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Research papers

Unravelling and understanding local perceptions of water quality in the Santa basin, Peru

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ABSTRACT

Water quality is an integral part of water security. Measuring the physico-chemical indicators for water quality can provide an objective picture of water health, but it does not provide information on lived experiences related to water quality, expectations of water resources, nor how the quality of water affects its usage. Perceptual information and traditional ecological knowledge on water quality can help to understand interactions between water and people, and thereby support locally appropriate sustainable water resource strategies. Accordingly, our project sought to collect and synthesise insights from local perspectives on water quality in the upper Santa River basin, Peru, a region where water quality directly relates to people's livelihoods. Perceptual data was collected via the Nuestro Rio mobile app ($N = 149$) as well as walking interviews ($n = 84$) (July-August 2021) in two main study areas, Olleros and Catac. We find that water quality perspectives differ within, and between, study areas and communities, however four overarching themes were identified, and are explored here: i) environmental indicators for water quality; ii) water uses; and iii) perceived causes of water quality; iv) water quality perceptions behind emotions. Most rural participants felt the main cause of poor water quality was mineral pollution, likely linked to local geology, however we also found that local perceptions of water quality depend on water usage, directly linked to domestic water use and agricultural livelihoods. Qualitative data highlighted the complex relationships between water quality, perceptions and emotions. More inclusive citizen-based science that considers what people observe, think and feel about the quality of their rivers can help provide a much deeper contextual understanding of dynamic human-water systems, with further benefits for improving water management and policy implementation.

1. Introduction

Good water quality is a precondition for human and ecosystem health and wellbeing, through provision for drinking water, irrigation, industry, recreation and tourism, and wildlife habitat. Under a changing climate, and especially in glacial-melt dependent regions, good water quality can become increasingly scarce, negatively impacting water security (Fortner et al., 2011; Carey et al., 2017; Guittard et al., 2017). As direct users of water resources, local communities can offer a deeper understanding of the socio-ecological context (Okumah et al., 2020) and provide important lived experiences related to water quality, expectations of water resources, and water usability. However, local perceptions and traditional ecological knowledge (TEK) are typically an under-estimated source of water quality information that can both complement physical measurements and improve understanding of the impacts of variable physical water characteristics.

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Due to its multifaceted nature, water quality itself is a complex environmental issue, encapsulating water quality indicators such as pH, clarity, smell and chemical composition. Another characteristic of the complexity of water quality is that a number of determinants are "hidden" from the naked eye (e.g. heavy metal content, temperature and oxygen levels (Flotemersch and Aho, 2021)) and require measurement and analysis in a laboratory or in-situ (e.g. pharmaceutical pollution (Wilkinson et al., 2022)). Comprehensive in-situ assessments of water quality determinants are challenging in many regions due to low accessibility and associated costs, in addition to the demands of sampling/monitoring programmes required to assess temporal and spatial dynamics. Yet, a majority of scientific assessments of water quality revolve around these in-situ assessments, which have their own limitations and biases. Despite the importance of TEK and local perceptions, this knowledge is often neglected or interpreted as too subjective (Reid et al., 2010; Flannery et al, 2020) and currently traditional water quality studies do not provide information on how the human perspective is integrated and expressed.

Water quality is affected by both natural processes as well as anthropogenic processes (e.g. human activities, water use, water governance) (Anderson, 2016; Magnússon et al., 2020). For example, water quality issues can be linked to land and water management, but these factors are not always illuminated when looking purely at physical measurements. However, to use human perceptions as a valid proxy for water quality, these perceptions need to be measured systematically, establish a dialogue with quantitative data where possible, and also be better understood. The relationships between public perceptions and environmental quality, including water quality, are complex because perception is influenced by past experiences, and a variety of individual variables (e.g. socio-cultural and socio-demographic variables), in addition to environmental factors (Steinwender et al., 2008; Okumah et al., 2020). Importantly, perceptions of water quality can differ based on user group, location and between the lay and expert community (Okumah et al., 2020; Flotemersch and Aho, 2021). However, understanding the uniqueness of different communities and stakeholders is needed in addressing the complexity of water resource governance (Stringer et al., 2009; Okumah et al., 2020). Awareness of people's perceptions, understanding and concerns about their local environment can help to improve our scientific communication, and it can also help to evaluate the development and implementation of policies and adaptation strategies (Steinwender et al., 2008) as well as create a sense of responsibility when changes in resource management are necessary.

Therefore, we suggest more interdisciplinary, community-centred approaches to water quality research and water resource management are needed to fully cover all aspects of this multifaceted issue, to facilitate sustainable management of water and to include communities at the core of our scientific understanding. Here, we focus on an Andean mountain region where climate change is affecting the ecosystems, populations and livelihoods, with water quality being one of the ecosystem services most negatively impacted. The aim of this study was to investigate the local perspectives of water quality in our study region, the Santa basin, Peru. Whilst there have been many physical science studies in the region, research is often disconnected from local water users and is conducted through the natural science lens (Dextre et al., 2022). We combined two sources of perceptual data: i) quantitative responses and ratings on perceptions and emotions surveyed in the Nuestro Rio App; and ii) qualitative data from walking interviews providing a more in-depth perspective. Our research enabled us to unravel local perspectives on good and poor water quality, and identify some of the key water quality indicators and concerns of the population themselves based on their knowledge and their direct relationship with water. This research helps to keep bridging the gap between hydrology and social science, and illustrate the importance of increasing and including understandings from the human aspect for sustainable water management.

2. The Santa basin, Peru

2.1. Study region

The location of this study is the Upper Santa River basin, which sits within the Santa basin (11,661.51 km^2) in the Northeast of Peru (ANA, 2015) (Fig. 1). The Santa River and its tributaries provide an essential water supply for the >1.6 million people living along the 300 km river, making the river extremely important for livelihoods in the region (Recharte et al., 2017). The population living in the basin is concentrated within the city of Huaraz and small towns along the Santa River, as well as a widely-dispersed rural population. This region has been well-studied scientifically in the past decade, however mainly from a physical science perspective (Carey, 2005; Carey et al., 2017). The quantity and quality of surface and subsurface water is crucial for communities of the basin for domestic water use, agriculture, and livestock. The strong seasonality of precipitation in the region makes this even more significant, as precipitation is very limited during the dry season (May – September) and during drought events (Morera et al., 2017). Glaciers and wetlands are important sources and contributors of river discharge, especially in the dry season. For example glacier meltwater can contribute 20–30% of river discharge (Mark et al., 2010), but up to 90% of river discharge for the main Andean city of Huaraz during droughts (Chevallier et al., 2011; Buytaert et al., 2017; Schoolmeester et al., 2018). However, climate change and glacier loss are also affecting the quality of water services. Because of the reliance on glacier meltwater, and being situated at higher elevations which are experiencing higher rates of warming (Bradley et al., 2006), rural and upland indigenous communities are most vulnerable to climate change impacts (Rangecroft et al., 2013; Bowling et al. 2021). Furthermore, in many remote rural areas, access to treated water is limited, meaning that poor water quality can significantly negatively affect access to safe water for human consumption, agriculture and livestock.

For this paper we focused on two study areas in the upper Santa basin located on the glaciated western slopes of the Cordillera Blanca mountain range (Fig. 1): i) Olleros study area, which comprised of the Olleros sub-basin and its upstream and downstream populations including part of the Andean communities[1] of Canray Grande and Cordillera Blanca; and ii) Catac study area, which incorporates the sub-basins of the Yanayacu and Pachacoto and its upstream and downstream populations of a part of the Andean community of Catac (Fig. 1). For the purpose of this paper we divided each study area considering the following two aspect: hydrological (sub-basins, location upstream or downstream), and socio-political (e.g. belonging to a town or a rural community).[2] Subsequently, for this research, the Olleros study area contains four different study "communities": i) Olleros upstream, ii) Canray Grande, iii) Cordillera Blanca, iv) Olleros downstream, whilst the Catac study area contains: i) Catac upstream 1, ii) Catac upstream 2, iii) Catac Pastoruri and iv) Catac downstream. Considering the different areas of data collection allows for the important identification of patterns in differences and similarities across the study region and participants.

The dominant landscape in both study areas is that of agro-

[1] In Peru a "Comunidad Campesina" or Peasant community is an autonomous institution recognized by the state in their organisation, communal work and use of their land. They are "integrated by families that inhabit and control certain territories, linked by ancestral, social, economic and cultural ties expressed in the communal property of the land, communal work, mutual aid, democratic government and the development of multisectoral activities" (CEPES, 2018, p. 46). As the peasant communities involved in the study are located in the Andes, we will use the term Andean communities.

