Water Science

ScienceDirect

Water Science 32 (2018) 318–337

journal homepage: www.elsevier.com/locate/wsj

Research Article

A DPSIR-analysis of water uses and related water quality issues in the Colombian Alto and Medio Dagua Community Council

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Received 3 May 2017; received in revised form 17 May 2018; accepted 10 June 2018
Available online 9 July 2018

Abstract

A portion of Colombia's water resources is located on the Pacific coast within the territory of the Community Council of Alto and Medio Dagua (CC-AMDA). Though a harmonious balance between the communities' subsistent activities and nature was maintained for centuries, the appearance of modern modes of resource extraction has negatively affected the environment, especially the water resources. The Driver-Pressure-State- Impact-Response (DPSIR) framework was used to analyze water quality problems within this community council. The DPSIR analysis revealed that agriculture, mining, logging and infrastructure development constitute important sectoral drivers with some contribution from tourism and fisheries. Pressures included inputs of organic matter, sediment, nutrients and chemical contaminants to the Dagua river, and to the Bay of Buenaventura. These produced corresponding State changes in the water bodies. Impacts on human welfare were poor public health, reduced food and water security, economic loss and some displacement. Societal Responses included public protests and campaigns, legal actions and policy changes for improved governance. As a future policy option, the formation of community-based water resources management is recommended. Though DPSIR was able to link cause-effect relations, further empirical research on these water bodies is necessary to fill in existing gaps in the data set, particularly for public health threatening contaminants.

Keywords: Alto and Medio Dagua; Colombia; Community-based water resources management; DPSIR; Social–Ecological systems

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Peer review under responsibility of National Water Research Center.

ELSEVIER Production and hosting by Elsevier

https://doi.org/10.1016/j.wsj.2018.06.001

1. Introduction

Colombia has one of the richest fresh water resources in the world with seven hydrographic areas, with the Pacific contributing the highest discharge of water per area, at 0.124 $m^3 s-^1 km^2$, followed by the Amazonas with 0.081 $m^3 s-^1 km^2$ (Sánchez et al., 2010); although the former has a much lower rate of discharge (9.629 $m^3 s-^1$) compared to the latter (27,830 $m^3 s-^1$). In summary, the greatest overall contribution to the country's surface water resources is 27.83%, 19.23% and 9.63% from the Amazonas, Orinoco and Pacific hydrographic areas, respectively (Sánchez et al., 2010). Colombia has sixteen hydro-geological areas composed of various lithological materials containing varying reserves of ground water that cover about 74% of the country's surface area (Rodriguez et al., 2010).

With regard to the fresh water resources, 36% of the surface water is from the Amareles-Dagua hydrographic zone, and 8% of the national ground water reserve is within the Chocó-Pacific hydro geological area. The Pacific coastal waters, of which the Bay of Buenaventura forms a part, also constitute part of the territory's hydrological wealth. The management of part of these water resources is mainly the responsibility of the Afro-Colombian Community Council of Alto and Medio Dagua (CC-AMDA). The Afro-Colombians of CC-AMDA are descendants of Africans, transported to Colombia during the colonial period. They were settled in the Colombian part of the Chocó biogeographic region, in the province of Valle del Cauca, the rural region of the municipality of Buenaventura, along the Pacific coast. This Community Council combines the cultures and traditions of its African ancestry with that of Latin America. The main economic activities are agriculture, wood extraction, artisanal mining and the recently introduced industrial mining, artisanal fishing and tourism. These economic activities as well as recent infrastructure developments, such as road construction, are affecting the water quality of the Dagua river and consequently the Pacific coastal waters, including the Bay of Buenaventura (Avendaño-Uribe et al., 2013). In order to manage the water quality, it is first necessary to identify the causes and consequences of its deterioration. Once the existing water management measures have been evaluated, it may be necessary to either strengthen them or recommend a new policy direction that would enable improvements to the water quality. For this study, a modified Driver-Pressure-State-Impact-Response (DPSIR) framework was used to analyze the water uses and associated water quality issues (Elliott et al., 2017). The research project Community-based Management of Environmental Challenges in Latin America (COMET-LA) focussed on community based models as a response to environmental challenges in Latin America and included the CC-AMDA as a study site. The choice was made based on the review of secondary sources and empirical data from the field, and from discussions with members of the Community.

Council and other stakeholders (Avendaño-Uribe et al., 2013). The main approach of the project was to use Ostrom's Social–Ecological Systems Framework (SESF) (Delgado-Serrano et al., 2015, 2016, 2017a). In the present study, the DPSIR approach was followed to analyze the cause-effect relationship of environmental dysfunction. This supplies pertinent policy recommendations, to create an appropriate community based management model.

1.1. Aim and objectives

The aim of this paper is to define appropriate policy responses that enable the planning and implementation of management alternatives for sustainable use of water resources by the CC-AMDA. The specific objectives consist of identification and analysis of: **(i)** the various socio-economic drivers leading to water quality deterioration; **(ii)** pressures related to the identified drivers; **(iii)** impacts on humans resulting from state change; **(iv)** responses taken to date.

1.2. Research question

The natural resources of CC-AMDA have been providing ecosystem services to local communities for centuries, enabling a harmonious balance between humans and their surrounding environment. However, the recent appearance of modern modes of natural resources extraction such as mechanized gold mining, use of agrochemicals, logging (to satisfy timber demand from cities), and construction of new infrastructure have produced negative impacts on the environment, and most importantly on the water resources (Aguirre et al., 2017).

So the research questions that are addressed in this paper are:

- **Why** has the water quality of aquatic resources in CC-AMDA deteriorated?

