of international development agencies worldwide, the framework tends to oversimplify the complex reality of socio-ecological systems (Gobin et al., 2004; Niemeijer & De Groot, 2008).

The DPSIR grants more attention to environmental than to social considerations (Svarstad et al., 2008). Its applications tend to ignore the fact that environmental changes usually have a larger impact over low-income and vulnerable social groups (Duraiappah, 1998). This can challenge the achievement of environmental justice, which focuses on

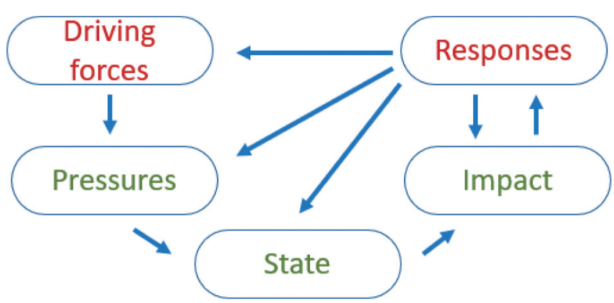


Figure 1. The drivers–pressures–state–impact–responses (DPSIR)

redressing the environmental burden placed on low-income and minority communities, who are the most vulnerable groups usually impacted by human-driven environmental changes (Bullard, 2018). Furthermore, by usually placing attention to the highest levels of decision-making and ignoring the local levels, the DPSIR framework implicitly creates a hierarchy of actors, which can reproduce inequalities between stakeholders and actors within the system, (Carr et al., 2007). The analysis of scales may be beneficial in order to consider an individual assessment of socio-environmental processes at the scale at which they operate and to associate them with different levels of administration and social organization (Leemans & De Groot, 2003). Neglecting these crucial aspects heavily compromises the sustainable development of socio-ecological systems. On the contrary, the maintenance of essential ecological processes and life support systems contributes to sustainable development because it allows the present and future generations to meet their needs (Brundtland et al., 1987).

The complexity of the socio-environmental systems relies on several layers of social, political and economic institutions, and the environmental consequences behind their interactions (Teodosiu et al., 2009). Rather than simplify this complex reality, the sustainability of a socio-environmental system depends on the dissection of its complexity, and on the detailed understanding of the relations between its subsystems and their variables (Ostrom, 2009). Embracing the complexity of the connection between the social and the environmental system is crucial for sustainable development (Carr et al., 2007). Human systems are a fundamental component of socio-environmental systems, holding the capacity to shape environmental changes (Cote & Nightingale, 2012). Thus, they may not be conceived as isolated from each other with conflicting interests. One of the mechanisms to manage the relationship between human and socio-environmental systems in a mutually beneficial manner is through appropriate environmental policies (Jordan, 2001). However, they can at times lack a long-term vision which might then negatively influence the desired sustainable development outcome (Pezzey, 2004).

In this article we thus propose the incorporation of spatial and social considerations in the DPSIR framework for the policy development of river basin management. We aim to illustrate how the incorporation of these elements can contribute to a more effective and sustainable river basin management policy, with more attention devoted to the interests of the most vulnerable local actors. To that end, we analyse how social and environmental aspects are intimately intertwined in the Katari River Basin in Bolivia. This watershed is heavily contaminated due to mining, industrial, urban and agricultural developments, which have had a significant environmental and social impact.

In the methodology section we present a semi-quantitative method to identify the relation between driving forces/pressures and policy responses. Moreover, we also introduce how social characteristics were incorporated. This is based on the scalar analysis and assessment of impacts over vulnerable communities linked to the environmental changes. The results section is organized based on the three key regions within the Katari River Basin case study in order to provide a detailed analysis of the process reproducing environmental impacts. In the discussion section we analyse how the inclusion of spatial and social characteristics influences river basin policy developments and their potential implications. Furthermore, we attempt to answer the following questions: How can the DPSIR spatial analysis enhance river basin policy management? How does the inclusion of a scale analysis within the DPSIR applications influence the understanding of a river basin process? How may an environmental justice approach of the DPSIR framework enhance policy targets to reduce the burdens over the most vulnerable social groups? In the final section, we present our conclusions regarding these questions.

Methodology

Case study: the Katari River Basin

The Katari River Basin was identified for several reasons as an adequate case study to understand how social and spatial characteristics may influence the DPSIR framework. First, the case represents the most populated river basin in Bolivia, home to approximately 1.3 million inhabitants, and the region is characterized by one of the highest population growth rates in the world (Arbona & Kohl, 2004). During the 1970s and 1990s, the river basin received substantial migration from rural indigenous communities from the north-eastern Bolivian Andes. Currently, more than 93% of the population is located in urban areas upstream, leading to an important asymmetry between rural and urban communities. Second, the rapid population growth has generated three main anthropogenic pressures on the river basin system: housing, industry and agriculture. Indeed, the rivers incorporated in the system collect the major part of the contamination produced by these human developments upstream, which affects the socioenvironmental conditions of the system downstream. Third, the river basin discharges its outflow in Titicaca Lake, which is the most important water resource in the Andes Region. Fourth, for over 15 years, local, regional, national and international agencies invested in river basin management policies to improve the situation of this river basin. However, recent studies show that contamination remains a significant problem (Agramont et al., 2019; Archundia et al., 2017).

The Katari River Basin can be divided into three regions based on the main anthropogenic developments within the system (Archundia et al., 2017). The first region is characterized by the presence of mine waste accumulated from over a century of mining activities. The second region incorporates urban and industrial settlements allocated in the cities of El Alto and Viacha. The third region is mainly characterized by the presence of rural communities that currently practice agriculture and cattle-raising as their main form of livelihood.

The Katari River Basin first called the attention of national authorities in 2002 when rural indigenous communities located in the third region began large protests due to severe contamination (CGEPB, 2014). Since 2004, various environmental policies have been developed, and partially implemented, with the aim to restore the system. Despite these efforts, the ecological degradation of the past decades has not been reversed.

Methods: a modified DPSIR analysis

In order to apply the DPSIR analysis to the Katari River Basin case study, data related to the driving forces (D), pressures (P), impacts (I) and policy responses (R) were collected through a secondary data review of public policies, official government reports and scientific publications (Table 1). Furthermore, to collect data associated with the changes

Table 1. Reports and publications employed for the analysis.