[2] The study communities Canray Grande and Cordillera Blanca were created from the peasant communities of the same name, whilst Olleros is the district where they are located. In the case of Catac the territory of the district is similar to the peasant community, so different communities were created according to their hydrological location inside Catac.

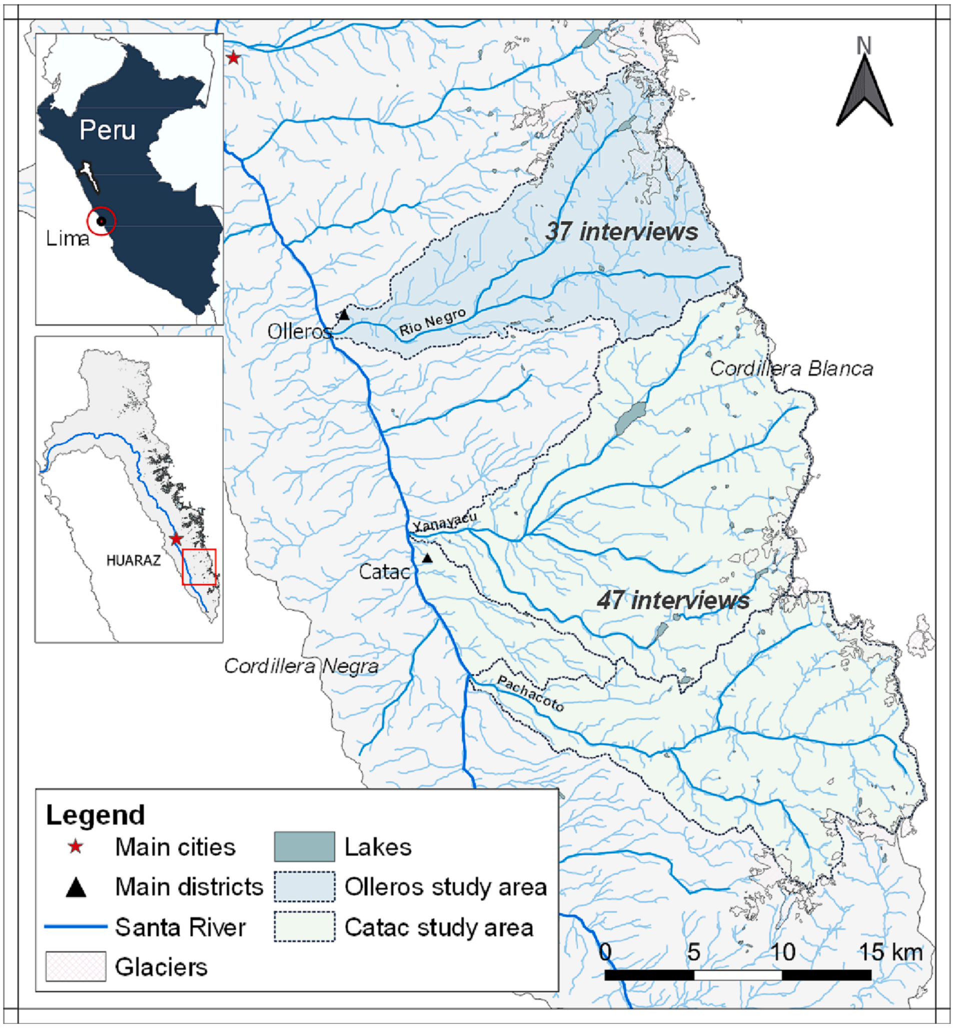

Fig. 1. The overall study region of the upper Santa basin, with two focus study areas of qualitative data collection: Olleros (37 interviews), Catac (47 interview).

biodiverse cropland centred on potatoes and fodder crops, and some forested areas. Land use consists of rain-fed agriculture in the lower zone and cattle and sheep grazing in the upper zone. Above 4,400 m a.s.l. land use is for conservation of wildlife and tourism as a transition zone toward glaciers, wetlands and pristine landscapes as part of the Huascaran National Park (HNP). The three Andean communities mentioned share the lower and narrow cropland zone and the upper and wider rangeland zone. Thus, the main livelihood is raising grazing livestock complemented with subsistence agriculture, except for Catac which has more diversified activities and services, such as tourism. Therefore, the main water uses in the study areas are for human consumption, livestock consumption, crop irrigation and other domestic uses.

2.2. Water quality issues in the Santa basin

Like many other countries, and regions in Peru, the Santa basin faces water quantity and quality problems due to pollution, population growth, climate change, rapid urbanisation and industrialization (e.g. Aylas-Quispe et al., 2021). The availability, useability and use of the water is affected by the complex interrelations of physical, social, political, and cultural factors across multiple spatial and temporal scales (Carey et al., 2014). Existing research has identified a number of water quality issues in the study area, mainly assessed via methodologies from the natural sciences. Water quality in the upper Santa basin is negatively affected by both natural factors and natural sources of contamination (e.g. precipitation, climate, topography, geology, soil erosion, etc) as well as anthropogenic activities (e.g. mining, agriculture, urbanisation, wastewater) (Magnússon et al., 2020). The main pollutants identified typically include heavy and trace metals, which are very harmful due to their toxicity, persistence and possible bioaccumulation and biomagnification in the food chain (Custodio, 2019).

In rural areas of the study region, where access to treated water is limited, many communities in the Santa basin have problems with a phenomenon known as Acid Rock Drainage (ARD), which is the exposure of metal-rich rocks to the atmosphere, causing the entrainment of metals in water bodies, negatively impacting access to safe water for human consumption, agriculture and livestock. ARD in this region is mainly caused by glacial retreat over metal-rich geologies, but also by mining activities (Guittard et al., 2017). Several previous studies have identified poor water quality in a number of sub-basins using natural science methods and data due to ARD (e.g. Cordillera Blanca in the Olleros region, Quillcay in the Huaraz region) (Fortner et al., 2011; Grande et al., 2019). The Rio Negro (Olleros sub-basin, Fig. 1) is known to be a heavily-contaminated river due to ARD processes (Grande et al., 2019). Fortner et al, (2011) coupled geochemically observed poor water quality in the Cordillera Blanca community with the likely exposure of additional sulphide-rich outcrops from ongoing glacial retreat. Low pH values below 4 were measured by this study, which is significantly lower than observed pH measurements for other glacier-fed streams worldwide. Sediment is also known to be a water quality issue for the city of Huaraz (Morera et al., 2013).

3. Methods

3.1. Data collection

Qualitative and quantitative data from participants was collected between April and September 2021 using a mixed-methods design with two elements: 1) structured questionnaires via the Nuestro Rio mobile app; and 2) semi-structured interviews based on the Nuestro Rio app questions. The mobile app "Nuestro Rio" was designed by the research team to collect geospatial data of water quality perceptions, and was launched in April 2021. The Nuestro Rio app questionnaire was designed in Spanish as the most accessible language for the study region (see Supplementary material S1 for the Nuestro Rio app questions in English). The first part of the app survey asked participants to take a geo-referenced photograph of a chosen water body (e.g. river, stream, canal, lake), then to evaluate the water quality on a Likert scale from 1 (very poor) to 5 (very good) and explain why they gave that value. The second half of the survey focused on the participant's emotions about water quality. The survey focussed on five basic human emotions, with a Likert scale for each (1 = Not at all, 5 = Extremely): Anger, Fear, Happiness, Sadness, Surprise (Russell, 1994). Demographic data (age, gender, occupation) was also collected in the questionnaire for all participants. Fieldwork was conducted during July-August 2021 in various districts and communities across the study region to engage participants one-to-one using the mobile app on fieldwork tablets, to help facilitate engagement with the app for those who were not familiar with this kind of technology.

When in the field conducting the survey questionnaire, some participants were simultaneously interviewed, allowing for more in-depth knowledge and perceptions of water quality to be recorded. We followed a non-probabilistic snowball sampling approach as the target population was located in very remote and dispersed areas. The only inclusion criteria for this study was that participants were 18 years of age or older, and with an interest in participating. We adapted the "walking interview" method to our research needs for its flexibility for participants to engage in a way that is sensitive to their local context (Evans and Jones, 2011; King and Woodroffe, 2019).