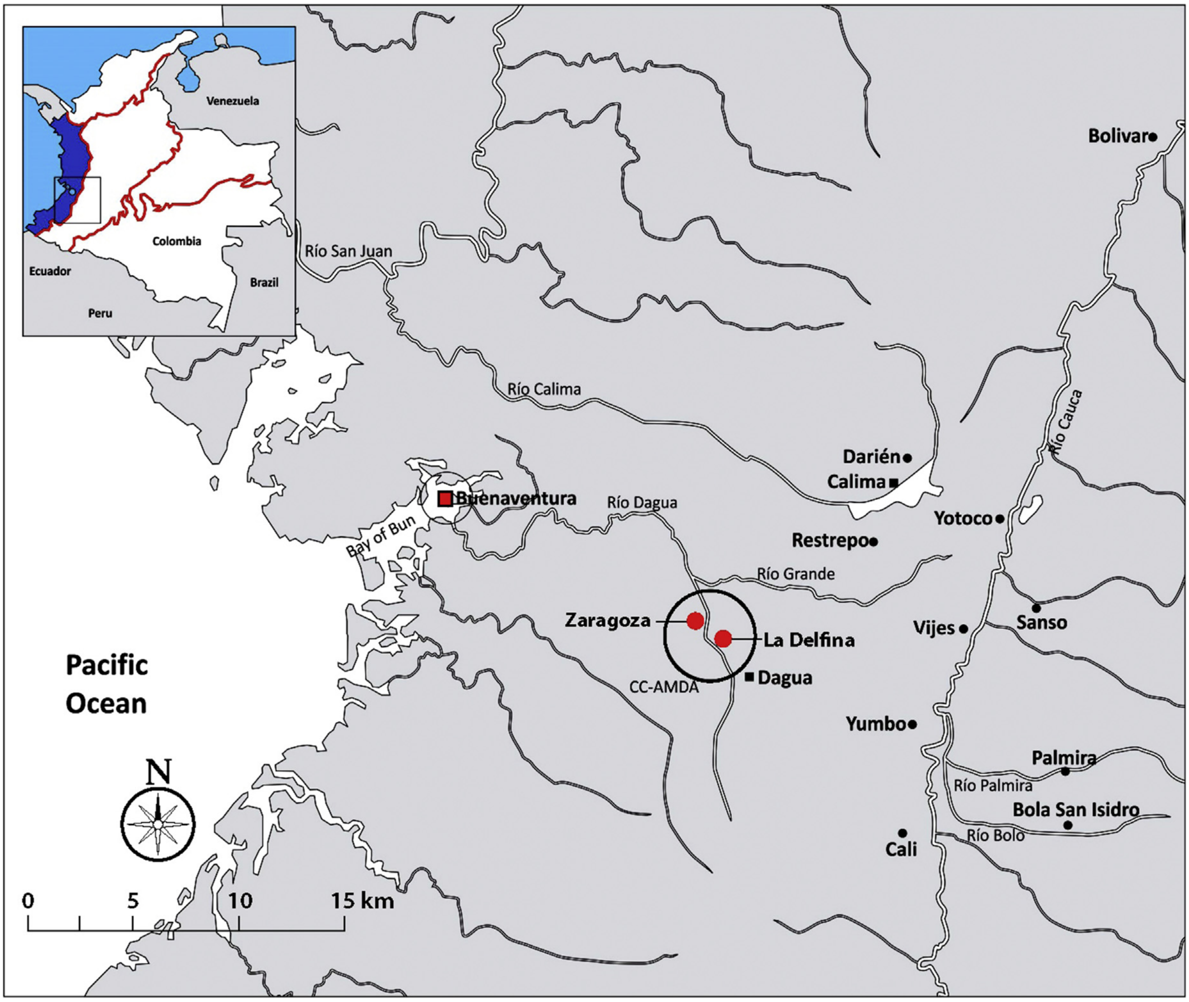

Fig. 1. Map of CC-AMDA (redrawn by Finn, 2015; NILU & by Md Kurshid, 2017; UCA).

- **What** are the economic drivers and consequent pressures that have contributed to the deterioration of water quality?
- **How** does the water quality deterioration impact the community?
- **How** can the water quality be improved?

2. Methods

2.1. Study area/system definition

Social–Ecological systems (SESs) are defined as complex systems integrated with social and ecological subsystems, in which diverse organized human and ecological nodes permanently interact (Berkes et al., 2003; Janssen et al., 2006; Becker, 2011). In the context of this study, The CC-AMDA is part of a Social-Ecological system where the boundaries are determined by the distance to which local inhabitants will travel to use their natural resources, including water (Farah-Quijano et al., 2012).

CC-AMDA is located in the upper and middle basin of the Dagua River in the rural part of the municipality of Buenaventura, in the province of Valle del Cauca, the Chocó biogeographic region of Colombia (Fig. 1). The Dagua River Basin is the most important water source for the ecosystem in Valle del Cauca (Aguirre et al., 2017). CC-AMDA has six communities occupying an area of 9423 ha. Two of these communities, Zaragoza and La Delfina are the focus of this study. Zaragoza consists of 106 households and a total population of 495 inhabitants, and La Delfina has 99

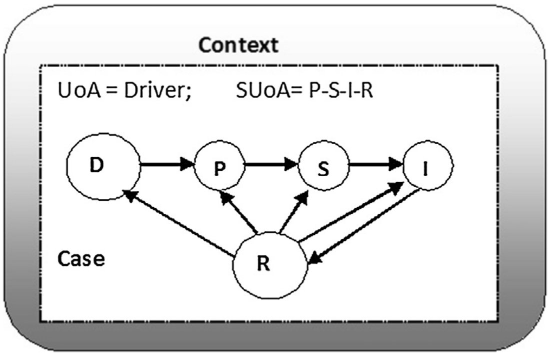

Fig. 2. Case study design; based on Yin (2009).

households and a total population of 395 inhabitants. The economic activities in this community council range from agriculture through fishing to mining.

Geologically the Chocó-Pacific hydrogeologic area is composed of transitional and fluvial sediments of the quaternary period located at the banks of the Rivers Atrato, Baudo and San Juan, and covers an area of 3.2 million km^2 (Rodriguez et al., 2010). These sedimentary rocks include limestones, siltstones, mudstones and sandstones. The same source further explains that the aquifers are unconfined, sedimentary formation with a depth of 800 m, having a total reserve of about 439,000 Mm^3 of water. There is a north-northeast depression in the hydrogeologic area, possibly influencing the direction of water flow.

Apart from the aquifers, the water resources in CC-AMDA include rain, springs and tributaries for surface drainage. Dagua River is the most important surface water resource for this Community Council. The river, from its source in the Andean highlands of the Valle del Cauca province to its mouth in the Pacific ocean (CVC, 2007), covers a drainage basin of 1700 km^2 and produces an annual discharge of 3970 Mm^3 (Restrepo and Kjerfve, 2000). Further, the aquatic resources include more than 15 tributaries (Álvarez et al., 2010). The Bay of Buenaventura is included in this study as it is directly connected with the Dagua river, thereby, constituting an important system boundary.

Though data on the amount of ground water used in CC-AMDA is not available, about 412 Mm^3 of ground water is used per year in the province of Valle del Cauca; out of which 383.9 Mm^3 (93.17%) is for agriculture, 19.61 Mm^3 (4.75%) for industry and 8.6 Mm^3 (2.08%) for domestic purposes (Rodriguez et al., 2010). These figures could potentially provide an indication of the use of ground water by the rural communities of CC-AMDA.

2.2. DPSIR

The DPSIR framework has evolved from Stress-Response (S_R) framework since 1979 (Friend and Rapport, 1991) through Pressure-State-Response (P-S-R) (OECD, 1993) to DPSIR framework (EEA, 1995). The framework has been extensively used for analyzing environmental problems emanating from human activities (e.g. OECD, 1993; EEA, 1995; Bidone and Lacerda, 2003; Elliott, 2002; Karageorgis et al., 2006; Borja et al., 2006; Haase and Nuissi, 2007; Bell, 2012; Kagalou et al., 2012). The framework integrates natural, social and economic information (Bidone and Lacerda, 2003) and facilitates the integration of conservation functions and socio-economic development (Caeiro et al., 2004). It also helps to identify what policy direction to follow that enhances the sustainable utilization and appropriate management of water resources. The tool has also been criticized for its simplistic uni-directionality, among others. Nevertheless, the present study has attempted to rectify some of its shortcomings such as uni-directionality by following a multiple DPSIR cycle approach recently suggested by Elliott et al., (2017). In line with an adaptive nature of the framework it is still in evolution (Elliott et al., 2017). Therefore, DPSIR, in its present form and using multiple DPSIR cycles, can be used as an analytical framework for linking data from the CC-AMDA with the proposition that anthropogenic activities have contributed to the deterioration of water quality in CC-AMDA. Fig. 2 shows that the Unit of Analysis (UoA) is the human-ecosystem interaction expressed as the Driver (D). The other elements of DPSIR (Pressure, State change, Impact and Response) are considered sub units of the analysis (SUoA) as they are consequences of the Driver in the chain, thereby enhancing the insight into the case study (Yin, 2009). The bigger rounded rectangle represents the case study, whereas the dashed line represents the indistinct boundary between the