DPSIR elements	Sources
Driving forces/pressures	Archundia et al. (2017); CGEPB (2014); MMAYA (2010); PDCKYLM (2018)
State	Vice-Ministry of Water Resources (2019); Archundia et al. (2017)
Impacts	CGEPB (2014); Gloria Rodrigo et al. (2018)
Responses	CGEPB (2014); MAYA (2018, 2019); Katari River Basin General Assembly (2019)

in the environmental state, a water quality monitoring campaign was implemented in alliance with the Bolivian Ministry of Water and Environment in May 2019. Additional data related to the water quality environmental state changes were collected through a secondary data review of scientific research in this field. The analysis of changes in the environmental state were presented based on surface water quality indicators referenced under the Bolivian environmental regulations.

In order to understand how spatial and social characteristics may influence the sustainability of the river basin's policies, this research incorporated two complementary features in the Katari River Basin's DPSIR framework application. First, the spatial analysis was included to understand the relations between policy responses and the driving forces/pressures. Second, social considerations were incorporated into the DPSIR framework categories.

To provide a spatial dimension to the driving forces and pressures within the Katari River Basin, a land-use map of the watershed was performed. To develop the land use pattern of the Katari River Basin, an unsupervised image classification employing ArcMap 10.2 iso clustering and maximum likelihood tool was applied to a 2 m resolution Sentinel 2-A satellite image. At the same time, driving forces (land-use patterns) and the local administrative jurisdictions were overlapped to identify the links between sources of environmental degradation and the local managerial jurisdiction. To spatially assess the responses, a secondary data review of policies implemented in the Katari River Basin for the period 2004–19 was applied. This policy analysis identified the spatial allocations where these responses/measures were implemented. Moreover, the policy analysis also identified the stakeholders that implemented the responses. The DPSIR spatial analysis incorporated the assessment of the relationship between policy responses and driving forces, to facilitate assessment of the sustainability of river basin management efforts. Responses spatially directed to manage environmental driving forces, which are the sources of the problems, were considered as more sustainable and effective in the long term in comparison with measures to handle other elements of the framework such as impacted regions, which deal more with short-term symptoms.

To incorporate social characteristics, two additional aspects were included in the adapted DPSIR framework: the social impacts related to environmental services and the scalar configuration. First, environmental services refer to environmental functions and their capacity to provide natural resources upon which the livelihood of communities depends, the influence on public health, and the local socio-economic links (Reid et al., 2005). To identify changes in environmental services influenced by the modification of the Katari River Basin environmental state, we applied a secondary data review of official reports and scientific publications recalling shifts in the local livelihood and local public health issues. Furthermore, to articulate the environmental justice approach, this analysis focused on vulnerable communities subject to such modifications, which are located in the third region of the Katari River Basin. Consequently, the literature review paid special attention to stakeholders living in the rural communities located downstream from the main environmental driving forces and pressures that heavily increase their local vulnerability. These communities are a minority group in relation to the population of the entire socio-ecological system.

Second, the scalar configuration refers to the different public management layers according to which the social system is organized and structured. In order to incorporate the scales, this research distinguished different public management layers related to the Katari River Basin and identified the driving forces/pressures level at which the processes took place. Moreover, through a secondary data review, this research also assessed the scale at which the policy responses for the period 2004–19 were developed and implemented. The analysis is based on the relation of the level at which driving forces take place and the managerial level at which policy responses are developed and implemented.

In order to better understand the socio-ecological system, the driving forces/pressures and policy responses were initially analysed separately for each of the three regions: the mining region, the urban–industrial region and the agricultural region. This separate analysis allowed one to comprehend the nature of the anthropogenic development, its spatial allocation, the management jurisdiction and the responses implemented to manage these developments. However, to understand the upstream–downstream relationships and the linkages within the socio-ecological system, the environmental state modification and socio-ecological impacts assessed the nexus among the three regions under study.

Results

Katari River Basin's spatial and social DPSIR analysis

Figure 2 presents the results of the land-use assessment in the river basin. It shows the spatial location of the environmental driving forces: mining at the north-east region below the glacial zone, housing and industry in the cities of El Alto and Viacha, and agricultural practices that incorporate cattle-breading and crops in the municipalities of Pucarani, Laja and Viacha, which are mainly composed of rural indigenous communities. Although 10 municipalities share spatial jurisdiction within the Katari River Basin, the main process taking place incorporates just five of these municipalities: El Alto, Viacha, Laja, Pucarani and Puerto Perez.

The scalar configuration for the Katari River Basin is composed of five layers of formal management. At the highest level, the governments of Bolivia and Peru created the Lake Titicaca Binational Autonomous Authority (LTBAA) international agency.[1] The second layer is comprised of the Ministry of Water and Environment (MWE). In 2016, the MWE developed a specific decentralized arm named the Katari River Basin Management Unit to implement the river basin plan which was developed in 2010 and officially launched in 2016. The third layer is the State Autonomous Government of La Paz. The state government incorporates the State Secretariat for the Rights of Mother Earth, which is the unit responsible for regulating the environmental issues in all provinces within the state of La

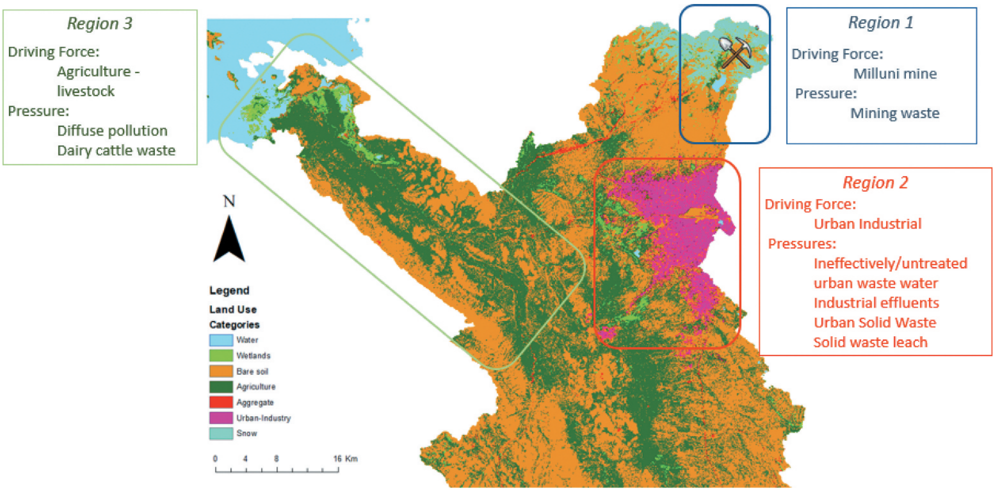


Figure 2. The Katari River Basin and regions of anthropogenic influence.