The walking interviews followed the same structure as the app. Once the research objectives were explained, participants were asked for their informed consent to participate and to record the whole process, from the moment the participant took researchers to their nearest river or stream, until the interview was finished. Where preferred, some interviews were conducted in participant's first language (e.g. Quechua) in order to provide linguistic comfort (Abfalter et al., 2021), thus, an interpreter accompanied the research team during fieldwork, and was a crucial part of the team. To ensure best practice in data collection, the interpreter was trained in the data collection techniques before the fieldwork and when necessary translated responses simultaneously to fill the survey (Rangecroft et al., 2021). All data collected was recorded in its original language (Spanish or Quechua) for transcription, but all Quechua transcripts were then translated into Spanish to ensure one comparable dataset, necessary for data analysis.

It is important to note that this fieldwork was designed and conducted in partnership with organisations that were already building participatory processes with the communities studied. These research partnerships also made it possible to conduct data collection in the second year of the COVID-19 pandemic (2021), when many Andean communities in Peru were still not allowing outsiders to enter their lands. Due to the pandemic, the communal assemblies, which are the spaces where communities normally authorise this type of research action, were not operational, so key gatekeepers of the communities granted permission to research in these communities. Although community authorities had already been informed and had authorised the study in the community, personal consent was also requested during data collection, not only because of the requirements on the UK ethics approval side, but also as a way of showing respect for the participants.

3.2. Data analysis

We recorded a total of 349 data entries on the Nuestro Rio app across the entire study region of the upper Santa basin. However, for our data analysis, we focused on data entries only from the two main study areas (N = 149), Olleros (n = 57) and Catac (n = 92). Quantitative data analysis was conducted on this numerical data from the survey, and qualitative data analysis was conducted only on the interviews (n = 84), of which 37 were from Olleros area and 47 from Catac area. Since participants were simultaneously interviewed whilst filling out the app, Likert scale ratings recorded for water quality assessment and emotion rating (section 3.2.1) were the same in both datasets (app and interviews), but the information obtained through interviews provided the enriched qualitative data for identification of themes through coding (section 3.2.2).

3.2.1. Quantitative data analysis

Likert scale data on participant perception of water quality was obtained firstly in the Nuestro Rio app database. For data analysis, we used descriptive statistics to get an overview over the participants demographic profile and to summarise average water quality perceptions, as well as emotional levels from participants across different communities and study areas. The mode was used to represent the most frequently perceived water quality scale and emotion rating. For water quality, the Likert scale data was then reduced from five water quality categories into three to allow for comprehensive comparison between perceived poor (1 very poor and 2 poor), neutral (3 neutral) and good water quality (4 good and 5 very good). This data is referred to as water quality assessment (WQA) throughout the study. In addition, linear regressions were conducted to analyse how much variance in water quality perceptions can be explained through emotions and demographic variables. Furthermore, the difference in water quality perceptions group means (e.g. gender, age) where possible were tested for statistical significance differences (95% confidence interval) in IBM SPSS v28 (e.g. independent t-test, one-way ANOVA).

3.2.2. Qualitative data analysis

Qualitative data was processed from the 84 interviews collected from both study areas. Interviews were transcribed, and translated from Quechua into Spanish where necessary, for coding. An initial coding frame was established based on the research purposes, and subsequently refined and expanded through an iterative and emergent inductive coding process. Two rounds of coding in the base language (Spanish) were carried out using N-Vivo software, with the aim of reducing coding bias in the analysis (Borda et al., 2007; Salinas Meruane and Cárdenas Castro, 2008) and to obtain more nuanced data categories (Abfalter et al., 2021). Coding of the qualitative data identified themes and patterns regarding: i) environmental indicators for water quality; ii) water uses; iii) perceived causes of water quality; iv) water quality perceptions behind each emotion rated in the survey (see Table 1).

For the purposes of this research, we define an environmental indicator for water quality as both an observable and/or measurable impact on natural resources and social systems, and as the actions that caused these impacts (Heink and Kowarik, 2010). Thus, indicators that express an observable or perceived impact on water quality have been coded separately from indicators that express a cause. Water uses were also classified as a separate coding category as this is important for understanding which factors influence the perception of water quality (Okumah et al., 2020). Emerging information provided by the participants that expressed a reason or motive behind each emotion assessed in the app survey was coded as emotions (Table 1).

Table 1
Results from interview coding (water quality indicators, water uses, perceived causes, emotions).

Main coding theme	Sub-theme	Description
Indicators of water quality	Poor water quality indicators	Bad smell (stinks); yellow or reddish colour; sour & lemon-like taste; dirty sensation; presence of sediment (capers); harmful (to animals, plants, human beings); stains or paints; less quantity of water
	Good water quality indicators	Odourless (does not stink); colourless (clear or crystalline); sweet taste; clean sensation; presence of biota; not harmful; does not stain or colour; good quantity of water; no oxides
	Neutral water quality indicators	Little biota; sometimes dirty; it is natural, but people make it dirty; water quantity varies; it is good for animals, but not for drinking; water is used for irrigation, but not for drinking; it is good for washing, but not for drinking; it comes yellow, dirty; it is a little flawed; it has minerals
Water use	Not useable	Not useable for animals; Not useable for irrigation/crops; Not useable for human consumption/drinking water; Not useable for washing
	Useable	Useable for animals; Useable for irrigation/crops; Useable for human consumption/drinking water; Useable for washing; Aquaculture
Perceived causes of poor water quality	Pollution	Sewage; agrochemicals; litter; presence of minerals; glacial retreat; animal waste
	Governance issues	Inadequate infrastructure; lack of maintenance; limited funding; unwillingness of authorities
	Water source	Wetland; hills; lake; gully
	Social/cultural	Bad habits (e.g. people lack environmental education; people dump their rubbish)
	Other	Wet season; less quantity; without filtration; climate change
Perceived causes of good water quality	Water source	Glacier; lake; gully; spring
	Social/cultural	Good habits (e.g. cleanliness, care of water sources)
	Other	Abundant quantity; filtration
Emotions	Happiness	Reasons behind (e.g. there is enough water; because it is useful/can be used; it is not polluted; because it is pretty & natural; because it tastes sweet)
	Anger	Reasons behind (e.g. not useful for animals or drinking; it tastes bad; it kills crops)
	Fear	Reasons behind (e.g. it is harmful; for the future; because it stains; because it is sour)
	Sadness	Reasons behind (e.g. decrease of the quantity of water; because it isn't useful for irrigation; it isn't useful for human consumption; because it has trash; because it isn't useful for animals; because there are no punishment for mistreating the water; because of the future; for flood risk; because it is changing)
	Surprise	Reasons behind (e.g. change of the colour; because it cannot be used; when it is polluted; when it has minerals; when there is a drought; because it stains the clothes)

4. Results

4.1. Sample characteristics and descriptive statistics

A total of $N = 149$ from two study areas (Catac and Olleros) have been collected via the Nuestro Rio app, of which 55% of the participants identified as female, and 45% as male. The core 50% of our sample were aged between 34 and 61 years of age, with a mean age of 48, a maximum of 87 and a minimum of 18 (the minimum age required for participation). In terms of occupation, a wide range of occupations were indicated, but half of the participants identified with agriculture/livestock (52%). When asked how the water quality of the river or stream in question was (1 = very poor to 5 = very good), using the mode to represent the most common response, overall perception level was positive ($M = 4$, $SD = 1.31$). However, after aggregating the water quality response scale into three condensed categories (1 = poor to 3 = good) to show us the water quality assessment (WQA), the most common response became 1 (47%), reflecting an overall negative perception of water quality compared to 41% of positive impressions for the study areas. On a sample level, participants reported varying levels of negative emotions, with sadness as the strongest negative emotion rated ($M = 4$, $SD = 1.34$), and anger ($M = 1$, $SD = 1.39$) and fear ($M = 1$, $SD = 1.32$) being much lower. Strong positive emotions have also been reported, through happiness ($M = 4$, $SD = 1.55$) and surprise ($M = 4$, $SD = 1.29$).

Using the app data available ($N = 149$), differences in means were statistically analysed to explore significance amongst water quality perceptions with demographic data. No statistically significant differences were found in water quality perceptions (1–5) with gender, age or occupation, or between study areas (see Supplementary Material S2). Differences in water quality perceptions means were observed between communities (explored further in section 4.2, and S2). However, small sample sizes of occupation categories and participants per community limited the statistical analysis for these certain aspects. Finally, adding the demographic variables (gender, age, occupation) to the regression analysis did not explain additional variance.