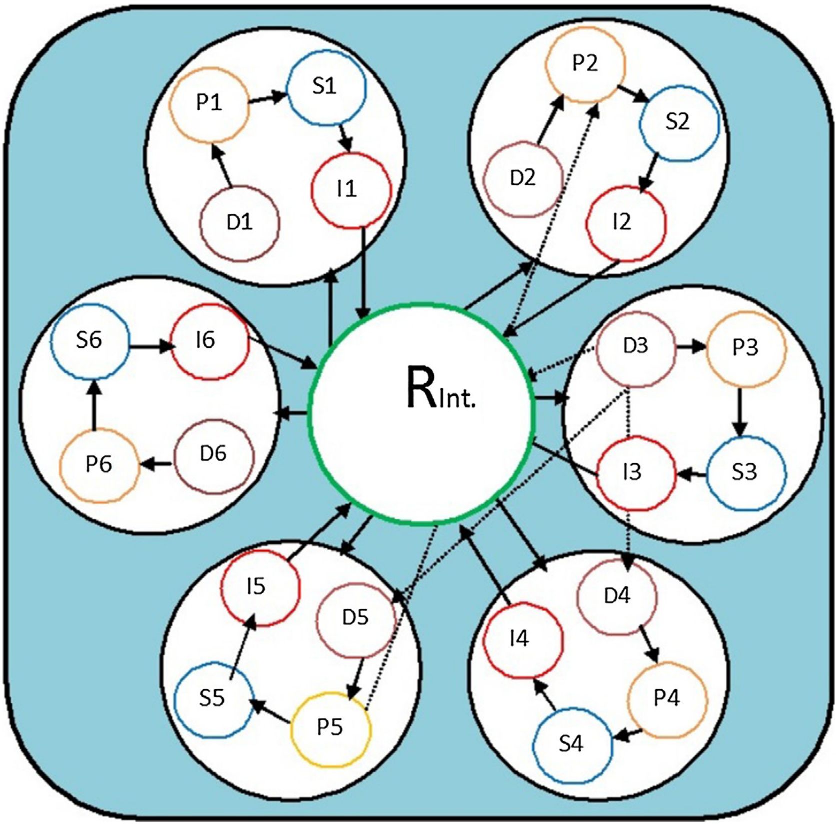

Fig. 3. Conceptual representation of multiple DPSIR cycles; based on Atkins et al. (2011) and Smith et al. (2014). D1–D5 refer to drivers 1–5. P1–P2 refer to pressures 1–5. And the rest of the categories do the same.

case and its context. The case is the water quality issue and the context is the socio-economic–ecological interactions associated with water use. "D" and "R" are represented by bigger circles to indicate their direct connection with the two research questions. "D" answers *why* the water quality of the studied water bodies has deteriorated and the "R" answers *how* it can be improved.

The variety of information gathered from documents, interviews, observations and survey data related to water quality issue were analyzed using DPSIR. In general the EEA (2003) definition of DPSIR is followed. However, in agreement with the suggestions from previous works (e.g. ELME, 2007; Cooper, 2012; Elliott et al., 2017) the impact refers only to human welfare, and the impact on the environment has been moved to the State category. Due to the presence of multiple drivers, multiple DPSIR cycles were used (Fig. 3). This approach helps describe and quantify (if sufficient means are available) interactions among multiple drivers and pressures (dashed arrows).

Additionally, this approach helps overcome the uni-directionality of the DPSIR analysis by showing the interactions between categories. Furthermore, it facilitates the adoption of an integrated response (Rint.), directed at one or more categories of the DPSIR framework,which are indicated by a single arrow each.

2.3. Literature study

The information used for identifying the drivers, pressures, state change, impact and previous responses in this study is largely secondary data from the national hydrology institute (IDEAM) and the regional environment authority (CVC). Deliverables of the COMET-LA project and other literary sources were also used. Generally a wide variety of published and grey literature supplied information for the case study (Table 1). Except for legal documents belonging to the government such as Laws (ley) and Decrees (decreto) promulgatedby the *Presidencia de la Republica* (1974–2010; Presidencia de la Republica de Colombia, 2008, 2010), which date back to the 1970s, the data used for this study were published between 1990 and 2017.

Table 1
Sources of information.

Source of information	Drivers: Econmic sectors and activities	Pressures	State	Impacts on human welfare	Response	Legal/policy/ resource management issues	Social, economic & natural resource issues
Books	X	X	X			X	X
CVC docs.			X		X	X	
Com.Council docs.	X				X	X	X
Deliverables	X					X	X
Government docs.						X	
IDEAM docs.	X	X	X			X	X
Interviews	X		X	X	X		
Journals	X	X	X	X			
News papers	X			X	X		
Survey data	X	X	X	X	X		
Observations	X	X	X		X		

2.4. Interview, observation and survey

A semi structured, focused interview consisting of 23 open ended questions was conducted in a 2-day field trip to the communities in July 2013. In line with essentially a qualitative research method, interviews were conducted in Zaragoza to data saturation point whereby no additional information related to the water quality issue was obtained. Triangulated with observations, literature study and surveys, the saturation point in Zaragoza was 8 households and this served as a basis to determine the sample size of interviewees in La Delfina, which has closely comparable demographic and economic situation. But to be on the safe side, 2 more interviews were included in both villages beyond the saturation point. Those who are actively involving now, and had actively involved in the past in the productive system, and had lived in the area for more than five years were included in the interview. Those who are neither involving nor had involved in the productive system due to age and other reasons, as well as those residing in the villages for less than five years were not included. The informants were briefed on the aims of the study and their consent was sought and obtained. Ten household representatives were interviewed from each village representing about 10% of the households in the village. Whereas the individual households were selected randomly, the general strategy was to cover the entire village and to achieve a broad representation in terms of sex, age and occupation. There was a good gender ballance where most of the respondents under the age of 60 (Table 2), indicating that all of them were productive citizens. The proportion of uneducated community members is higher in both villages. The questions started with the respondent's economic activities (i.e. Drivers) and then covered water resources, water use and cost, water quality and sanitation, and health issues. During the visits, observations were also made of facilities for rain water harvesting, water storage and sanitary conditions, as well as the economic activities in the villages.

A survey was also conducted with the participants of the stakeholders' forum organized by the COMET-LA project in Buenaventura (July 2013). It comprised of representatives of community and public organizations', researchers, different professionals and students. Prior to the survey, a letter briefing the objectives of the survey and requesting collaboration was distributed to the participants. With their full consent 23 people were questioned. The gender proportion of the respondents was fifteen males to eight females. The analysis made was for the whole of CC-AMDA. The analysis was completed for CC-AMDA, represented by the two villages of Zaragoza and La Delfina. From the literature study (CC-AMDA, 2012a,b) and survey responses, it was established that the other four villages of CC-AMDA were similar for social, cultural, economic and management aspects.