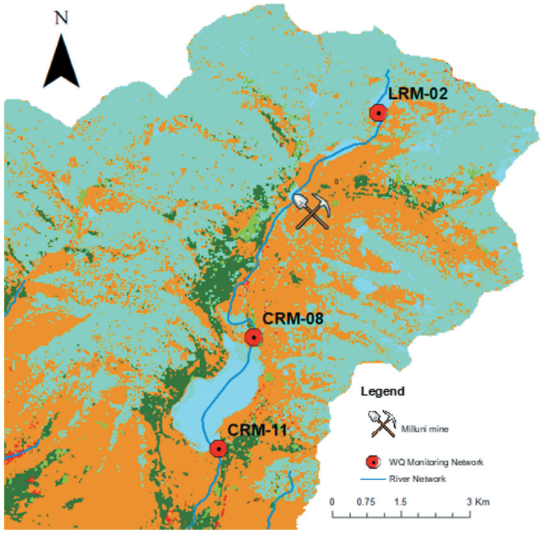
Paz. The fourth layer is composed of the municipal governments of El Alto, Viacha, Laja, Pucarani and Puerto Perez. Based on the current legal framework, all these municipal governments are granted environmental and water services management responsibility under their specific jurisdiction.

The DPSIR analysis was developed separately for the three regions in the Katari River Basin. We will first present the spatial distribution of environmental driving forces and the pressures. This will be followed by a discussion of the changes in the environmental state in terms of water quality indicators as well as their social and environmental impact. Finally, policy responses developed for the period 2004–19 will be analysed to assess the spatial match with driving forces/pressures within each region.

Region 1: The Milluni Valley

The first region, at the highest river basin section, corresponds to the Milluni Valley at 4450 masl. In this region, mining operations started in the 18th century. In the 1920s, La Fabulosa Mine Consolidated, a private enterprise owned by British shareholders, accessed the first concession contract to exploit tin, lead and zinc (Salvarredy-Aranguren et al., 2008). Later, from 1975 to 1986, a public company, COMSUR, operated the mine. At present, most of the mineral's reservoirs have been exploited, and the Milluni mine is not under an official concession contract anymore. However, more than a century of operations left a legacy of environmental problems in the river basin.

Figure 3 shows the land-use patterns and the water quality monitoring network in the Milluni Valley, as well as water quality indicators in three monitoring stations. At LRM-02, close to the Huayna Potosi glacial, water quality is the highest of the whole hydrological system. This is reflected by the majority of water quality parameters being under permissible levels according to Bolivian water environmental legislation. However, below this point there is a major environmental pressure consisting of 2 million m^3 of mining



	EC	pH	As	Al
	µS/cm	-	mg/L	mg/L
Monitoring Station	Class A 0 to 140 Class B >140 to 300 Class C >300 to 500 Class D >500 to 1600 Critical > 1600	Class A 6.0 to 8.5 Class B >8.5 to 9.0 Class C >8.5 to 9.0 Class D >8.5 to 9.0 Critical < 6 y > 9	Class A 0 to 0.05 Class D 0.05 to 1.0 Critical > 1.0	Class A 0 to 0.2 Class B 0.2 to 0.5 Class C 0.5 to 1.0 Critical >1.0
LRM-02	75.5	8	0.01	0.04
CRM-08	1392	2.84	0.79	1.75
CRM-11	1161	2.78	0.05	1.27

	Cd	Fe	Zn	Mn
	mg/L	mg/L	mg/L	mg/L
Monitoring Station	Class A 0 to 0.005 Critical > 0.005	Class A 0 to 0.3 Class C 0.3 to 1.0 Critical > 1.0	Class A 0 to 0.2 Class C 0.2 to 5.0 Critical > 5.0	Class A 0 to 0.5 Class B 0.5 to 1.0 Critical >1.0
LRM-02	0.002	0.53	0.03	0.33
CRM-08	0.111	128.14	31.65	7.27
CRM-11	0.054	45.22	17.02	3.5

Figure 3. The Milluni Valley.

waste composed of sulphide minerals generated by the Milluni mine (CGEPB, 2014). When exposed to the atmosphere, this mining waste produces constant acid mine drainage. Due to the composition of the acid mine drainage, the environmental state of the water resources in the region and downstream has been heavily modified.

The effects are more significant at the Milluni dam, which is the second most important reservoir in the region, with the capacity to store 10.3 Mm^3. This water reservoir is employed to supply drinking water to the cities of El Alto and La Paz through the Alto Lima and Chuquiaguillo treatment plants, respectively. The water quality at the Milluni dam, measured at CRM-11, holds high levels of acidity and high electrical conductivity. Under the local regulations, these waters cannot be used for any purposes and represent a high risk to public health. Furthermore, high levels of aluminium, arsenic, cadmium, manganese and zinc were also detected there.

Furthermore, a large heavy metal concentration coming from upstream can be observed in sediments downstream. The sediments evaluated in regions 2 and 3 exceeded heavy metal permissible levels established by the Environmental Protection Agency 2002 and were composed by arsenic, copper, mercury, chrome, lead and zinc (CGEPB, 2014). Furthermore, heavy metals contamination was also found in local fauna and flora present in region 3 in a form of xenobiotic content, and thus potentially in the local food chain (Gloria Rodrigo et al., 2018).

Concerning the responses linked to the Milluni mine, the analysis for the period 2004–18 reveals only two responses that were actually implemented. First, the local water operator channelled the clean water upstream from the Milluni mine to bypass the mine waste area and to avoid the contamination of the surface water (Pérez, 2017). During the wet season, the channelized water is employed to supply the water operator's drinking water plant. However, the bypass channel flow is insufficient to supply the demand in the dry season. As a result, the drinking water operator mixes waters from the bypass channel and the contaminated Milluni dam outflow to meet the demand. To neutralize high acidity present in the dam outflow, the drinking water operator incorporated a pre-treatment process, which constitutes the second response. This additional process clearly increases the operational costs for the production of drinking water. The pre-treatment plant later delivers neutralized water to two drinking water treatment plants where metals are sedimented. Ironically, while these two drinking water treatment plants remove the heavy metal contamination from the raw water to provide safe drinking water to the cities of La Paz and El Alto, the facilities discharge the removed toxicological content to the surface water bodies neighbouring the drinking water plants (Pérez, 2017), increasing the social and environmental impacts downstream.