4.2. Water quality assessments

Average perceptions of water quality have been calculated for the entire study region using the app data (Fig. 2a) as well as for both study areas (Olleros and Catac), and the communities sampled within them using interview data (Fig. 2b and 2c) to understand geographical variation. Local perceptions of water quality, shown through participants' water quality assessments, were found to vary across the study areas, and across different study communities, but some common themes appeared. Across the upper basin, hotspots of perceived poor water quality were identified, such as certain sub-basins (e.g. Pachacoto subbasin in the Catac study area, Fig. 2c), downstream areas (e.g. Olleros downstream, Fig. 2b, Catac downstream, Fig. 2c) and urban areas (e.g. Huaraz city, Fig. 2a, app data). Conversely, hotspots of perceived good water quality were also identified, such as Canray Grande on the northern tributary of the Rio Negro in the Olleros study area (Fig. 2b) and Catac upstream 1 on the tributary in the Yanayacu sub-basin in the Catac study area (Fig. 2c). Overall, a more negative water quality assessment was found for the study area of Catac compared to the Olleros study area. Whilst these quantitative perceptions of water quality identify these geographical patterns, this data alone does not provide insight into why participants rated their water quality this way.

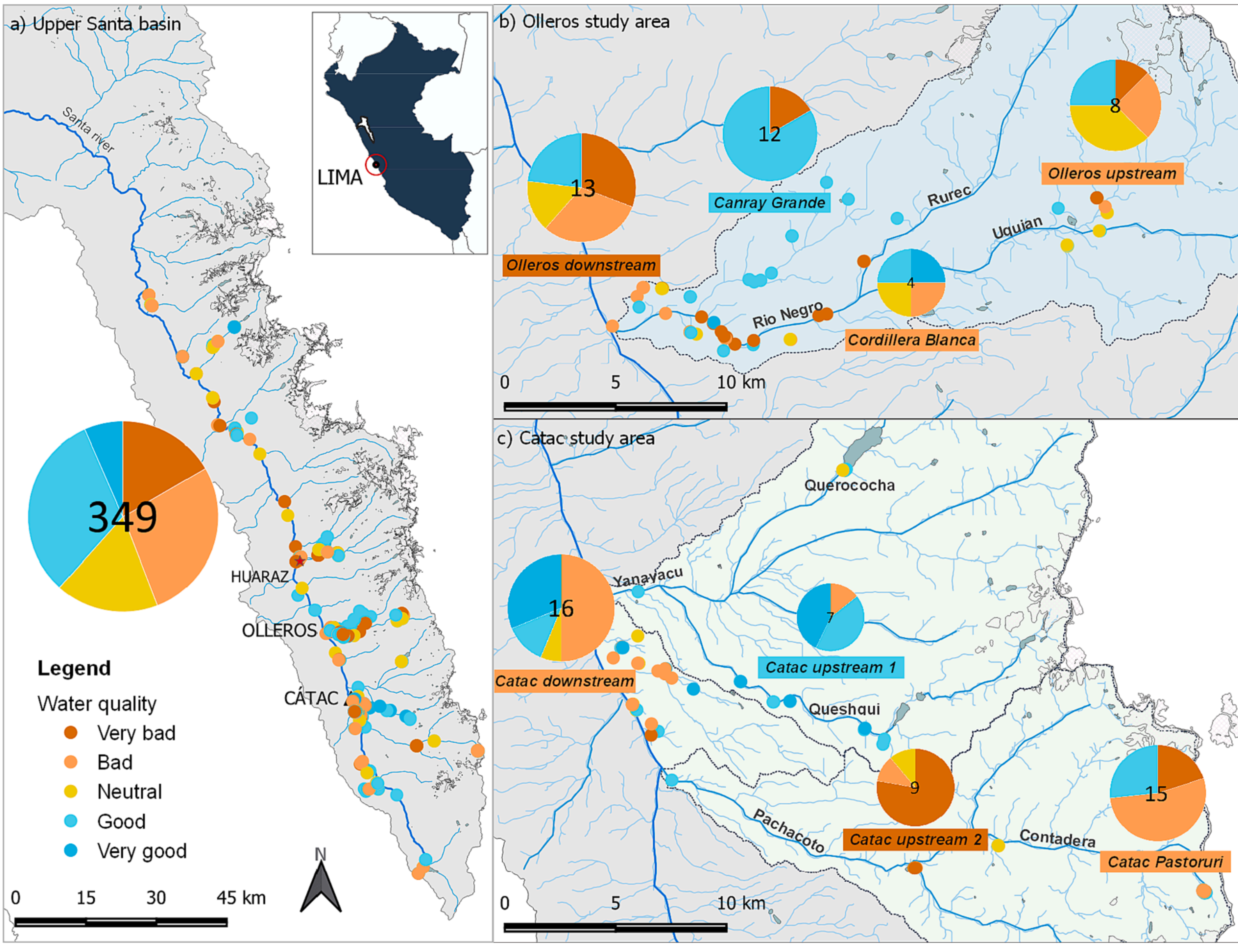

Fig. 2. Water quality perspectives across the study region with pie charts summarising app results (left) and interview study area results (right). a) Overall water quality perspective results across the upper Santa basin from the Nuestro Rio app. Number stated in the centre of the pie chart illustrates the number of data points. 2b) Water quality perspectives from interviews in the Olleros study area, with; 2c) Water quality perspectives from interviews in the Catac study area. Pie chart size and number stated in the centre of each pie chart illustrates the number of interviews.

The qualitative data can support the understanding of these perceptions, similarities and differences further.

4.3. Drivers of water quality perceptions

Coding results from the interview data identified key indicators of poor and good water quality, strong links between water use and water quality, perceived causes behind water quality, and participants' emotions linked to water quality. Findings suggest the dominance of organoleptic properties (e.g. taste, smell, visual) as key indicators of water quality, as well as traditional ecological knowledge (TEK) and water useability. The qualitative data also drew out socio-economic context, and the complex relationship between water quantity and quality, explored further in this section.

4.3.1. Indicators of water quality

Some key indicators of poor and good water quality that correspond to organoleptic properties, water useability and changes observed over the years have been identified from participant responses (Table 1; Fig. 3). Harmfulness, taste and colour were the most common indicators for poor water quality across the two study areas (Fig. 3a). The yellow or reddish colour of the water and staining of items due to the colour, as well as the sour, acidic or "lemon-like" taste of the water were some of the main observable water attributes indicating poor quality. In line with our findings, other studies (e.g. Morales et al., 2020; Okumah et al., 2020) also found that organoleptic properties such as taste, colour, and smell were common indicators of water quality for local populations, with unsuitable water being linked to turbid appearance, unpleasant flavour, metallic smell, a yellowish appearance, and a salty taste (Morales et al., 2020).

On the other hand, indicators of good water quality were mainly associated with the presence of biota in the water, the clear colour of water or the feeling that the water is clean, harmless, and free of oxides (Table 1; Fig. 3b). These key indicators suggest the dependence on direct water use (e.g. harmful and taste) and the importance of visible water quality (e.g. colour, clarity). However, indicators such as the presence of biota and the useability (or lack of) for activities and livelihoods also shows the importance of TEK and insights from participants due to their direct water use and reliance. For the interview participants, agriculture/livestock occupations dominated in the Olleros participants (92%), and nearly half of the Catac participants (43%). We also find that good and poor water quality indicators are also closely associated with the quantity of the water (abundance, or lack of) and the usefulness of water (explored further in section 4.3.2) (Table 1).