3. Results

3.1. Drivers

According to the interviews conducted in La Delfina and Zaragoza, a survey made among the stakeholders' forum participants in Buenaventura, as well as previous works (Avendaño-Uribe et al., 2013; Farah-Quijano et al., 2012;

Table 2
Composition of respondents.

Community council		AMDA				
Village		La Delfina		Zaragoza		Total (%)
Sex	Male	4	40%	5	50%	45
	Female	6	60%	5	50%	55
Age structure	18–30	4	40%	3	30%	35
	31–40	–	–	2	20%	10
	41–50	3	30%	3	30%	30
	51–60	2	20%	2	20%	20
	61–70	2	20%	–	–	10
Education	None	2	20%	2	20%	20
	Primary	4	40%	5	50%	45
	Secondary	2	20%	0	0%	10
	College	2	20%	3	30%	25
Occupation	Farmer	1	10%	–	–	5
	Small scale trader	2	20%	0	–	10
	Miner	–	–	–	–	–
	Student	3	30%	1	10%	20
	Mixed (Farmer/Miner)	2	20%	5	50%	35
	No work	2	20%	3	30%	25
	Other	–	–	1	10%	5

CC-AMDA, 2012b; Ortiz-Guerrero et al., 2014), the main socio-economic drivers identified in the focused SES of CC-AMDA are agriculture, logging, gold mining, fisheries, infrastructure development and tourism.

Agriculture is generally the most important economic sector. But villages within the same council may attach different significance to different sectors. For example, the village of Zaragoza attaches more importance to mining than the village of La Delfina (Interviews, 2013). It should be noted, however, that a community engages in multiple economic activities at different seasons so that a clear categorization of individuals with specific occupations becomes difficult.

Furthermore, there are interactions among socio-economic drivers. For example, infrastructure development facilitates growth in tourism and timber extraction activities. At the same time, it increases road transportation with the consequent increase in air and water pollution. Paradoxically, it also facilitates communication among social groups and encourages collective action for improving social and environmental conditions.

3.1.1. *Agriculture*

Approximately 167 families in CC-AMDA are involved in agriculture, growing over 25 types of fruits and vegetables (Farah-Quijano et al., 2012). Subsistent agriculture in the community council is practiced at three levels: family plots, farm plots and hills (CC-AMDA, 2012b). Fruits and vegetables are cultivated on family plots and there are small sheds for the juvenile chicken and pigs, and tanks for juvenile fish. Farm plots are poly- cropping fields combining agro-forestry, crops and medicinal plants, as well as monoculture farms cultivating different types of fruits and tubers. These farmlands were originally along the banks of Dagua, but due to the pressure from mechanized mining and road construction, they have had to move to higher grounds (CC-AMDA, 2012b). The hill plots are used for poly-cropping and agro-forestry, and are also inhabited by wild animals. Eighty percent of the farm plots consist of poly-cropping farming, with sizes ranging from less than one to five hectares, whereas the hilly areas have 43% of the land for hunting, wood extraction, reeds and medicinal plants (CC-AMDA, 2012b).

3.1.2. *Mining*

Though gold mining has been practiced at an artisanal level since pre-Colombian times, the introduction of mechanized mining since 2009 represents a recent and important driver of environmental change. According to the report by the Colombian miners' association, Colombia produced about 34,300 kg of gold in 2008 (WRM, 2011). Similar figures have been reported by WGA (2011) showing that the Colombian gold production increased from 21 ton in the year 2000 to 27 ton in 2009, with an estimate for a further increase to 32 ton in 2010. About 50% of the country´s gold is produced by 200,000 small-scale miners (Siegel, 2011).

The Dagua river is known as a centre for small scale gold mining. In CC-AMDA, about 10% of the working population uses three days or more per week for mining activities, but in the last few years' immigration of outsiders to the community, especially to Zaragoza, has increased the number of people involved in gold mining to 26% (CC-AMDA, 2012b). According to Morales (2012), 1207 ha of land was designated in CC-AMDA for mining. Furthermore, since 2009 the mechanized mining occurred along the Dagua river, culminating with 234 excavators and 50 dredging machines within a stretch of only 6 km, and accompanied by an increase in the number of inhabitants from 2100 to 4800 (Lasso et al., 2011). Indeed, entrepreneurs from cities like Cali, Medellin and Bogotá were attracted to this gold rush along the Dagua river increasing the population from a 100 local families to 10,000 fortune hunters (WRM, 2011). Activities include digging sediment from the river bed and banks, resuspending sediment and using substances such as mercury and cyanide for gold extraction.

3.1.3. Logging

The illegal trade of timber in CC-AMDA is caused by the current market demand for construction and household needs, coupled with having only a few economic alternatives (CC-AMDA, 2012b). This is despite the Community Council´s formal control over the territory and timber extraction.

3.1.4. Tourism

Tourism is an emergent activity, which has not yet developed to a significant level. In CC-AMDA about 23 families were engaged in this activity (Farah-Quijano et al., 2012). It consisted of sales of traditional products like coconut and sugar-cane drink, or provision of services such as food sales, assistance in trips for bathing, assistance for access to site toilets, parking and car wash (CC-AMDA, 2012b).

3.1.5. Infrastructure development

Infrastructure development in the region is growing, especially because law 1617/2013 has highlighted Buenaventura as a special industrial port sector, biodiverse and eco-touristic district. The construction of the two-way asphalted highway from Santiago de Cali to Buenaventura has resulted in a range of pressures on the Dagua river including the deposition of rubble and sediment, resulting in observable impacts on the ecosystem. Further pressures have resulted from the rise in population from the increase in the numbers of construction workers.

There is also a forthcoming project for the construction of an oil pipeline that will cross the collective territories. The oil supply is expected to meet the needs of the port area, but the process of construction of this macro-project will affect CC-AMDA (Farah-Quijano et al., 2012). There are plans for the progressive expansion of the port infrastructure of Buenaventura which will also affect the rivers that run through Community Councils. The port of Buenaventura is the largest on the Pacific coast of Colombia and important for trade with Asia.

3.1.6. Fisheries

Fishing is artisanal based on line fishing with hooks or on nets (CC-AMDA, 2012b). Although fishing is essentially for subsistence, it is one of the most important protein sources for the community (Avendaño-Uribe et al., 2013), so that food security depends on this activity. Fresh water species such as *Agnostomous monticola, Brycon Meeki, Pseudocurimata lineopunctata* are fished along the different parts of the river and *Chaetostoma marginatum* are fished along the coast (Lasso et al., 2011). The activity involves the use of net for catching the fish.

3.2. Pressures

The Colombian chemical record (ONUDI-MADS, 2012) reveals that in the year 2007; 219 types of pesticides and 28 types of fertilizers were produced and imported into Colombia constituting 28.4% and 3.6% of the total chemicals in the country respectively. Further, 282,433 ton of pesticides and 20,766,959 ton of fertilizers were used (ONUDI-MADS, 2012). Fertilizer consumption in Colombia is 441.71 kg/ha (FAO, 2010).