These two responses (bypass and pre-treatment) can be classified as impact responses since they deal with issues of the already contaminated surface water rather than the source of the environmental problem itself. Managing the mining waste could be a beneficial policy response for the whole river basin since it would result in a better drinking water quality for the cities of El Alto and La Paz, and in the control of the socio-environmental impacts for the indigenous rural communities downstream and around Titicaca Lake.

Based on the 2014 National Comptroller environmental audit, the responsibility for the lack of measures to improve and restore the environmental impacts produced by the Milluni passive mine waste can be assigned to the Ministry of Mining and Metallurgy, the Ministry of Water and Environment, and the State Government of La Paz and the Municipal Government of El Alto. The results of this environmental audit state that:

> the Ministry of Water and Environment, the Ministry of Mining and Metallurgy, and the State Government of La Paz did not develop actions tending to improve and restore the environment affected by the Milluni passive waste. On the other hand, the Municipal Government of El Alto has worked on the interinstitutional coordination, partially developing actions related to the issue.

The National Comptroller requested the Ministry of Water and Environment, the Ministry of Mining and Metallurgy, the State Government of La Paz and the Municipal Government of El Alto to report their actions to manage, reduce or mitigate the environmental problems caused by the Milluni mine. Their reports not only reveal a lack of effectiveness of the environmental policies they developed and implemented, but also limited coordination between these governmental agencies (CGEPB, 2014). This shows a significant problem of governance at the river basin scale.

Region 2: Urban industrial area El Alto–Viacha

The second region is characterized by the presence of major urban settlements mixed with industry randomly distributed within the cities of El Alto and Viacha. El Alto and Viacha hold the largest population size representing 93.4% of the residents within the Katari River Basin (PDCKYLM, 2018). The city of El Alto was initially planned to be an industrial park for the neighbouring capital La Paz. However, since then, it has experienced substantial immigration rates (Arbona & Kohl, 2004), which have not been accompanied by appropriate infrastructure and management developments. Consequently, the Katari River Basin suffered considerable environmental degradation due to a lack of wastewater services, industrial environmental control and monitoring, and proper urban solid waste management (Chudnoff, 2009).

The environmental pressures produced by the urban and industrial forces incorporate four types of burdens: household wastewater, industrial liquid discharges, urban solid waste and land field leach disposed of in the rivers crossing the cities of El Alto and Viacha. First, the cities of El Alto and Viacha jointly discharge 20 Mm^3/year of untreated or ineffectively treated urban wastewater to the Seke and Seco rivers (CGEPB, 2014) increasing by seven times the rivers' natural flow irrespective of the season (Duwig, 2014). As a result, the Seke River receives 20 Tn/year of organic pollutants in terms of chemical oxygen demand and biological oxygen demand increasing eight and 12 times the concentrations of these two indicators, respectively. Moreover, the Seke River discharges more than 160 Tn/year of total dissolved solids, which include the presence of dissolved heavy metals. Furthermore, this river releases close to 1 Tn/year of nutrients, nitrogen and phosphorus, raising the total nitrogen concentration 24 times (CGEPB, 2014). The Seco River further receives 8000 Tn/year of organic pollutants, chemical oxygen demand and biological oxygen demand, increasing 58 and 22 times the concentrations of these two indicators, respectively. The Seco River releases more than 30,000 Tn/year of total dissolved solids and over 400 Tn/year of nutrients in the form of nitrogen and phosphorous (CGEPB, 2014). For instance, the Seco River increases 55 times the total nitrogen concentration after crossing this region. Furthermore, both rivers, Seco and Seke, experience an exponential increase in faecal coliform contamination and electrical conductivity, and a significant reduction of dissolved oxygen. These results are qualified as critical according to the Bolivian surface water quality regulations meaning that these waters cannot be employed for any purpose. Figure 3 shows in detail the environmental state changes before and after crossing the urban–industrial region based on surface water quality indicators.

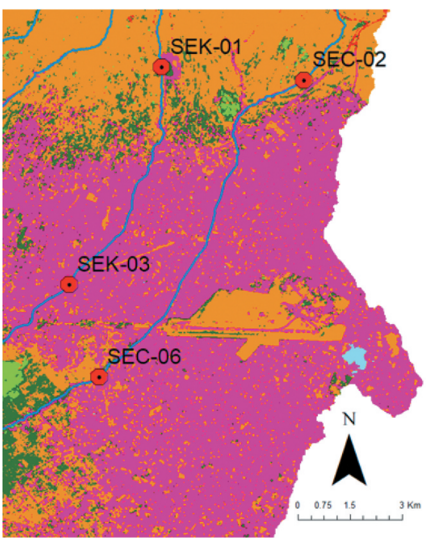
The Puchukollo wastewater treatment plant (WWTP) is the only system processing urban wastewater produced by the city of El Alto. Nevertheless, this WWTP holds a capacity to treat less than 50% of the urban liquid wastewater generated by El Alto (Archundia et al., 2017). Therefore, considering a population close to 1 million inhabitants, there is an alarming volume of untreated urban wastewater discharged in this second region. To increase the complexity, the unique WWTP in El Alto also receives effluents generated by diverse industries settled within this city. Some factories are connected to the household sewer system under an agreement contract between the local water operator and the industries without significant control or monitoring (CGEPB, 2014). Consequently, the Puchukollo WWTP not only has insufficient capacity to treat El Alto urban wastewater, but also is further overwhelmed by industrial wastewaters delivered to this facility without previous announcement or coordination (PNUMA, 2011).

The solid waste management represents another crucial environmental pressure in this region. The urban solid waste recollection service in El Alto has a service coverage of only 63.5% of the city. As a result, the city annually releases 800 Tn of solid waste into the rivers (PDCKYLM, 2018). Due to the marked seasonality in the river basin, the accumulated solid waste is carried downstream during the rainy season, travelling through the rural communities to be finally delivered to Titicaca Lake. Additionally, the land fields collecting the urban and industrial solid waste of El Alto and Viacha, Villa Ingenio and Santa Barbara, respectively, discharge a significant volume of the land field leach over the rivers crossing these cities, incorporating high organic content and heavy metals among other contaminants (CGEPB, 2014) (Figure 4).