In the Catac study area, the knowledge or perception of the water being harmful was the main indicator, and was strongly associated with organoleptic properties such as the sensation that the water is dirty, has a sour taste and a dyeing effect on objects (Fig. 3a). Similarly, the colour of the water was the most common indicator of poor water quality in the Olleros study region, as well as the taste and harmfulness of the water (Fig. 3a):

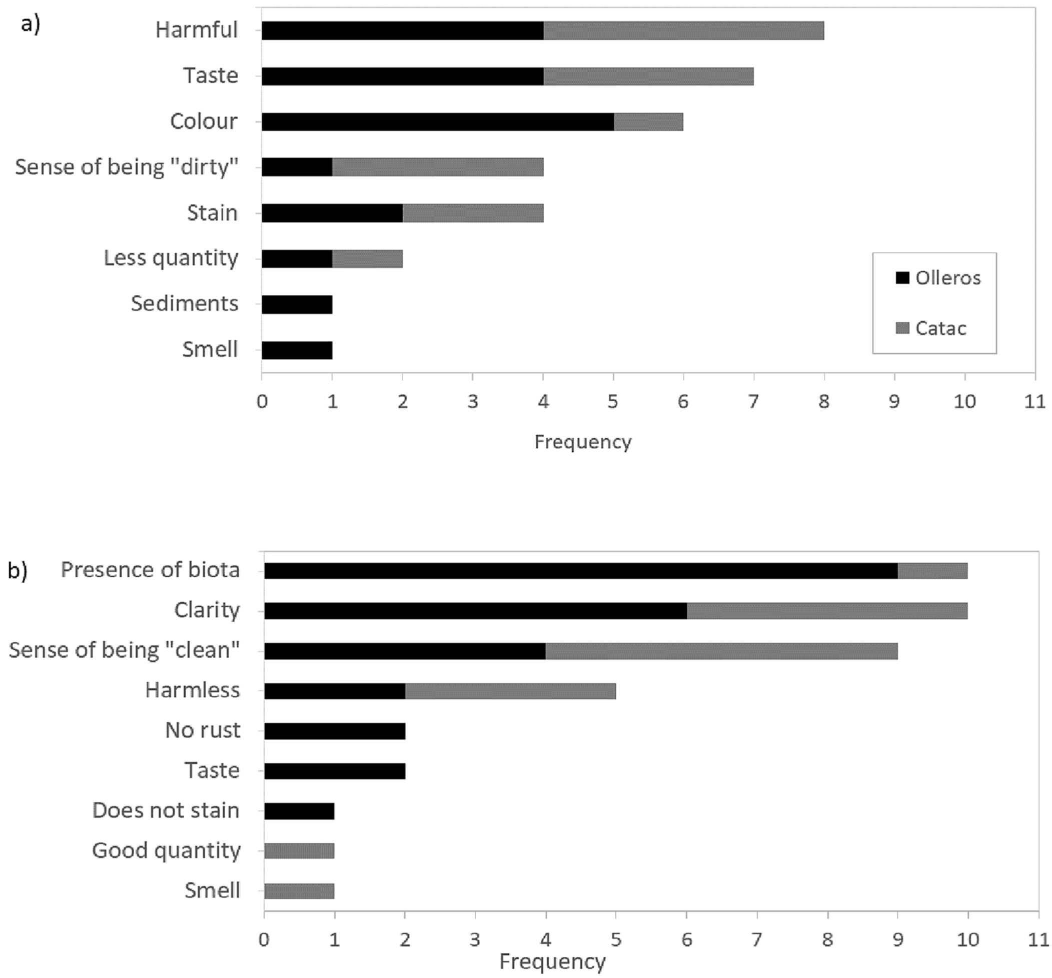

Fig. 3. Perceived indicators of a) poor water quality and b) good water quality based on frequency of references made in interview data for both Olleros (black) and Catac (grey).

> *"...Everything is yellowish. When we wash, it also leaves everything yellow, it stains [the clothes]. But before it wasn't like that, now little by little everything is turning yellow." (OLL06, Canray Grande, July 1, 2021)*
>
> *"Bad, very bad, look yellow it comes out. It is very sour, it stinks and the animals do not drink this water either. When we water, it is also killed by the barley, the pastures, what we sow … It is not suitable for the kitchen, for washing clothes, it stains, it is useless. When you cook, it's also like thick gelatin, yellow, it stains the bucket, it stains the pot, it's very ugly." (OLL33, Olleros downstream, July 6, 2021)*
>
> *"When you hang [the clothes] it was white, but when it is drying it turns yellow. [untranscribable] and when we cook, there are times when it sits like cocoa at the bottom, when [the] water boils it stays like cocoa in the pot." (OLL27, Cordillera Blanca, July 5, 2021)*

In both study areas the indicators of good water quality were mainly associated with the observation of either animals or plants present in the water (e.g. trout, ducks), the clear colour of water (clarity), and the perception that the water is clean, harmless, and free of oxides (Fig. 3b). The presence of biota was much more common as an indicator in the Olleros study region, e.g. *"This is good water. It brings trout, everything; it brings quite a lot of trout" (OLL09, Canray Grande, July 2, 2021).*

4.3.2. Water use

Local perceptions suggested a strong relationship between water uses and perceived water quality. Human consumption was a key indicator of water quality, with "not usable for human consumption" often indicating poor water quality and "usable for human consumption" often indicating good water quality (Fig. 4; Table 1). This is likely to be strongly linked to the lack of water treatment available to these communities, and their direct water use for everyday life and their livelihoods. Other indicators of poor water quality were linked to its inability for use for animals, irrigation and washing, mainly in the Olleros study area (Fig. 4). Conversely, the usability of the water for different activities (e.g. animals, irrigation, washing, bathing) were stated by participants as reasons for good water quality (Fig. 4). The useability of water also lends itself to be an explaining factor for neutral water quality perceptions, for example, water that was dirty but still considered useable. In both study areas there is a priority of the population to use water for both human and animal consumption, even more than for irrigation. This shows the close relationship between the main livelihoods of the population and water, as livestock is the main economic activity in the study area:

> *"Well, animals can consume, but it's also how can I tell you; it has several defects that can affect animals because of the fact that it has a lot of, a lot of minerals that is rust, so it's not healthy as claimed." (CA09, Catac Pastoruri, July 31 2021)*
>
> *"… This water is clean, it is not contaminated, the water is clean. There are times when the animals drink water when it is clean." (CA03, Catac downstream, July 31 2021)*

4.3.3. Perceived causes

Our research found that the most common perceived cause of poor

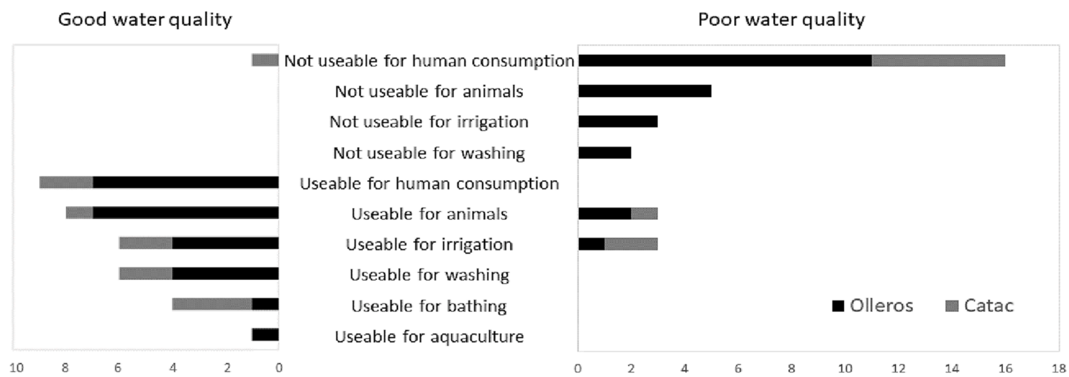

Fig. 4. Water uses for good and poor water quality. Frequency of references in qualitative data from interviews for both Olleros (black) and Catac (grey).

water quality across the two study areas was pollution, specifically due to the presence of minerals (Fig. 5a). It is evident from this data that rural communities in the study regions are aware of the presence of minerals or soils, and that it strongly impacts their sense of water quality. In the Olleros study area, nearly 80% of the references to causes of poor water quality were associated with pollution, of which nearly half are due to the presence of minerals in the water or soil. Other causes included pollution from glacial retreat, pollution from sewage (grey-water discharge), presence of rubbish in water bodies, and animal waste (animal excrement, animals tread in water) (Fig. 5). Although not as common, there were also responses which associated the perceived poor water quality to the source of the water:

> *"Right now, this river is getting a little bad because of the capers, but it used to be a little purer water. Now there are oxides coming out of different parts of the river and that is why it is deteriorating. From the same corner of the gully, from the lake that comes out, the water is still pure. But in the course of the water that comes from different streams it is contaminated." (OLL21, Olleros upstream, July 5, 2021).*

A similar pattern was observed in the Catac study area where perceptions around the main reasons for poor water quality were also associated with pollution (Fig. 5a). Of the responses mentioning pollution, 35% due to animal waste (animal excrement, animals tread water) and 35% name the presence of minerals in the water or soil:

> *"For me it is very bad because this water contains a lot of oxide, a lot of minerals come from the hills and at first glance you can see that there is a lot of oxide, since it stains the stones, the grasses, it kills the herbs that are growing. And besides, when you drink water here, even a Mate tastes ugly, that is, it tastes like metal, something like that." (CA35, Catac Pastoruri, July 31 2021)*