The coastal and marine waters monitoring report by INVEMAR (2005) stated that organo-chlorine pesticides were not used for agriculture along the Chocó Pacific coast between 2001–2005. Nonetheless, despite the absence of historical records about these chemicals, monitoring done by INVEMAR (2005) revealed their presence at a few

Table 3
Water quality status of Dagua river and the bay of Buenaventura for non-consumptive uses.

Criterion	Dagua river	Bay of Buenaventura	Standard	
			1° contact	2° contact
Bacterial contamination (TC,FC)	8000–9100 MPN/100 ml (TC) (INVEMAR, 2012)	>1000 MPN/100 ml (TC)	TC < 1000	TC < 5000
		>200 MPN/100 ml (FC) (GLA, 2008)	FC < 200 (national standard)	FC < 1000 (national standard)
Organic contamination	Low = 83% Medium = 15% High = 2% (GLA, 2012a)	No data	Organic contamination index 0.2– 0.4 = low >0.4 to 0.6 = medium >0.6 to 0.8 = high (national standard)	
Nutrient contamination	1.6–2.05 mg/l DIN 0.28 mg/l PO_4 (INVEMAR, 2012)	No data	>0.02 mg/l P: eutrophic (national standard) N standard unavailable	
Mercury contamination	<0.2 ppm (sediment) (Álvarez, 2010)	0.01–0.018 ppm (water column)	0.5 mg/kg (fishing products) (national standard)	
		0–0.198 ppm (algae) (Ospina and Peña, 2004)	Algal and sediment standards unavailable	
	1.36 ppm (bivalves) (Alvarez, 2013a)	0.4 ppm (sediment) (Álvarez, 2010)		

locations, which was attributed to the release of the chemicals to combat malaria, and by loggers to control insects rather than by farmers. If the use of agrochemicals is low in the Chocó region in general, its use in CC-AMDA is probably lower.

However, in recent years, different types of agro chemicals are being used in the Valle del Cauca, including nitrogenous and phosphate fertilizers, persistent and mobile herbicides and pesticides containing amides, carbamates and diuron (Páez, 2011). Data on the amount of agrochemicals used in CC-AMDA is unknown. There is also fumigation of illicit crops releasing substantial concentrations of Glyphosate into the air and ultimately into the aquatic ecosystem (Sánchez-Garzoli and Schafer, 2012). Associated with artisanal gold mining is the use of Mercury. For each gram of gold mined, 13–14 g of mercury is used (Restrepo, 2015) releasing into the environment much more quantity of mercury than the gold produced.

In 2005, Dagua river, released polluted water equivalent to 3.6 ton of biological oxygen demand (BOD), 0.73 ton of total nitrogen (TN), 0.41 ton of total phosphorus (TP), and about 36 ton of suspended solids (SS) per day to the Pacific coast (INVEMAR, 2005). INVEMAR (2012) reported an increase in the release of the above substances between 2005 and 2012. For example, in 2011 the releases of polluted water (as BOD), dissolved inorganic nitrogen (DIN), phosphate and SS were 14.5 ton, 8.71 ton, 3.01 ton and 131.5 ton per day respectively. This can be attributed to an increase in economic activities such as agriculture (nutrient release), gold mining and logging (sediment release), tourism and population increase (domestic waste release). INVEMAR (2012) reported that due to mining activities, the contribution of suspended solids from the Dagua river was higher than had been recorded historically. Waste water was identified as the priority health problem in the community, associated with epidemics of water borne diseases (WBD).

3.3. State

Table 3 relates the values for water quality from the Dagua river and the Bay of Buenaventura with the standards for non-domestic uses of water.

a Dagua river

Water quality monitoring done by the CVC on Dagua river between 2006 and 2012 (Álvarez, 2006; Alvarez, 2007; CVC, 2007; GLA, 2008, 2009, 2010, 2011, 2012a), at six monitoring stations with a biannual sampling frequency (72 samples in total), showed values of drinking water of 64%, 33% and 3% for good, medium and low quality, respectively.

Whilst 55% of the water for agriculture could be used for the majority of the crops, only 45% was suitable for crops requiring high quality water. With respect to organic contamination, 83%, 15% and 2% showed values of low, medium and high contamination, respectively. On the other hand, the monitoring of the Dagua river reported by INVEMAR (2012) between 2001 and 2012, revealed that total coliform (TC) concentration exceeded the standard (for secondary contact) of 5000 MPN/100 ml both during rainy and dry seasons. Historically, the coliform concentration of this river has been the highest in Valle del Cauca with an average TC concentration of 9100 MPN/100 ml in the wet season and 8000 MPN/100 ml in the dry season (INVEMAR, 2012). This is in line with the increasing population that the mining activity attracted along the rivers thereby increasing the volume of domestic waste. Consequently, the Dagua river does not meet some of the national standards stipulated by decree 1594/1984. For example, with the current load of TC, the water quality is unsuitable for both primary (swimming) and secondary (boating) contacts, and the water needs appropriate treatment for human consumption and irrigation.

With respect to nutrients, INVEMAR (2012) reported that the river had a dissolved inorganic nitrogen (DIN) concentration of 2.05 mg/l in the wet season of 2012, and 1.6 mg/l in the dry season of 2011. The phosphate concentration was 0.28 mg/l during the rainy season. But this pattern is not always apparent at all stations, with, for example, a DIN concentrations ranging between 1.5 mg/l and 2 mg/l in the dry season and a lower value of 1 mg/l in the wet season (INVEMAR, 2012). Generally, the monitoring done by the same institution between 2001 and 2012 recorded mean DIN concentrations ranging between 1.3 mg/l and 1.5 mg/l. This indicates that the river is among the important contributors of nutrients (N, P) to the coastal areas owing to the direct discharge of untreated domestic waste.

The Dagua river has been contaminated by mining, resulting in modifications to the water flow, siltation of temporary puddles and deterioration of the river banks (Lasso et al., 2011; Gutierrez et al., 2012). The estimates for mercury from the sediment in Dagua river between 1998–2010 revealed an average concentration of less than 0.2 mg/kg (Álvarez, 2010). A recent work by Alvarez (2013a) estimated a mean concentration of 1.36 mg/kg for mercury in bivalves from the Dagua river, which is a value almost three times higher than the standard legal limits of 0.5 mg/kg for fish products (Resolution 776/2008). Likewise, De Miguel et al. (2014) indicated that mercury concentration in fish ranged from 0.026 to 3.3 mg/kg arising from artisanal gold mining in Colombia. The same authors further state that the mercury concentration in fish of Valle del Cauca ranged from 0.16 to 0.5 mg/kg.

Perafan et al. summarized the changes caused by mining in the rivers as follows: reduction and even loss of river flow, low oxygen, organic pollution from oil and grease originating in the drilling machines, increasing concentration of mercury, cyanide and harmful solid waste. Other sources of sediment have been logging-induced deforestation and excavation of the river banks that increased the sediment load and caused modifications in the river flow (Lasso et al., 2011). These disturbances also contributed to the reduction in the fish stock of the river.