The social and environmental impacts caused by the industrial–urban region is worsened by the mining impact upstream in region 1 and becomes manifest in the region downstream. Consequently, this driving force can be considered an indirect driving force for the rural indigenous communities in region 3. The socio-environmental impacts, product of the aggregated driving forces from regions 1 and 2, will be further discussed in the following section.

An analysis of the policy responses in the period 2004–18 shows a limited focus on only one of the four environmental pressures within this region, namely urban wastewater. Furthermore, only three measures were implemented in that period. First, in 2008, the Vice-Ministry of Drinking Water and Sanitation carried out a project to increase the Puchukollo WWTP's capacity. However, this project has not been entirely implemented and has resulted in an increase of only 5% of Puchukollo's processing capacity (CGEPB, 2014). Second, although the MWE accessed funding to develop a second urban wastewater treatment plant in the city of El Alto in 2014, rural communities neighbouring the water works rejected the project (ERBOL, 2015). Unfortunately, due to the continuous attempts on behalf of the local communities to prevent its construction, this infrastructure has not yet been developed (Página7, 2018). Third, in 2016, the central government provided the funding for and implemented the construction of the first water treatment plant in the city of Viacha. It is expected that this infrastructure will initiate its operation in the second semester of 2020.

The policy responses implemented during the period 2004–19 spatially located in the urban–industrial region reflect a significant focus on wastewater infrastructure developments in the cities of El Alto and Viacha. The municipality of Viacha is on a good path to resolve the environmental problem related to urban wastewater. However, it is important to note that the volumes of wastewater are proportional to the size of the populations. As



	Monitoring Station	EC µS/cm	OD %	pH -	Fecal Coliforms MPN/100mL
		Class A 0 to 140 Class B 140 to 300 Class C 300 to 500 Class D 500 to 1600 Critical > 1600	Class A >80 Class B 70 to 80 Class C 60 to 70 Class D 50 to 60 Critical < 50	Class A 6.0 to 8.5 Class B 8.5 to 9.0 Critical < 6 y > 9	Class A 0 to 5 Class B 5 to 200 Class C 200 to 1000 Class D 1000 to 5000 Critical > 5000
Seke River	SEK-01	324	99.9	5.16	23
	SEK-03	1188	60.6	8.63	>1100
Seco River	SEC-02	72.6	103.4	7.21	43
	SEC-06	806	60.4	8	>1100

	Monitoring Station	N_T mg/L	NH_3 mg/L	BOD_5 mg O_2/L	COD mg O_2/L
		Class A 0 to 5 Class B 5 to 12 Critical > 12	Class A 0 to 0.05 Class B 0.05 to 1.0 Class C 1.0 to 2.0 Class D 2.0 to 4.0 Critical > 4.0	Class A 0 to 2 Class B 2 to 5 Class C 5 to 20 Class D 20 to 30 Critical > 30	Class A 0 to 5 Class B 5 to 10 Class C 10 to 40 Class 40 to 60 Critical > 60
Seke River	SEK-01	3.2	2.23	62	102
	SEK-03	76	59.94	779	782
Seco River	SEC-02	0.15	0.08	15	9
	SEC-06	55	39.03	335.6	520

Figure 4. Urban–industrial region.

El Alto's population is 10 times larger than Viacha's, the environmental pressure linked to the urban wastewater of El Alto remains the largest urban wastewater problem in the entire Katari hydrological system.

On the other hand, the public policies implemented during the period 2004–19 did not deal with the surface water bodies waste nor with industrial discharges to the urban sewage. Furthermore, the urban solid waste and the land field leach released to the surface water bodies crossing the cities of El Alto and Viacha were also not dealt with. Consequently, the policies were not able to handle the large contamination originated by these types of environmental pressure from region 2.

Region 3: Downstream agricultural area

The third region of the Katari River Basin system is a rural region characterized by agriculture, livestock and dairy production practiced by Aymara indigenous communities. This region is composed of the municipalities of Laja, Pucarani, Puerto Pérez and a rural section of Viacha. Together these three municipalities represent only 6.6% of the total Katari River Basin's population.

The main environmental driving forces identified in the indigenous rural region are linked to agriculture, livestock and dairy production. The environmental pressure consists of diffuse pollution generated by agriculture and livestock waste. However, a comparison of the environmental contamination between the urban–industrial region and the rural–indigenous region shows that the former is certainly the greatest source of pollution. For instance, region 2 shows an increase of 716.85 and 320.25 mg/l of biological oxygen demand at the Seke and Seco rivers, respectively. In comparison, an increase of 6.4 mg/l of BOD5 at the Katari River can be observed in region 3. Similarly, region 2 increases 680 and 511.5 mg/l of chemical oxygen demand at the Seke and Seco rivers, respectively. In comparison, region 3 only increases 12 mg/l of BOD5 at the Katari River. Concerning nutrients, region 2 shows an increase of 60.8 and 54.85 mg/l of total nitrogen in the Seke and Seco rivers, respectively. In comparison, region 3 increases 4.57 mg/l of total nitrogen at the Katari River. At the same time, the urban–industrial region increases 57.21 and 38.95 mg/l of ammonia at the Seke and Seco rivers, respectively. In comparison, agricultural/grazing land use increases 2.02 mg/l of ammonia at the Katari River. Consequently, beyond being an environmental driving force, the indigenous rural region can be qualified as the most socio-environmentally impacted region considering that all the aggregated pollution developed by the mining waste and the urban industrial contamination is delivered to region 3.

The socio-environmental impacts present in this region are not produced locally. Instead, they are caused by exogenous environmental driving forces upstream, as the aggregated pollution comes from the Milluni Valley and urban–industrial regions. There are two specific locations that are highly impacted: the rural communities of Chonchokoro, Kiluyo and Cabaña, and Cohana Bay.

In the medium section of the Katari River Basin, below the cities of El Alto and Viacha, the rural communities of Chonchokoro, Kiluyo and Cabaña are the first impacted social systems. These local communities used the surface water bodies to fish, for agricultural purposes and to process potatoes with an ancestral Andean technique ('*chuño*'[2]). However, the high levels of contamination forced these communities to shift the local livelihood to cattle-raising and dairy production (Gloria Rodrigo et al., 2018). These rural indigenous communities claim that they do not employ river surface waters for any purposes but grazing areas.

