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Assessment of Arequipa's Hydrometeorological Monitoring Infrastructure to Support Water Management Decisions

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Abstract: Hydrometeorological monitoring of weather, streamflow, and water quality is essential for understanding available water resources, protecting populations from hazard, and identifying changes in environmental conditions over time. To meet such competing goals, monitoring networks require representative parameters, uniform sampling protocols, and stable locations, selected to reliably measure the phenomenon of interest. However, budgets are always limited, and immediate operational needs and short-term decisions often influence monitoring decisions. Here, the hydrometeorological monitoring systems in Arequipa, Peru, are examined with respect to established criteria for their ability to support these competing goals. The Arequipa Department in Peru has a well-established, stable, weather monitoring program, although reliance on manual observers results in variable data quality. The lack of observations in high altitude areas limits estimation of water availability, and high temporal resolution, automatic stations are needed to improve flash flood warnings. The streamflow monitoring system is designed to quantify water transfers throughout this heavily managed system. Twenty-one discharge monitoring stations were identified to serve as Historic Hydrologic Reference Stations, but many were only operational in the 1960s and 1970s and cannot be used to evaluate environmental trends. Twelve stations are identified that should be maintained for establishment of a future reference network. State sponsored water quality monitoring in the Department is fairly new, and a stratified sampling method has been used to maximize sample locations. Uniform sampling in fewer locations along intermediate sized tributaries, at least two times per year, would improve the reliability of the system and allow better detection of change over time.

Keywords: *water quality network design, climate networks, reference hydrologic networks, environmental data, monitoring infrastructure, environmental change*

The Arequipa Department in Peru is a region of significant climate and topographic variability that can be roughly divided into two topographic/climatic regions: the semi-arid, high-altitude Andean Altiplano and the desert. The Department is home to over 1.4 million people (INEI 2017), substantial mining activities, and more than 70,000 ha of irrigated agriculture, all competing to use the limited water supply from the Andean Mountains. To meet the increasing demand for water supply, due to urban population growth and increased sectoral water demands (Salmoral et al. 2020), water resources from the Andean Altiplano are highly managed with eight reservoirs and hundreds of kilometers of canals and tunnels that include complex water diversions between watersheds (Stensrud 2016).

Additional scarcity comes from local sources of water contamination that can limit public and agricultural water use. As with many parts of the world, Arequipa suffers from anthropogenic sources of water contaminants related to the lack of sewage treatment (Alarcón 2019), unregulated dumps (Magaña and García 2016), indiscriminate use of agrochemicals (Carreño-Meléndez et al. 2019), and mining activities (Bottaro and Sola Álvarez 2018; Delgado et al. 2019), as well as natural sources of arsenic, boron, and chromium (Lopez Arisaca 2018; Pinto Paredes 2018; Tapia et al. 2019). This highly managed landscape is also one of the most affected by climate change in the world (Urrutia and Vuille 2009; Salzmann et al. 2013). The increase in temperature and consequential retreat of tropical glaciers (López-Moreno et al. 2014; Schauwecker et al. 2014; Kochtitzky et al. 2018) adds uncertainty to a water resources system that already operates close to its limit (Vergara et al. 2007; Chevallier et al. 2011).

In a region with such complexity and high demand for water resources, it is necessary to have high quality, robust monitoring of water resources systems, including weather, river discharge, and water quality, to support human activities and guide decision making (Goody et al. 2002; Bradford and Marsh 2003; Telci et al. 2009). The challenge is that the design of environmental monitoring networks reflects the intended goal of the original network, but often existing networks must meet newer competing operational goals and financial constraints (Bradford and Marsh 2003). Weather and climate monitoring networks may support multiple goals including predicting daily weather, advising farmers, warning of severe weather events, managing national and regional water resources, aiding transportation, and establishing benchmark conditions against which changes due to climate change can be assessed. Similarly, discharge monitoring programs have many of the same goals, but may also be needed to establish benchmark flow conditions, identify trends in runoff related to changing climate conditions, and provide daily flow required to complement water quality monitoring (Slack and Landwehr 1992; Bradford and Marsh 2003). Finally, the overall goals of water quality monitoring networks may include support for timely decisions regarding human exposure, evaluating habitat needs, identifying pollution sources, detecting accidental releases and emerging issues, quantifying trends in current water quality, and managing regulations regarding total load (Strobl et al. 2006; Telci et al. 2009).