- Bay of Buenaventura

Water quality monitoring was conducted by CVC between 2000 and 2011, in the Bay of Buenaventura, at 30 sampling points with a biannual sampling frequency. In total 720 samples were taken in twelve years, the analysis of which revealed the deterioration of the water quality in the Bay of Buenaventura. For example, out of 192 samples collected from eight sampling points near the access canal to the port and the built-up area near the Cascajal island, on the average, 84% were below the standard for primary contact due to total coliforms, whereas 52% of the samples exhibited abundance of total coliforms that made the water unsuitable for secondary contact (GLA, 2012b). In general, the inner part of the bay closer to the urban centers was suitable neither for primary nor secondary contacts due to the direct release of untreated domestic waste and a low flushing rate (Alvarez, 2013b). As recently as 2013, almost all the samples analyzed for coliforms revealed the bay to be unsuitable for both primary and secondary contacts (Ospina and Peña, 2004).

Ospina and Peña (2004) further stated that the mercury concentration in the water column of the Bay of Buenaventura ranged between 0.001 and 0.018 ppm, and in algal species the accumulation ranged between 0 and 0.198 ppm. The same source asserted that the mercury concentration had increased 22 times between 1995 and 2002. Álvarez (2010) in its monitoring report of the sediments in the Bay of Buenaventura in 1998–2010 indicated that the maximum mercury concentration was 0.4 mg/kg, which is lower than the contamination standard (1 mg/kg) set by the environment protection agency (EPA). On the other hand, Siegel (2011) stated that the mercury concentration in the Bay of Buenaventura was three times higher than the standard. However, data on mercury concentration from mining was not available.

- Ground water

Data on the quantity and hydro-chemistry of ground water in CC-AMDA was not available. This calls for an inventory of ground water sources and a study on their hydro-geological and hydro-chemical characteristics.

3.4. Impacts

Socio-economic impacts

Parts of the river and the bay are unsuitable for primary and secondary contacts due to high bacterial load. This has both a social and an economic impact by denying the local communities recreational activities such as swimming and boating and by reducing the quality of the environmental conditions for tourism and fishing.

Fumigation of illicit crops using the chemical Glyphosate causes water pollution and affects non-target food crops, without achieving its desired goal of eradicating illicit crops (Meza, 1999; Walsh and Sánchez-Garzoli, 2008; Youngers and Walsh, 2010). As fishing in this territory is for subsistence, the communities' welfare regarding food security is compromised due to water pollution. Moreover, according to Perafan et al., pollution of some rivers flowing into the Pacific coast had affected the fish stock in the bay so that fishermen needed to travel further offshore, incurring increased costs. The combination of the use of Glyphosate to control illicit crops; mercury and heavy machinery in gold mining had changed the river´s ecological status leading to a rapid decline of fish population and producing a socio-economic impact reflected in the loss of fishing catch and revenues, loss of fishing jobs and a threat to food security (Farah-Quijano et al., 2012).

Plots of farm lands have been pushed further back from the river by excavation for gold extraction. For example only 27% of the farm plots along the river bank remained while the rest had been destroyed by excavation for gold (CC-AMDA, 2012b). In Zaragoza more than 60 ha of quality valley farm lands were destroyed in one year (CC-AMDA, 2012b). This resulted in a socio-economic and cultural impact expressed as a threat to food security as access to food basics was more costly, and interruption of traditional agricultural practices was forced upon the communities (Farah-Quijano et al., 2012).

Public health impacts

The unsuitability of parts of the two water bodies for primary and secondary contacts due to the high bacterial load has affected the health of the community whose livelihood is associated with these water bodies. Pathogens in domestic waste water have been the cause of water-borne diseases affecting the public health (Avendaño-Uribe et al., 2013). Indeed, the World fact book places Colombia in the list of countries with high risk of water borne diseases (CIA, 2005).

European Commission (2002) classifies Glyphosate as non-carcinogenic and non-genotoxic but associates it with some degree of short and long term reproductive, liver and gastro intestinal toxicity. Glyphosate, while being vindicated of its harm by its producers and some authors (WHO, 1994; Monsato, 2002, Farmer et al., 2005), it is blamed by others for being toxic to humans (Richard et al., 2005; Song et al., 2012). Reports from Afro-Colombian community groups indicate widespread skin, respiratory, and gastrointestinal problems after fumigations take place (Sánchez-Garzoli and Schafer, 2012). In addition to Glyphosate, mercury poisoning of humans and other fauna has been observed (Perafán et al., 2013).

3.5. Responses

Before proceeding with responses, a brief description of the legal and institutional background regarding water policy both at the national and regional level is necessary. This helps to identify the mismatch between policy and implementation that is affecting the water quality of the aquatic resources in CC-AMDA. Table 4 summarizes some of the legal and institutional entities responsible for water governance in Colombia.

Water governance at the national level

The history of legislation on water and the environment in Colombia dates back to the 1930s when Regional Autonomous Corporations (RACs) were set up (CVC, 2012a). Though a sanitation code in the form of decree 1371 of 1953 was made for the regulation of waste water, the first most important measure taken by the government regarding water management was the creation in 1954, of the *Corporacion autonoma Regional del Valle del Cauca* (CVC) to manage land and water (CVC, 2012a). In the subsequent years, about 33 regional authorities – RACs – were formed to manage water resources at a regional level. The National Institute for Renewable Natural Resources and Environment

Table 4
Legal and institutional frameworks on water in Colombia.

Legislation	Function	Implementing institution
Constitution Article 49	Health & sanitation development.	Government
Constitution Article 366	Potable water & sanitation development.	Government
Decrto 2811 de 1974	Management of renewable natural resources	MESD[a]
Decreto 1541 de 1978	Management of fresh waters	MESD, MoH[b], RAC
Decreto 1594 de 1984 (3930 de 2010)	Management of the quality of all types of water	MESD, MoH, SGC[c],
Decreto 1875 de 1979	Prevention of marine contamination n	DIMAR[d]
Ley 99 de 1993	Creation & empowerment of MESD	Government
Decreto 1575 de 2007	Management of WQ for human consumption	MESD, MoH, SPRS[e]
Policy 3810 de 2014	Rural water supply and basic sanitation	VASP[f]

[a] Ministry of Environment and Sustainable Development.
[b] Ministry of Health.
[c] Servicio Geologico Colombiano.
[d] Dirreccion Maritima y Portuaria.
[e] Super–intendancy of Public and Residential Services.
[f] Vice ministerio de Agua y Saneamiento Basico.

(INDERENA) was established in 1968 and subsequently transformed into the Ministry of Environment and Sustainable Development (MESD, 2014).