The Molecular Biology and Biotechnology Research Institute found elevated concentrations of heavy metals in the local vegetation. Local flora registered elevated concentrations of arsenic, copper and mercury (Gloria Rodrigo et al., 2018), showing evidence of the incorporation of the xenobiotic content in the local food web. Community members recognize that their dairy products are contaminated, and local markets tend to reject their produce. Consequently, they usually hide or change its origin to commercialize them at the local markets. The presence of this type of contamination in the local food web can be also extrapolated to the local drinking water sources. Community members expressed their concern for a potential contamination infiltration towards their local drinking water wells. Due to the composition of contaminants, there is a high risk for the health of the local community:

> you can see the waste waters and totally contaminated. Before, since this river was clear, we used to dehydrate a little of our product [potato], we used to make *chuño*, we carried [our potatoes] to the river and we had good *tuntas*,[3] for our consumption or to sell. Now, in this river there is no fish, there is no *suchi*,[4] there is nothing in this river, is totally contaminated. And now, we poor, drink what infiltrates.(Chonchokoro community member, 73 years old; Gloria Rodrigo et al., 2018, p. 78)

The second group of indigenous rural communities (Cohana Grande, Pampa Cohana, Tacachi and San Pedro) impacted by the Katari River Basin's changes in the environmental state is located at the discharge area known as Cohana Bay. Since these communities are settled in a river delta, historically the local livelihood depended on the diverse and extensive fish populations. However, the large increase of pollution strongly impacted 30 km^2 of Titicaca Lake at this discharge zone (CGEPB, 2014), which produced eutrophic waters (Duwig et al., 2014), heavily limiting the ecosystem's capacity to sustain aquatic life. Consequently, these communities were forced to shift the local livelihood from fisheries to dairy livestock production:

> They even used to come from other islands to fish [Taripe y Surique], they fished with nets. At four in the afternoon they used to launch their nets and at four in the morning they used to get the fish, around 138 to 173 kg.(San Pedro community member, 36 years old; Gloria Rodrigo et al., 2018, p. 78)

Community members observed that the problems of contamination began approximately 15 years ago, and that the contamination has progressively increased, also impacting their new form of livelihood. For instance, the problems of the solid waste carried by the surface water bodies and disposed in this region heavily impact the dairy livestock:

> the animals get sick when eating that, and there is no way to treat that part. For instance, when an animal eats a lot of plastic bags, they remain in the animal stomach and become a braid which stocks the other things that the animal eats and the animal dies.(Pampa Cohana community member, 52 years old; Gloria Rodrigo et al., 2018, p. 78)

There is also evidence of heavy metal presence in surface waters, sediments, soil and the local vegetation holding potential toxic and xenobiotic effects (Gloria Rodrigo et al., 2018). At the same time, elevated concentration of heavy metals such as arsenic, chrome, copper, iron, lead and zinc were observed within Cohana Bay's sediment samples. Even more problematic is the fact that there are alarming concentrations of arsenic, cadmium, lead and mercury within the local vegetation employed by the communities to feed their dairy cattle (CGEPB, 2014). Consequently, these toxicological agents are now present in the local food web, increasing the health risks of the indigenous population consuming these dairy products.

Furthermore, a 2019 study (unpublished) showed evidence of significant microbiological contamination. A total of 95% of the sampled drinking water sources showed evidence of the presence of *Escherichia coli* and total coliforms in the communities settled in this region. The presence of *E. coli* can be linked to gastrointestinal diseases and persistent diarrhoea (Nataro & Kaper, 1998), which is the second cause of mortality in children under five years old, and the leading cause of malnutrition in the same group (World Health Organization (WHO), 2017).

Concerning the policy responses, region 3 is where most responses were developed during the period 2004–19. A total of 33 policy measures were implemented within this rural indigenous region (see Table A1 in the Appendix). From 2006 to 2013, the Titicaca Lake Binational Authority implemented nine policy interventions focused in Cohana Bay. From 2007 to 2013, the State Government of La Paz implemented the Cohana Bay Cleaning Program, which included the development of drinking water infrastructure, deworming of dairy cattle, cattle waste management and the development of sanitation services within the rural communities. In 2010 the Ministry of Water and Environment, in alliance with the Catalan Agency for Development, released the Katari River Basin Management Plan (MMAYA, 2010). However, this plan was not implemented until 2016. From 2018 to 2019, the Katari River Basin Management Unit implemented 11 policy measures located within region 3 and in neighbouring areas. The new river basin management plan developed in 2018 increased the spatial scope to an additional 19 municipalities (Figure 5).

Discussion

Incorporating a spatial assessment within the DPSIR framework allows one (1) to understand the sources reproducing socioecological distress within the Katari River Basin and (2) to unveil that policy responses are implemented without taking such an understanding of source-impact relation into account. The analysis of the Katari River Basin in this way shows that the majority of environmental driving forces and pressures are spatially located in regions 1 and 2 upstream. On the other hand, the majority of policy responses implemented in the past 14 years have been located in region 3 downstream. Consequently, policy response efforts deal with symptoms of the problems only. Regardless of the amount of efforts policymakers invest downstream, if the sources of socioecological distress are not managed upstream, the social and environmental impacts will remain present. Our analysis of the pressure-impact relation in the Katari River Basin confirms previous findings showing how environmental pressures manifest themselves over different social systems. This is even more