Remote sensing is often considered as a potential source or supplement for in-situ observations in regions with sparse measurement networks, but remote sensing products still require in-situ observation networks to yield useful information. Satellite derived precipitation products have been found to underestimate high precipitation events, and to have significant errors in regions of complex topography that are resistant to the development of a global correction technique (Bartsotas et al. 2018), thus requiring local measurements for highest accuracy. Streamflow measurements are a proposed product of the Surface Water and Ocean Topography (SWOT) (Biancamaria et al. 2016) mission scheduled for launch in 2022, but rivers in the Department are narrow and often in deep canyons, which will make accurate observations difficult except near the river mouths. Finally, the remote sensing of water quality is limited to constituents that are optically visible or that can be correlated to those that are visible, both of which requires significant in-situ observations to develop predictive models (see e.g., Tan et al. 2016).

The ability of the existing, in-situ, monitoring infrastructure in Arequipa, Peru, to support disparate operational criteria is unclear. The goal of this study is therefore to assess to what extent the existing weather, river discharge, and water quality monitoring infrastructure can support water and agricultural management decision making in the Arequipa Department of Peru and how those networks could be improved. In particular, we evaluate the ability of each network to support 1) understanding of available water resources, 2) protecting human and aquatic health, and 3) identifying changes in environmental conditions over time.

In order to achieve this goal, available weather, river discharge, and water quality data sources were identified through document review, discussion with local contacts, and internet searches. The identified monitoring network data were then evaluated based on international standards. Based on the evaluation results, the strengths and weaknesses of each monitoring network were discussed, and finally, recommendations were made.

Material and Methods

Study Area

The current state of the monitoring infrastructure of the Arequipa Department, located in southwestern Peru (16° S, 72° W), was evaluated. Weather stations within 100 km of the border of the Arequipa Department were included, while hydrology and water quality infrastructure evaluation was extended to the boundaries of watersheds that are at least partially included in the Department. The Andean Altiplano is a wide, high-altitude region with average elevations of more than 3500 m, occupying parts of Peru, Chili, Bolivia, and Argentina. In the south of Peru, the region experiences a semiarid climate with more than 70% of the precipitation occurring during austral summer (December to March) (Moraes et al. 2019), with precipitation mostly fed by moist, easterly winds from the Amazon basin (Garreaud et al. 2003; Garreaud 2009). The desert region consists of a 70 to 90 km wide strip between the Pacific coast and the Andes. Annual average precipitation in the Department varies from 1.5 to 792.0 mm, while annual average temperature varies from -11.4ºC to 22.7ºC (Moraes et al. 2019).

Weather Stations

Weather station data were acquired from the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI) and National Oceanic and Atmospheric Administration (NOAA). Daily precipitation, and maximum (Tmax) and minimum (Tmin) air temperature since the start of data acquisition (1930s for some stations) are available from SENAMHI (2020a; 2020b). Four types of stations are available: 1) conventional stations with real-time data availability (CRT), 2) conventional stations with deferred time data availability (CDT), 3) automatic stations (AUTO), and 4) hydrology stations (HYDRO). CDT and CRT stations collect daily precipitation, Tmax, Tmin, and relative humidity through manual observers; AUTO stations record hourly precipitation, temperature, humidity, and wind direction and speed; HYDRO stations record hourly precipitation data.

SENAMHI stations are not available from the NOAA Global Summary of the Day (GSOD) or Global Historic Climatology Network (GHCN). One station, the Rodrigues Ballon airport in the city of Arequipa, is available only in the GSOD. It is administered by the Peruvian Corporation of Airports and Commercial Aviation (CORPAC), not SENAMHI, and records daily precipitation, snow depth, daily average, maximum, and minimum air temperature, average dew point, maximum wind gust, maximum sustained wind speed, average visibility, and atmospheric pressure. The Rodrigues Ballon data analyzed in this paper were downloaded from the GSOD dataset (DOC/NOAA/NESDIS/NCDC 2020), while all other datasets were downloaded from SENAMHI.

Following the adoption of the Kyoto Protocol in 1997, many countries sought to identify, protect, and extend a global reference climate network (RCN). These stations had to follow monitoring principles, first proposed by Karl et al. (1995), and later adopted by the Global Climate Observing System (GCOS) (WMO 2019). General goals of such networks include stabilizing existing observational capacity, identifying critical variables that are inadequately measured, identifying non-climate related discontinuities in measurement records, and correcting those issues when identified. As an example, by 1999, the U.S. had identified 144 stations across the continental U.S. that met the selection criteria to form a RCN, and identified 29 additional locations where stations were needed to represent regions of significant climate sensitivity (NRC 1999). The U.S. had 130 RCN stations being monitored in 2013 (Diamond et al. 2013), while approximately one thousand GCOS surface network stations were operational around the world in 2015 (WMO 2015).