The environment and water bodies in Colombia are given legal protection through several laws and decrees. The Colombian constitution highlights the development of potable water and sanitation. Health and environmental sanitation are part of the government's obligation (Article 49) to ensure potable water supply and public health (Article 366). Decree 1541/1978 refers to the management of fresh water with the objectives of fulfilling the principle stated in the national code of natural renewable resources (Decree 2811/1974), which is the use of resources for human, economic and social development. Decree 1594/1984, later significantly revised by decree 3930/2010, is concerned with the quality of surface, ground, and estuarine, marine and waste waters. The water quality guideline under Chapter 4 of this decree serves as a basis for decision making concerning the regulation and determination of the physico-chemical and bacteriological characteristics of the water sources for human consumption, agriculture, livestock, recreation and preservation of fauna and flora. Similarly, decree 1875/1979 dictates the norms for the prevention of marine contamination. All the decrees and laws were promulgated between 1974 and 2014 (Table 4).

At the regional level, RACs are the highest authorities concerning the environment. For example, CVC, one of the RACs, has the responsibility of monitoring water and imposing sanctions for infractions of the law; it can go as far as confiscating materials harmful to water resources. With respect to water quality for human consumption, the health secretariats are responsible for ensuring the provision of potable water (Law 1575 of 2007).

Water governance in CC-AMDA

In CC-AMDA, the Community Council has the power to manage water. This power emanates from article 13 of the national constitution, which protects the rights of discriminated and marginalized groups. Law 70 of 1993 respects the rights of the black community and attributes collective ownership of virgin lands occupied by them in the Pacific basin (Congreso de Colombia, 1993). Decree 1745 of 1995, which implements the creation of community councils, enables the Community Council to make rules on its territory to administer, utilize and protect natural resources.

Therefore, the Community Council can establish its own internal rules at the community level with the approval of the general assembly. For example, industrial mining, wood extraction, commercial hunting, the use of herbicides, dynamite and chemicals are prohibited in CC-AMDA (Farah-Quijano et al., 2012). External institutions can contribute to the enforcement of the internal rules of the Community Council. For example, the CVC may confiscate illegally extracted materials (e.g. timber, animals). The municipality of Buenaventura can close illegal mining enterprises. The government prohibits cultivation of illicit crops and will eradicate wherever they are identified. Thus, the Community Council has links, and interacts with various government, as well as public institutions and non-governmental organizations-NGOs (Fig. 4).

Fig. 4. Governance and stakeholders' map.

3.5.1. Past responses

Public responses

Different responses to the corresponding drivers, pressures or impacts are already in place. For example, in CC-AMDA, various organizations came together in 2010 to protest against the destruction of forests and the rivers by logging, mining and other development activities. This resulted in a social emergency declaration calling for raised awareness of damage to the natural environment (OPT, 2013).

Institutional responses

A concerted action was called against illegal mining. This led to the conclusion of the Agreement 27/2007 among the Ministry of Mines and Energy, the Ministry of Environment, the Attorney General's office, and the Institute of Mine and Geology (Guttierez et al., 2012). The aim was to design and implement strategies to preventing, detecting and punishing illegal mining throughout the country.

Following the accord, interventions were made into 106 of 173 illegal mining activities, 16 sites were closed and 691 machines were confiscated in 2010 throughout the country (Guttierez et al., 2012). The authors further stated

Table 5
Summary of the results of the six DPSIR cycles conducted for the analysis of water uses and water quality issues within the territory of the CC-AMDA.

No	Driver	Pressure	State	Impact	Response
1	Agriculture	Nutrients	Nutrient concentration/eutrophication	Food and water security	*Previous responses*
		Glyphosate	Water pollution	Human health Food & water security	Legislation, legal action, public campaign and protest
2	Mining	Mercury, sediment	Mercury concentration (metal pollution), turbidity, aquatic biophysical change	Human health, Food and water security Social and economic	
3	Infrastructure development	Sediment	Turbidity, Aquatic biophysical change	Food and water security Social and economic	*Recommendations*
4	Logging	Sediment	Turbidity, Aquatic biophysical change	Food and water security Social and economic	Strengthen implementation power, Establish CBWRM
5	Tourism	Organic pollutants	Coliform load, BOD	Human health Social & economic	
6	Fisheries	Organic pollutants	Coliform load, BOD	Human health Social & economic	

that in 2011, while the general attorney's office reported 1042 cases of illegal mining and 16 cases of environmental pollution, the Ministry of Environment reported the closure of 78 mining sites.

CVC carried out several inspections of illegal gold mining and observed about 16 excavators along the banks of the middle basin of the Dagua river. The national police aerial inspection revealed the activities of 60 new excavators, and in collaboration, these two governmental entities confiscated three machines and arrested 12 people (B-Cali, 2012). According to the same source, these operations were carried out in the face of attacks by the illegal miners including burying anti vehicle mines along the highways. These measures, however, seem insufficient to the community who claimed that the CVC and the police reacted too late to their call (Guttierez et al., 2012). The scope of the illegal mining in the Afro-Colombian territories has forced the CVC to urge the national government, the police and other administrative bodies of Buenaventura to put an end to the illegal mining activities.

Technical responses

CVC has helped technically with the installation of piped water supply in the village of La Delfina, as well as enabling storage and distribution of rain water (Farah-Quijano et al., 2014). Further measures to avoid the contamination of the water bodies by garbage had been implemented by shop keepers (Table 5).

3.6. Indicators

Indicators are values derived from parameters that provide information about a phenomenon, and they should neither be too numerous, so as to avoid cluttering the overview, nor too few to provide sufficient information (OECD, 1993). The OECD (1993) further elaborates that the selection of indicators depends on policy relevance, analytical soundness and measurability. Developing indicators depends on definition of what one wants to indicate (Gari et al., 2015). Indicators are useful to qualitatively assess the magnitude of Pressures, the extent of State change and the severity of Impacts. Moreover, they help to assess the effectiveness of Responses made by measuring the degree of progress towards management targets (OECD, 1993). This can be achieved by comparing the type and frequency of responses and the change in any one of the DPSIR categories. Last but not least, indicators highlight the type and technological level of drivers.

Based on this, a number of indicators have been proposed in Table 6 for the DPSIR categories. The indicator selection process followed a simple logic that the magnitude of activities is a function of the availability of object of action (e.g. agricultural land, mines), actors (e.g. farmers, miners) and technology (e.g. equipment). That means the magnitude of an activity can be determined by considering the extent (quantity) of the object on which the activity takes place, how many actors are involved in the activity and what type of tool or technology they are using.

4. Discussion

On the basis of the available data, the Dagua river seems to be contaminated by domestic sewage rendering it unsuitable for human consumption. As means of treatment are not available in the community, this is a priority issue for public health. The Bay of Buenaventura is affected by organic pollution, but eutrophication does not appear to be a problem at present. The reports of mercury contamination are inconclusive. Nevertheless, the consideration of potential health effects and the precautionary principle indicate that careful monitoring of mercury in sediments and bivalves should be implemented. So, more research on the Pressures and the resulting State change of this water body is essential.