However, in Catac, after pollution, governance issues such as lack of maintenance, inadequate infrastructure, limited funding, and unwillingness of authorities, was the second main perceived cause of poor water quality, and more frequent than in Olleros. Bad habits of the population were also mentioned as a perceived cause in the Catac study area:

> *"They throw rubbish, anything goes in. As you can see, everything is changing, there is no improvement of the canal. It is wasted, abandoned here in Carpa by the herds, there is no improvement of the canals and neither the municipality nor anything else is coming." (CA05, Catac upstream 2, July 31, 2021).*
> *"Because there is no support to make canals, we need a budget so that there is maintenance, cleaning, so that it doesn't get dirty." (CA28, Catac upstream 2, July 31 2021).*

Our data on perceived causes of good water quality showed that for the study areas, abundant water quantity was an important reason for good water quality, as well as the source of the water (Fig. 5b). Participants from the community of Cordillera Blanca (Olleros) perceived the pre-filtration of the water, either natural or with human intervention (phytoremediation systems) as a cause of good water quality, which could be linked to the recent bioremediation wetlands in this region (Zimmer et al., 2018). In the Catac study area, the main cause of good water quality perceived by participants is related to the water source (e.g. glacier, lake, spring), as well as abundant quantity of water, and good habits of the population (Fig. 5b):

> *"Because mostly here the water that comes from the lakes is protected by the Huascaran National Park and there are people who look after it … And apart from that there is orientation, there are people who guide the people and the visitors so that they don't pollute, so that they don't throw rubbish away." (CA10, Catac Pastoruri, July 31 2021).*

The data suggests that water quantity (abundant or not) is intrinsically linked to both positive and negative water quality assessments (explored further in section 4.3.4) as it is perceived as a cause for both poor and good water quality (Fig. 5), as well as a cause for neutral water quality assessments. Other causes associated with neutral water quality perceptions were related to the physical environment and a temporal context. For example in the Olleros upstream community, a participant in the Uquian stream stated that water quality is *"sometimes bad, sometimes good"* (OLL22, Olleros upstream, July 5 2021).

4.3.4. Emotions and water quality

The link between water quality and emotion was another main theme coded (Table 1). Linear regression with the Nuestro Rio app sample ($N = 151$) illustrated that emotions explained a lot of the variance in participant's water quality perceptions ($R^2 = 0.59, p < 0.001$). It is interesting to note here that happiness ($b = 0.36, p > 0.001$) and sadness ($b = -0.32, p > 0.001$), as well as fear ($b = -0.15, p > 0.05$), came out as significant model predictors, whilst anger and surprise did not. Adding demographics (i.e. gender and age) did not significantly improve the regression model. However, with the interview data it was possible to deepen the understanding of this relationship, beyond the rating scale used in the app to measure the intensity of each emotion raised, allowing us to unravel the reasons or motives behind each emotion related to water quality, and identify new emerging emotions. The qualitative data from the interviews showed a much more complex situation where emotion, water use, water quantity, concerns and local governance all emerged to complicate this potentially strong relationship.

Sadness was the most frequent emotion mentioned within the interview data (Fig. 6), especially in the study area of Catac whose participants associated a higher proportion of a feeling of sadness with the decrease in the quantity of water (31%), followed by the glacier retreat (15%) and the lack of respect and care for the population (12%). Participants interviewed in Olleros associated a feeling of sadness with the decrease of water quantity (22%), with the impacts on water uses such as not being suitable for drinking (11%) or not suitable for irrigation (11%), and when it caused flooding (11%). **Anger** was also a

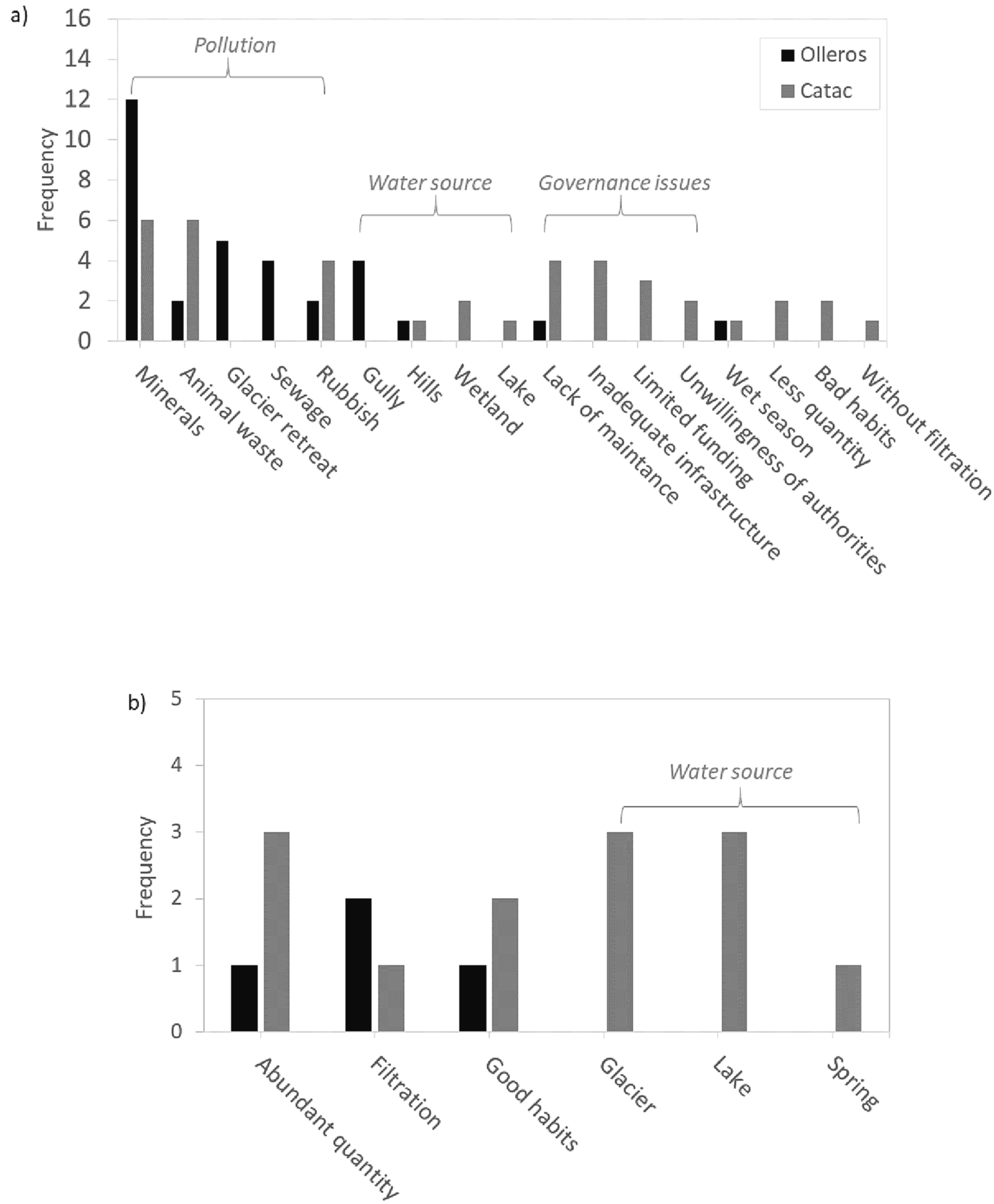

Fig. 5. Perceived causes of a) poor water quality and b) good water quality. Frequencies of references in qualitative data from interviews for Olleros (black) and Catac (grey).

common emotion mentioned (Fig. 6) with participants feeling angry because the water was not suitable for animals (20%), not suitable for drinking (20%), and not suitable for irrigation (15%). A feeling of anger mentioned by participants was also associated with the lack of respect and care for the population and with the impression that the water was dirty. Interlinked to these perceptions of poor water quality, **fear** was also expressed as an emotion. Participants explained that they felt afraid of their water because it was harmful, because of the colour, because of its taste, and for the future. This can be strongly linked to the pollution of water. The sense of **surprise** was mostly associated with the feeling that water is changing over the years.