Based on the RCN approach, we used the following criteria to evaluate Arequipa's weather station network and select stations with the fewest long-term issues as candidates for a regional monitoring network:

1. Gross errors checks and missing data percentage – For precipitation, all values less than zero and larger than 125 mm were removed, while for Tmax and Tmin, all values less than -30°C and greater than 50°C were removed (Moraes et al. 2019). Temperature values were established to be +/- 10°C from the recorded extremes in the region. The precipitation value is equal to

highest observed daily precipitation event known to be true (Cacya et al. 2013). Missing daily data percentage by station was calculated after gross error checks.

2. Active data collection – Stations still actively collecting data, including newly established stations not currently meeting data duration requirements were identified for continued future use.
3. Site location and density – The spatial density required for meteorological observations was based on the phenomena being measured, and also by exposure, so regions with greater climate and terrain variability need a higher density of observations (WMO 2018). Methods used for this assessment are described later.
4. Data collection frequency and duration – Most historical measurements were recorded daily, but sub-daily measurements are important for prediction of erosion (Brown and Foster 1987) and flash flooding (Bronstert and Bárdossy 2003) events. Record lengths for both are important.
5. Metadata availability – Supporting documentation for correction of observation biases due to changes in station location or instrumentation (Karl 1995) was identified.

Evaluation of site location and density across the Department was completed using a Kernel density map (Silverman 1986) calculated with a search area of approximately 10,000 km^2. Only active (as of March 2020) temperature and precipitation stations (CRT, CDT, GSOD, and AUTO) were used for the station density calculation. As relying on stations from only inside the Arequipa border would create a border effect that would bias our assessment with a lower station density close to the Department's border, we included an additional 37 active SENAMHI stations that are located within 100 km of the Arequipa Department's border.

Stream Discharge

Stream discharge is measured by several regional and local agencies in Arequipa and are available through two agencies including the National Water Authority (ANA or Autoridad Nacional del Agua), and the Autonomous Authority of Majes (AUTODEMA or Autoridad Autónoma de Majes). ANA is part of the national system of environmental management, under the Ministry of Agriculture and Irrigation (Ministerio de Agricultura y Riego) of Peru (ANA 2020). The National Water Resource Information System (SNIRH or Sistema Nacional de Información de Recursos Hídricos) section provides daily streamflow data measured by ANA or partner agencies (SNIRH 2020).

AUTODEMA is a regional agency that was established to regulate and maintain water resources for agricultural and urban use in the District of Majes (Bnamericas 2019). It was established in 1982 to manage the Majes-Siguas irrigation project and regulates reservoirs in two major watersheds within the region (the Quilca-Vitor-Chili and the Camaná) (AUTODEMA 2018). AUTODEMA provides daily discharge records from eight reservoirs and flow through four water diversions on a daily basis from 2009 to present.

Since the U.S. Geological Survey (USGS) first established a Hydrologic Benchmark Network (HBN) for the U.S. in 1971, many countries have established Reference Hydrologic Networks (RHN) - collections of streamflow gauging stations that are maintained with the intention of observing how the hydrology of watersheds responds to variations in climate (Cobb and Biesecker 1971; Whitfield et al. 2012). A complete understanding of temporal changes requires a consistent, high resolution measurement system, free from human influence (Bradford and Marsh 2003). A record length of at least 20 years is preferred, although newer stations (< 10 years) may be included since they will grow in importance (Bradford and Marsh 2003; Whitfield et al. 2012). Other criteria to be considered include the availability of data and metadata in electronic form, stable and good quality stage-discharge relationships following standard measurement practices, representativeness of the location, active data collection, and sustainability of the measurement location in its current state (Bradford and Marsh 2003; Whitfield et al. 2012).