Good environmental laws regarding water and sanitation are available for CC-AMDA, but the implementation of these laws and regulations are currently insufficient. Moreover, some policy directives are criticized for potentially weakening the traditional robust community based water management systems. For example, Delgado-Serrano et al. (2017b) express their concern over the policy directive 3810/2014 that may undermine the effective governance of Water Users Associations (WUA). Analysis of official plans (Alcaldía de Buenaventura, 2001; Alcaldía de Buenaventura, 2015), the programs of CVC (CVC, 2012b), field visits and workshops with stakeholders, showed that the municipality does not have permanent programs nor does it employ sufficient investment to deal with water issues; actions and programs of public institutions are not coordinated; watershed management plans are not available, and mechanisms do not exist to solve environmental conflicts and social demands regarding water quality and management in Dagua river. In general, available information explores social and ecological issues separately, and proposed policy solutions are too narrow and designed on a micro scale with aim of solving specific issues. As a result, water management in this river can be characterized by a lack of coordination among public institutions, poor communication among stakeholders and public institutions, and absence of permanent action regarding water issues.

Nonetheless, the organization of the community into councils demonstrates that CC-AMDA has the necessary structural arrangements to resolve many of these problems, particularly, with the collaboration of concerned governmental and non- governmental institutions. The establishment of community-based water resources management (CBWRM) based on *WASH* frameworks (UNICEF-GWP, 2014) could ensure safe potable water, including sanitation and hygiene services, that guarantees the future water and health security of the CC-AMDA. This approach has been used effectively by rural communities in other low income countries. The effort will require continued dialogue with the CC-AMDA, as well as seeking a stronger collaboration with other stakeholders. The CBWRM could eventually be up-scaled to a catchment level with the involvement of other communities, adopting a broader scope for protecting the natural water bodies.

The DPSIR framework is useful for linking the water quality deterioration with its causes. Further, responses to the problems have been highlighted. The study includes several drivers, using multiple DPSIR cycles. This approach was an attempt to overcome the problem of uni-directionality of the DPSIR framework and to address several multidirectional interactions. But establishing links between all Drivers and associated Pressures, State changes and Impacts has not been possible due to data limitations. For example, quantitative data on the release of chemicals (mercury, glyphosate), nutrients, sediment and domestic waste in to the water bodies are lacking or insufficient. Data on a state of the water bodies, such as the concentration of substances like metals, and eutrophication are not adequate. Moreover, the specific contribution of the studied villages to the water quality deterioration of Dagua river has not been determined. This necessitates empirical field studies for quantitative determination of the load of contaminants emanating from each village.

However, applying the DPSIR approach to the study area is only a first approach that showes the general picture of the water quality situation in CC-AMDA. Moreover, it highlightes what data should be acquired for a future DPSIR analysis. Broader and regular empirical studies that can produce sufficient quantitative data related to the load and

Table 6
Indicators of the DPSIR framework relative to the water quality of the Dagua river and the bay of Buenaventura.

Economic activities (Drivers)	Indicators				
	Drivers	Pressure	State	Impact	Response
Agriculture	Area of agricultural lands (ha m^2)	Nutrient load (t/d)	Nutrient concentration (mg/l)	Food and water security loss (no. of people affected)	Legislation (no. of acts)
	No. of farmers Type of agriculture (No)	Pesticide load (g/d)	Pesticide concentration (ng/l)		
Mining	No. of mines	Sediment load (t/d)	Turbidity (NTU, JTU, Sechi disc)	Economic loss (monetary units)	Community campaigns (number)
	No. of artisanal miners		Mercury concentration (mg/l – in water column;		Emergency declarations (number)
	No. of industrial miners	Mercury load (g/d)	mg/kg – in bivalves, sediments)		Designing strategies (no. of designs)
	No. of equipments Type of equipments (No)		Reduction in fish stock (biomass – kg/ha)		Legal actions (number)
Logging	No. of timber industries No. of loggers	Sediment load (t/d)	Turbidity (NTU, JTU, Sechi disc)	Social impact (no. of people displaced)	Legislation (no. of acts)
	Type of timber industries (No)		Reduction in fish stock (biomass – kg/ha)		Community campaigns (number) Community actions (number)
Tourism	No. of tourist operators No. of tourists	Organic matter load (BOD load-t/d)	Pollution (BOD – mg/l, coliform load-MPN/100 ml)	Social impact (no. of people unable to enjoy natural water bodies)	Legislation (no. of acts)
Fishery	No. of fishers No. of fishing boats Type of fishing gears (No)	Organic matter load (BOD load-t/d)	Pollution (BOD, mg/l)	Various ailments (no. of people affected)	Legislation (no. of acts)
Infrastructure development	Area of infrastructural development. (km^2) Type of infrastructures (no)	Sediment load (t/d)	Turbidity (NTU, JTU, Sechi disc)	Prevalence of WBD (no. of people affected)	Legislations (no. of acts) Community-actions (number)

concentration of substances are required. Furthermore, both a qualitative and monetary assessment of the social and economic impacts is needed to supply sufficient data to link causes, problems and impacts within the DPSIR framework. A monitoring plan that includes all the relevant parameters should be implemented to evaluate the environmental and ecological status of the water bodies that can then be used as a data source for a future DPSIR analysis.

5. Conclusion and recommendations

Socio-economic activities and their consequences have affected the water quality of Dagua river and the Bay of Buenaventura to various degrees. Particularly domestic waste has made a considerable part of these water bodies unsuitable even for secondary contact. This has an important health implication to the community. Though the water could be adequately treated before it is safe for human consumption, the absence of even the rudimentary treatment system has magnified the health risk. At the present rate of mining and infrastructure development, the biophysical change and chemical contamination of the water bodies is a matter of concern. It is especially important as it poses a threat to the local communities whose livelihoods depend on the natural environment.

Despite data limitations, the DPSIR framework was able to describe cause effect relationship to the extent that data were available. The socio-economic activities led to the water quality deterioration of the Dagua River and the Bay of Buenaventura. Moreover, individual activities responsible for the environmental, social and economic impacts were identified. The impacts on the human welfare were manifested as health, economic and social problems. Though a number of responses were taken to alleviate the impacts, it was not enough, necessitating further strong actions.

To fill the data gap between the various categories of the DPSIR approach, it is necessary to conduct more empirical research on the pressures emanating from socio-economic activities, and on the state of all the water bodies. This helps to create a clearer link between categories in the DPSIR chain. It also illuminates possible interactions among the categories of DPSIR.

Strengthening the executive power of institutions responsible for the sustainable management of the water bodies should be effected by the concerned national, regional and local political authorities. For example, CVC should have a stronger collaboration with the regional government, with the police and the community councils. Besides, both CVC and the police should be quicker to respond. Upgrading the councils' power enabling it to take a stronger legal action against rule breakers is essential. The establishment of a CBWRM could make a substantial contribution to realizing these objectives.

The recommendations are briefly summarized below:

- Effort should be made towards the establishment of the future CBWRM, based on the *WASH* framework. A team of co-researchers recruited from the community council and the researchers of the Pontifica Universidad Javeriana (PUJ) could take an important part in this task.
- The existent water supply and sanitation facilities such as rain water harvesting and sewerage systems should be maintained through cooperation between the Community Council, the municipality, the regional government and NGOs.
- Regular monitoring of Total and Fecal Coliforms and BOD in the water, Mercury in the sediment and bivalves should be implemented by the CVC, especially close to the population centres.

Acknowledgement

This research was supported by the ERASMUS MUNDUS programme EMJD MACOMA, and by the EC 7FP Grant agreement 282845 (COMET-LA, http://www.comet-la.eu).

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