Yet **happiness** was also a very common emotion, appearing in all the communities despite their range in water quality assessments. 76% of the references that explained positive emotions also corresponded to participants who rated the water quality as good or neutral. Participants associated a feeling of happiness with access to water (32%), and with the perception of usefulness of water (18%). The water quality assessment results show good or poor water quality perceptions and why, but the quotes themselves show that it is not as straightforward as just good or poor water quality; some interviews suggested that the water might

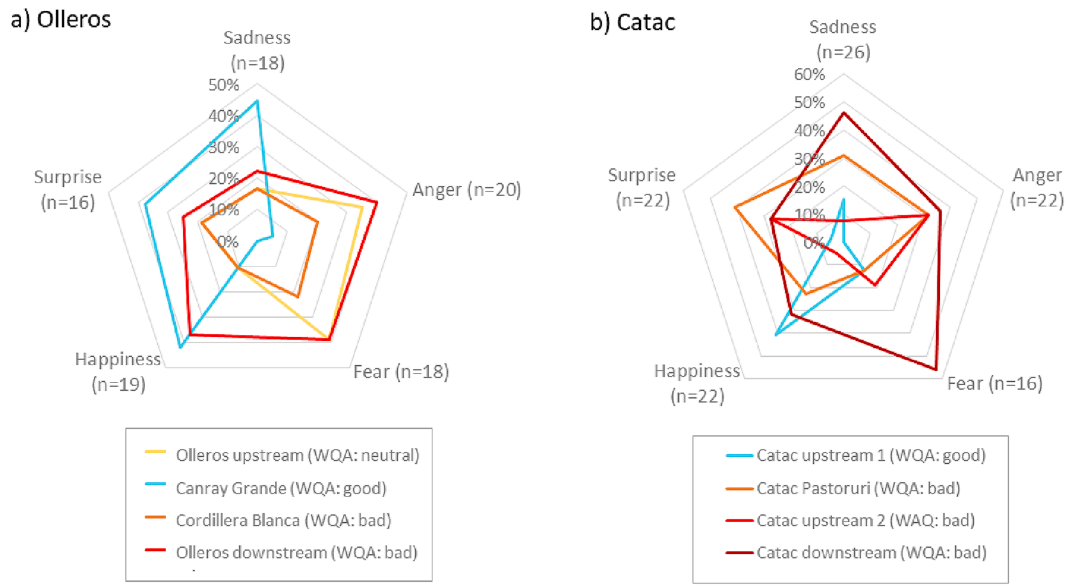

Fig. 6. Emotions and water quality for the different communities and study areas: a) Olleros study area and b) Catac study area. Water quality assessment (WQA) is stated for each community in the legend. Total number of references of each emotion are stated on the outside of the chart, and the percentage plotted represents the frequency of references in the interviews for each study area.

be poor but the participant is happy there is water, or that the water quality might be ok but it is not usable for certain things resulting in more negative emotions:

> *"Yes, before with this water one felt happy, content. Of course, one feels happy because we have water, but the sad thing is that the water is contaminated." (OLL34, Olleros downstream, July 6 2021)*

Whilst these emotions were specifically asked about in the semi-structured interviews for participants to rate, other emotions also emerged from the interviews. "Worry" was an emotion that was subsequently mentioned by several participants, due to the lack of respect and care for the population. Participants also mentioned negative emotions of "powerlessness" caused by the unwillingness of the authorities, "outrage" due to water misuse from the population. The emotion of "resignation" emerged from the negative responses to the feeling of surprise; participants interviewed stated that they did not feel surprised at all because this had always been their situation, or they were used to seeing their water like this. Furthermore, responses indicated a strong "concern" about the future, about their water quality, about their health, and that their water cannot be treated:

> *"I don't get angry, but [I feel] a little bad, sometimes because of the water; we have a concern. We worry, sometimes for the children: today, sometimes children drink this water and some illnesses can occur." (OLL34, Olleros downstream, July 6 2021)*

Results suggested that water quality and quantity was also linked to both sadness and happiness emotions, in a more complicated manner. Decreases in quantity of water was the main concern related to the emotion "sadness", however, participants also stated "happiness" because their water is abundant, and because the water is useable. Olleros downstream, where despite rating the water quality as mostly poor (Fig. 6a), participants expressed a feeling of "happiness" about the use and quantity of water. Conversely, despite the fact that in Canray Grande most participants rated water quality as good (Fig. 6a), negative feelings such as "sadness" and "worry" were still present in high frequency. This link between water quality, quantity and emotion provides us with a paradigm: often with less water, lower quality of water is perceived since there is a higher concentration of contaminants, due to less dilution option (ANA, 2016), however, we find that participants may have a positive water quality assessment but still have strong negative emotions, and we also find that water quality perceptions and positive emotions can be associated to poorer water quality and low abundance:

> *"Of course, happiness yes because [although] with polluted, dirty water, but, let's say it gives us some relief…" (CA24, Catac upstream 1, July 31 2021).*

5. Discussion

5.1. Local variability of water quality perceptions and key drivers

Similarities and differences in perceptions were found across the study region, and this diversity in participant responses is a key finding of our work. Variability in the perception of water quality is potentially linked to physical drivers (e.g. geology - specifically ARD, hydrology, glacier change, water sources), as well as social drivers (e.g. anthropogenic activities, participants relationship with land and water use, access to water, water governance, and local interactions), both interrelated to the organoleptic information on water quality provided by the participants (e.g. taste, colour, smell, flavour, etc.).

ARD is a naturally occurring phenomena in the glaciated upper Santa basin (Santofimia et al., 2017; Fortner et al., 2011; Grande et al., 2019), and is likely to continue to be problematic with further glacier retreat over local iron-rich geology, both in currently affected areas, and potentially in other regions in the future. Moreover, it is known that ARD caused by retreating glaciers negatively impacts on rural livelihoods in Peru (Paardenkooper, 2018), and it can be seen here that ARD is likely a major physical driver in the perception of water quality recorded. Overall, pollution due to the presence of minerals was stated as the main perceived cause for poor water quality in both study areas, often likely linked to locations affected by ARD. In the Olleros study area, negative perceptions of water quality were observed in more southern tributaries of the Rio Negro, coming from the Rurec and Uquian gullies (Fig. 2b), which are known to be the main sources of ARD in the Rio Negro sub-basin (e.g. Grande et al., 2019). For the Catac study area, more negative water quality perceptions were identified in the Pachacoto sub-basin (Fig. 2c), where previous research has found that 50% of the lakes and springs in the headwaters of Pachacoto sub-basin were affected by the ARD phenomenon (Santofimia et al., 2017). Local knowledge, combined with community experiences of previous and existing research on ARD in the study areas with may have been strongly influencing the water quality perception of participants (e.g. de Doria, 2010), especially in the Olleros study area where a participatory research method has been developed to implement human-made wetlands (bioremediation systems) to reduce ARD impacts on the Cordillera Blanca community (Zimmer et al., 2018).

On the other hand, while we have found that pollution linked to ARD is a dominant indicator and perceived cause of poor water quality, we have also found that ARD is far from the only factor affecting negative water quality perceptions. Local context can also provide information to understand participants' perceptions (de Doria, 2010), such as the identification of social drivers. For example, negative perceptions of water quality in Catac were not just related to natural pollution, but also related to social drivers such as governance, littering, and bad habits of the population (Fig. 5a). As suggested by Okumah et al. (2020), these are results that could be used to help prevent future pollutive behaviours that arise from negative perceptions of river water quality.

Useability of water for human consumption was also found to be a key indicator and/or reason for how water quality was assessed by participants, highlighting issues around access to safe water, and the close relationship between the main livelihoods of the population and water. Livestock farming is the main economic activity in both regions, and therefore the factors that drive the perception of water quality could be strongly associated with the useability of water for human consumption and livestock, and the behaviour of the animals; evident in the indicators referring to the harmfulness and usefulness of the water. Interview participants from the Catac study area were less involved in agriculture/livestock (43%) than Olleros participants (92%), perhaps also explaining some of the difference in water quality assessment and perceptions across the two study areas. Whilst a strong relationship was seen between animal activities and water quality, it was also observed that animal interactions with water also led to negative water quality assessments, with animal waste being the second most common perceived cause of poor water quality (e.g. Fig. 5a). This finding is similar to that of Morales et al. (2020) who found that participants stated that water shared with the livestock was often contaminated since the livestock habitually defecated, drank and bathed in it, and it was not suitable for human consumption.