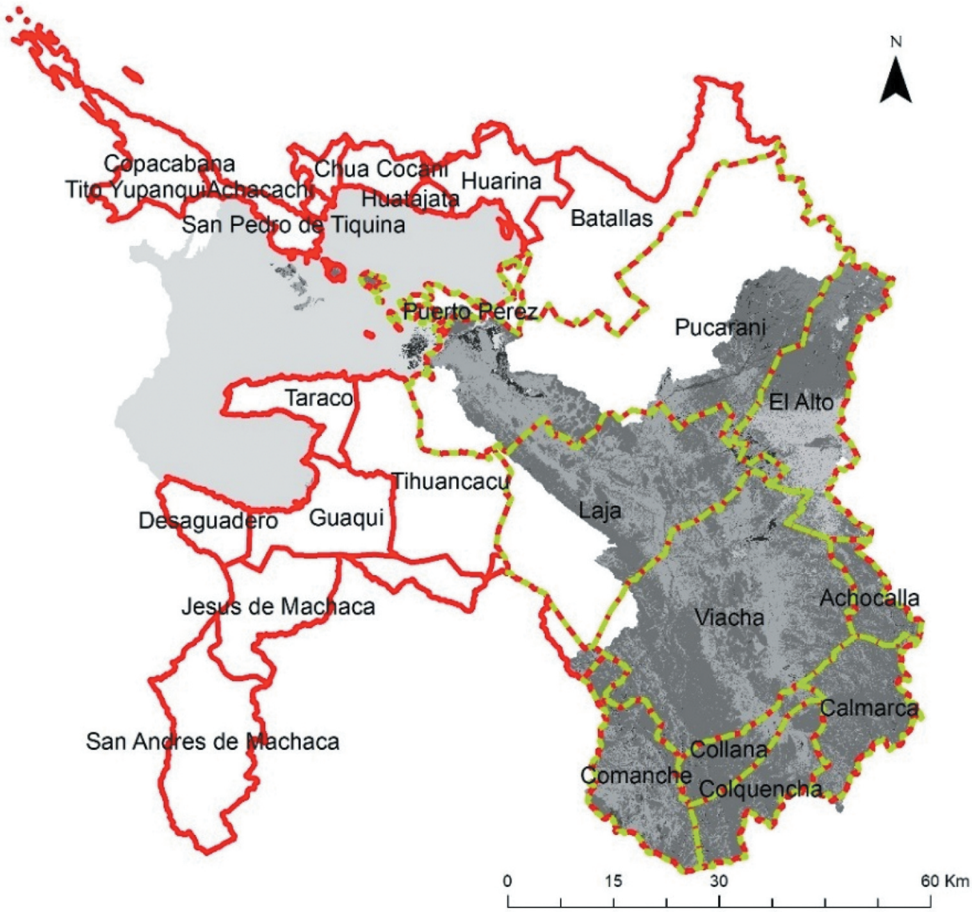


Figure 5. The regions addressed by the 2018 Katari River Basin management plan (red) and the municipalities sharing spatial jurisdiction within the Katari River Basin (green).

evident in large river basins as actions performed upstream have an indirect influence over communities allocated downstream (Anderson et al., 2019). To incorporate a spatial dimension within the DPSIR and the river basin management policy design could thus result in a more effective outcome in terms of the sustainability of these efforts.

The lack of effectiveness in the implementation of river basin policies to manage the environmental pressures visible in the Katari River Basin may also be due to the protagonist role of centralized government policy action at the highest levels. The limited local participation in the policy design and implementation can also be linked to a lack of understanding of the Katari River Basin as a multiscale system. Incorporating a scale assessment in the Katari River Basin DPSIR application shows that the majority of policy responses were designed and implemented by the highest layers of government (Table A1 in the Appendix), within the Lake Titicaca Binational Autonomous Authority, the Ministry of Water and Environment and State Autonomous Government of La Paz.

On the other hand, the Municipal Governments of El Alto and Viacha merely participated in these processes, even though the majority of environmental pressures originated in their jurisdiction.

By neglecting the local scale, fundamental knowledge, values and capacities are excluded. However, they represent a significant resource to design and implement river basin management policies. The multiscale assessment can thus provide greater detail on causal relations. This approach can favour a match between policy responses and the appropriate administrative level, with which local stakeholders, communities, and groups of organizations can relate and act upon. Incorporating the multiscale approach in the DPSIR framework can be an important improvement in terms of river basin management policy since it may enhance both effectiveness and subsidiarity in terms of policy developments and implementation. In the Katari River Basin the participation of the municipal governments of El Alto and Viacha can be considered crucial to solving the social and environmental impacts produced downstream in the hydrological system. Incorporating the scales assessment with the DPSIR allows one to identify key local actors for policy development and implementation which enrich policy responses aiming at sustainable management of the whole socio-environmental system.

The majority of research and studies employing DPSIR tend to assume a causal unidirectional relation of driving forces/pressures and impacts (Svarstad et al., 2008). However, the Katari River Basin shows evidence of more complex relations and the need for a further detailed analysis of this system. A more precise analysis should consider both the direct and indirect, as well as endogenous and exogenous natures of the driving forces category (Leemans & De Groot, 2003). A direct driving force is a factor that unquestionably influences the ecosystem process and that can be clearly identified and measured. On the other hand, an indirect driver can shape the level or degree of change produced by the direct driver. The distinction between endogenous and exogenous nature depends on the decision-making level, as some drivers can be considered endogenous at certain levels of decision-making but exogenous at others.

On the one hand, the Milluni mine's waste can be considered a direct driver based on the abrupt impact over the Milluni dam's water quality, which increases the public health risks and drinking water operation costs for the populations of La Paz and El Alto. On the other hand, the mine waste can be considered an indirect driving force causing a significant social impact towards the local public health and livelihood in rural communities and the ecosystem located in region 3. At the same time, the mining waste problem can also be considered an exogenous driving force in the eyes of local rural communities in region 3 since the management and control of this contamination is out of their local control. However, the same environmental pressure can be classified as an endogenous factor at the national government scale since the Ministry of Water and Environment and the Ministry of Mining and Metallurgy hold legal jurisdiction over these activities.

Furthermore, the impacts over region 3 must be conceived as a causal network (Niemeijer & De Groot, 2008) since they are produced by the aggregated driving forces/pressures located in regions 1 and 2 upstream in the form of acid mine drainage coming from mining waste, urban wastewater contamination, solid waste discharges and industrial contamination. Consequently, solving socioecological problems of rural communities in region 3 demands a detailed analysis of these driving forces networks and the scale at which they operate.

The conventional use of DPSIR applications mostly refers to biophysical environmental aspects of the system which do not always have a direct meaning to the social systems. The literature shows that just a small sample of DPSIR studies considers the socio-economic aspects associated with changes in the environmental functions (Maxim & Spangenberg, 2006). DPSIR applications recognizing the burdens on the social systems may reveal strong links between the social and environmental systems and the fundamental influence of environmental changes over social systems. The incorporation of social aspects within the Katari River Basin's DPSIR application shows evidence not only of effects over the biophysical system but also of fundamental social impacts on the most vulnerable parts of the social system. This impact is manifested in local public health based on the ecotoxicological burden within the food web and the impacts on the livelihood of the indigenous communities. Furthermore, river basin policies conceived from the perspective of environmental justice may allow one to incorporate targets to decrease the social burdens related to changes in the environmental state. This can be an advantage for river basin DPSIR applications to motivate local action and gain legitimacy at local levels.