5.2. Increased understanding of water quality from qualitative data

Qualitative data on what local water users observe, think and feel about the quality of their rivers and streams can help provide a much deeper contextual understanding of dynamic human-water systems. Here, through the use of interviews it was possible to deepen the understanding of these relationships beyond the rating scale used in the app, to unravel the reasons or motives behind water quality assessments, concerns and emotions. We found that fieldwork was essential in supporting data collection as a significant proportion of the Nuestro Rio app data entries were associated with fieldwork. The interviews themselves enabled a two-way dialogue, and allowed for the clarification of terms if needed. For example, "surprise" is an emotion that has no direct translation into Quechua, and therefore discussion was important when asking participants about this emotion. We also found that the term "water quality" itself needed clarification for several participants. Water quantity was a perception closely associated with water quality in both study areas, especially in the Olleros study area. The association between the two terms could be related to confusion around terminology by participants, or their use or understanding of alternative concepts. Whilst water quantity directly impacts water quality via dilution (ANA, 2016), the research here finds a much more complicated relationship between water quality, quantity and emotion.

For Wutich et al. (2020), understanding the impacts of water insecurity on mental health is also important in order to improve the overall efficacy of water management interventions. Although the scope of this research did not cover the relationship between water quality and mental health, with regard to complex relationships, overall a correlation between "negative" emotions and a poor assessment of water quality and vice versa can be observed. However, emotions such as happiness, fear and sadness were perceived in both assessments of water quality, and were not always associated with water quality, but with the quantity and permanence of water. Due to these complexities, and similarly to Okumah et al. (2020), our results indicate that a single indicator perspective may be a weak approach. For example, in our study regions, water quality may be poor, but if it is still useable for certain domestic and livelihood activities, or if it is abundant in quantity, the perception may be more positive than the measured water quality itself.

5.3. Potential implications for local water resource management

Perceptions and emotions vary on past experiences, individual variables, and environmental factors. Perceptions and emotions of local Andean community participants have developed on daily basis experience with a complex ecological relationship, but also with their social experience as individuals and as part of a community. Catac community is the largest community of the study region, with a strong communal organization, and this may have an effect on their expectations of their local authorities, reflected in their perceptions and emotions (e.g. governance issues in Catac interviews, section 4.3.3). The increased visibility and inclusion of these local perceptions and emotions is crucial for informing local water resources management and sustainable solutions. Incorporating and including local perspectives can bring with it the opportunity to gain some insight into past water quality perceptions. These local perceptions can be useful pointers to support other scientific data and can help to identify where future research might be needed to investigate potential trends affecting water quality, not just from an environmental perspective, but also socio-economic, cultural and political.

Overall, the variations observed within study areas and communities demonstrate the complexity of the topic of water quality, and the different perceptions, emotions and identified causes for different people. Capturing and understanding the uniqueness of different communities and stakeholders is essential for addressing the complexity of water resource governance (Stringer et al., 2009; de Doria, 2010; Okumah et al., 2020; Azevêdo et al., 2022). Furthermore, the variation across communities and study areas seen here also shows the importance of localised management, illustrating why water management should not be a one-fits-all approach. Instead, more inclusive citizen-based science and the co-production of science and solutions is necessary moving forward. For our study region, with this research we have seen that there is a desire from stakeholders directly impacted by the effects of climate change on water quality, such as rural communities, who are currently known to be excluded in decision making processes for the management of water services, to communicate these perceptions to local and regional decision makers (Dextre et al., 2022). Likewise, engaging local people in the decision-making process itself can help to empower them to influence water governance processes (Okumah et al., 2020).

Sustainable approaches to water management require broad community acceptance of changes in policy, practice and technology, which typically requires an engaged community (Dean et al., 2016). However, a critical first step in building this engaged community is to identify community knowledge about water and water management, an issue rarely examined in research (Dean et al., 2016). Therefore, understanding and integrating the views of resource users into policy design and implementation can help improve science communication and address the most important challenges, gain community support, enhance project ownership, helping to create "buy in" when changes to how water is managed are necessary, thus potentially avoiding policies being rejected by local people (Steinwender et al., 2008; Okumah et al., 2020). This research demonstrates a step towards this, but more research is required to truly integrate and communicate qualitative and quantitative data for water resource management.

5.4. Limitations and future research

Whilst our results cover a range of communities and participants, we acknowledge that our dataset is still a sample and might not be exhaustive in its representation. However, it is a first step to gathering, analysing and including qualitative data on water perceptions for our study region to: 1) improve our understanding of local water quality; 2) include local communities in the data generating process. Similar to Okumah et al.'s (2020) conclusions, we agree that while public perceptions of river water quality can guide water management policies, scientific measurements of water quality are equally as important, and therefore the datasets should be gathered in a complimentary approach to strengthen insights and actions for water resource management. We believe that the next steps for this research, and for others addressing water quality and water resource management, is to include the collection of both qualitative and quantitative data into research design, with consideration into synthesising these datasets to ensure they are valued similarly to obtain a holistic picture (e.g. Richter et al., 2022).

Whilst interdisciplinary, transdisciplinary and community centred approaches are required for future water resource research and management, we are fully aware that these approaches are more time intensive. It can take time to establish a shared vision and goal across researchers and project partners with different discipline backgrounds and experiences, as well as to establish a common language to communicate across disciplines (Rangecroft et al., 2021). Furthermore, fieldwork with local communities, such as that undertaken here, takes time and effort to establish community connections and trust, and therefore partnerships with existing research institutions, gatekeepers and field assistants are crucial for research success with regards to collecting data for analysing the research question (Rangecroft et al., 2021), especially within funded projects with short timeframes (e.g. 12 months). Finally, we fully acknowledge the limitations of the timing of the project (e.g. during the COVID-19 pandemic) on its citizen science and participatory aspects, however this research does showcase the importance of including local perspectives into water resource management issues and the value of qualitative data, setting the foundations for further co-production of knowledge and solutions in future research.

6. Conclusions

Physical measurements and quantitative data on water quality can provide a rich source of data, but these numerical values alone cannot provide insights into why water quality is perceived in a certain way by water users. Qualitative data can help to explain perceptions, highlight the complexities of the topic of water quality, gather lived experiences and traditional knowledge, and provide a contextualised understanding on how local communities directly interact with and rely on their water. This study has sought to address a gap in current scientific research on water quality in the Santa basin, Peru, by focusing on local perceptions of water quality to better understand variability and drivers of water quality concerns. Our findings help us to identify and unravel the main indicators of, and insights around, water quality from a local perspective, contributing to developing our understanding as a scientific community on this environmental challenge for regions facing water insecurity. Whilst these results can help to target improvements and interventions, they also highlight the importance of community-centred interdisciplinary approaches to co-produce essential sustainable water management with a more holistic and sustainable knowledge base.

Results demonstrated variability in perceived water quality, key drivers, and concerns for two study areas, highlighting the complexity of the topic, and the importance of including local perceptions into regional and local water resource management. We identified hotspots of perceived good and poor water quality, both from natural and anthropogenic causes, while additional data from walking interviews helped to explore some of the reasons behind these water quality assessments. Pollution from minerals was perceived as the main reason for poor water quality in the study areas, linked to ARD, but other perceived causes linked to social drivers were also found to be important, and the useability of water for human consumption was also found to be a key indicator. Qualitative data analysis highlighted a complicated relationship between water quality, water quantity, use and emotions. To facilitate more holistic water management strategies we need to integrate human perceptions, but also to encourage more co-produced knowledge and solutions. Inclusive citizen-based science that considers what people observe, think and feel about the quality of their rivers and streams can help provide a much deeper contextual understanding (e.g. useability of water, changes over time, traditional ecological knowledge) of dynamic human-water systems, with further benefits for improving science communication and policy implementation.

CRediT authorship contribution statement

Sally Rangecroft: Conceptualization, Methodology, Formal analysis, Visualization, Project administration, Funding acquisition, Data curation, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Rosa Maria Dextre:** Conceptualization, Methodology, Investigation, Data curation, Visualization, Project administration, Formal analysis, Writing – original draft, Writing – review & editing. **Isabel Richter:** Conceptualization, Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Claudia V. Grados Bueno:** Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Claire Kelly:** Conceptualization, Methodology, Validation, Supervision, Writing – original draft, Writing – review & editing. **Cecilia Turin:** Methodology, Validation, Supervision, Writing – original draft, Writing – review & editing. **Beatriz Fuentealba:** Methodology, Validation, Supervision. **Mirtha Camacho Hernandez:** Methodology, Validation, Supervision. **Sergio Morera:** Project administration, Supervision. **John Martin:** Methodology, Software, Supervision. **Adam Guy:** Methodology, Software, Validation. **Caroline Clason:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.129949.

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