Conclusions

The DPSIR framework has been widely accepted by academics and practitioners around the world to develop, design, and implement environmental policies and indicators. This research investigated how the incorporation of social and spatial characteristics within the DPSIR framework may influence river basin policy developments. One limitation of this study relies on the indirect analysis of social and spatial characteristics by assessing their current absence within the Katari River Basin's case. Nevertheless, this research offers some important contributions in relation to its inclusion within the DPSIR framework with several practical implications for river basin policy and management purposes.

This research demonstrated that spatial characteristics in the DPSIR analysis provide a better understanding of river basin socio-ecological systems. A spatial analysis allowed us to unveil the mismatch between environmental driving forces/pressures and 14 years of river basin policy responses in the Katari River Basin case study, heavily influencing its effectiveness. Therefore, the inclusion of spatial characteristics to the DPSIR framework might enhance the understanding of links between driving forcers/pressures and policy responses and be useful for river basin policy purposes.

The social characteristics incorporated in the DPSIR framework suggest two main conclusions. First, the implemented scalar analysis showed that the river basin policy was mostly limited to the highest layer of government within the Katari River Basin. The inclusion of this analysis within the DPSIR framework is useful to better understand the levels at which driving forces/pressures are taking place and to match these to the appropriate stakeholders/policy actors' levels within this typology of socio-ecological systems. Furthermore, this scalar analysis may stimulate local participation to take advantage of valuable local knowledge, capacities, and values in the design and implementation of river basin policies.

Second, the assessment of social impacts revealed its limited effectiveness from an environmental justice perspective. The local communities located downstream from the main driving forces and pressures have experienced severe negative impacts on their local livelihood and public health. However, 14 years of policy developments in the Katari River Basin were not sufficiently effective to tackle the sources of pollution influencing these social systems. The DPSIR applications that acknowledge the burdens on the social systems may reveal the links between the social and environmental systems and the fundamental influence of environmental changes on human systems. Finally, river basin policies conceived from the perspective of environmental justice may stimulate the incorporation of targets to decrease the social burdens related to changes in the environmental state.

Notes

1. This agency was created to promote and conduct action programmesand projects, and to develop and monitor the ordering, control and protection regulations for the management of Titicaca lake.
2. Dehydrated potato under an ancestral Andean technique aimed to preserve and store the potato for a long period of time.
3. Dehydrated potato under an ancestral Andean technique aimed to preserve and store the potato for a long period of time.
4. An endemic Andean fish.

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Appendix

Table A1. Policy responses implemented during the period 2004–19.

Period/ year	Actor	Type of measure	Description	Spatial allocation
2006	ALT	Project design	Project for infrastructure aiming to instal aerators to increase levels of oxygen and to harvest the vegetation product of the increase in nutrients at Cohana Bay	Cohana Bay
2007–13	State Government of La Paz	Cohana Bay Cleaning Program	Drinking water wells	Pucarani
			De-worming of cattle	Cohana Bay
			Dairy cattle waste ecological management	Laja
			Eco-sanitation services	Puerto Perez
			Drinking water wells	Laja
			Eco-sanitation services	Cohana Bay
			Eco-sanitation services	Puerto Perez
			Eco-sanitation services	Pucarani
			Eco-sanitation services	Puerto Perez
2007	ALT	Bi-national agreement	Binational agreement for the Recovery, Regeneration and Restoration of Cohana Bay and the Surrounding Areas signed by the Bolivian and Peruvian ministries of Foreign Affairs	Cohana Bay
2007	ALT	Consultancy study	The consultancy contract aims to study the potential use of the plants reproduced by the effect of the eutrophication for animal food	Cohana Bay
2008	ALT	Project implementation	'Mechanical removal of duck weed and watercress at Cohana Bay and Pajchiri'	Cohana Bay
2010	ALT	Project implementation	'Economic development of aquatic vegetation of Lake Titicaca'	Cohana Bay
2011	ALT	Project	'Aerator installation'	Cohana Bay
2012	National Deputy Commission	Inspection	National deputies visited the Cohana Bay and the impacted communities	Cohana Bay
2012	ALT	Project design	'Economic development of aquatic vegetation of Lake Titicaca' project design	Cohana Bay

(*Continued*)

Table A1. (Continued).

Period/ year	Actor	Type of measure	Description	Spatial allocation
2012	ALT	Project proposal	Reduction of pollution in the Cohana Bay based on the harvest of aquatic plants and their transformation into earthworm humus	Cohana Bay
2013	ALT	Project proposal	'Aerator installation'	Cohana Bay
2013	National Deputy Commission	Planning meeting	National deputies coordinated a meeting with authorities and mayors of five municipalities	None
2018	UGCK	Water quality study	Lake Titicaca water quality monitoring	Lake Titicaca
2018	UGCK	Water quality study	Implementation of 12 hydroacoustic probes to assess the aquatic fauna present in the lake	Lake Titicaca
2018	UGCK	Solid waste management	Implementation of solid waste containers in 200 schools, seven solid waste recollection campaigns and 91 road signs installed related to the protection of the environment	Rural indigenous region
2018	UGCK	Environmental protection	Two environmental protection campaigns in local radio stations and two audiovisual productions related to the KRDP	Rural indigenous region
2018	UGCK	Environmental protection	Reforestation	Rural indigenous region
2018	UGCK	Project design	Cohana and Pucarani micro-river basin management programme	Cohana Bay
2018	UGCK	Drinking water	Construction of 186 rain-harvesting systems for drinking water	Cohana Bay
2018	UGCK	Project design	Cohana and Puerto Perez micro-river basin management programme	Cohana Bay
2019	UGCK	Municipal policy development	The UGCK supported 23 municipalities with the development of a municipal regulatory framework for the solid waste management at their local jurisdiction. However, El Alto was excluded	Rural indigenous region
2019	UGCK	Waste solid collection	The UGCK implemented seven campaigns to collect solid waste in diverse regions of the river basin	Rural indigenous region
2019	UGCK	Project design	Livestock waste management in order to reduce the contamination produced by dairy cattle	Rural indigenous region

Note: ALT = Autoridad Bi-Nacional del Lago Titicaca/Titicaca Lake Bi-National Authority; KRBDP = Katari River Basin Director Plan/Plan Director de la Cuenca Katari; UGCK = Unidad de Gestión de la Cuenca Katari/Katari River Basin Management Unit.