Given the significant level of regulation in Arequipa and short duration of many of the gauging records, the goal for this paper became to identify a Historic Reference Hydrologic Network (HRHN) in Arequipa that can be used to increase understanding of the baseline hydrologic conditions, as well as the potential for creation of a Future Hydrologic Reference Network (FHRN) to better quantify the ongoing impacts of climate variability on water availability. The criteria used for inclusion in the HRHN are:

1. Data sufficiency – A minimum of 60 months of data available within a 10-year period; at least 50% of daily values must be present to calculate monthly flow. Alternatively, a minimum of five years of data, with at least 50% of daily measurements present each year.
2. Unimpaired conditions – Stations free from the influence of upstream dams and diversions.
    - The annual percentage of mean monthly discharge falls within the range of a reference station established before significant infrastructure was developed.
    - Where pre-/post- data were available, the change in mean annual flow (MAF), 7-day low flow, and Richard-Baker Flashiness Index are less than 10%, or the annual average flow fell within the range observed for pre-construction stations.
3. Representativeness – Geographical spread needs to reflect different natural factors influencing flow regimes (e.g., vegetation cover, catchment orientation, rainfall, snowmelt, geology, drainage area). Given the limited stations available, no stations were discarded due to representativeness.
4. Data availability – Only stations with discharge available electronically from SENAMHI and AUTODEMA were included in this analysis.

Additional criteria for the FHRN:

5. Active data collection – All active stations that meet the HRHN requirements were included; stations were considered active if online data were available through December 2018 given time delays in updating some online resources. This requirement supersedes the data sufficiency requirement.

The USGS develops regional regression relationships for prediction of the 100-year return period flood for ungauged catchments as a power law function, where the 100-year flood is a function of the basin average annual precipitation, the basin drainage area, and the average basin slope for a set of monitored watersheds in the region that are free from substantial human interference (Jennings et al. 1994). In some states, additional explanatory variables are introduced, such as precipitation. This same approach was used here to establish regional hydrologic curves for Arequipa, and alternative models were evaluated using Analysis of Variance (ANOVA). The 100-year return period flood was estimated for each HRHN station by fitting the Extreme Value Type I (EVI) distribution to the annual maxima series using the method of moments. None of the fitted distributions could be rejected using the Kolmogorv-Smirnov test with a significance level of 0.1. Watershed boundaries were delineated based on published station locations in QGIS.

Water Quality

In accordance with the provisions of the law No. 29338 on water resources (ANA 2019), ANA oversees water quality monitoring in the whole country. The water quality monitoring infrastructure considered in this study came from thirty-eight different Participatory Surface Water Quality Monitoring Reports released by ANA from 2011 to 2019 for the watersheds Ocoña, Colca-Majes-Camaná, Quilca-Vitor-Chili, and Tambo, the main watersheds present in the Arequipa Department (see e.g., ANA 2013 and Table 1). Similar work has been carried out by ANA in the years following these reports, although new reports have not yet been released (Ccanccapa-Cartagena, A.D., personal communication). Reports from 2011 to 2014 are available for download through ANA's publications repository (http://repositorio.ana.gob.pe). Reports from 2015 are available upon request (http://aplicaciones01.ana.gob.pe/tramitevirtual/). The reports have detailed information about the monitoring network, including location, sampling dates, methods, equipment used, parameters analyzed, results, and interpretation.

Parameters analyzed follow the recommendations from the Supreme Decree 003-2017-MINAM, which sets the Peruvian national water quality standards. These are divided

Table 1. Summary of water quality monitoring location done by the National Water Authority (ANA) from 2011 to 2019 in the four major watersheds in the Arequipa Department. Date of sampling, number of locations sampled, and number of water quality parameters quantified are included in the table.

Watershed	Sampling Date (Year)	(Month)	Measurement Locations	Measured Parameters	Report No.
Ocoña	2012	Nov-Dec	23	37	006-2013-ANA-AAA | CO-SDGCRH/JLFZ[1]
	2013	Nov	24	35	006-2013-ANA-AAA | CO-SDGCRH1
	2014	Apr	24	36	020 -2015-ANA-AAA | CO-ALA-OP/FGA
	2015	Sept	31	37	020-2017-ANA-AAA | C-O-ALA.O-P
	2016	May	31	38	001-2017-ANA-AAA | C-O-ALA.O-P
	2016	Nov	31	39	010-2017-ANA-AAA.CO-ALA.O-P-AT/AGFT
	2017	Aug-Sept	31	36	005-2017-ANA-AAA.CO-ALA.O-P-AT/AGFT
	2018	Apr	31	47	012-2018-ANA-AAA.CO-ALA.O-P-AT/AGFT
	2019	Apr	31	47	019-2019-ANA-AAA.CO-ALA.O-P-AT/AGFT
	2019	Oct-Nov	28	49	043-2019-ANA-AAA.CO-ALA.O-P-AT/AGFT
Colca-Majes-Camaná	2012	Oct	30	32	015-2012-ANA-SDGCRH/MPPC·JLFZ
	2013	Oct-Nov	38	37	011–2014–ANA–AAA I CO-SDGCRH/JLFZ
	2014	Mar	40	37	001-2015-ANA·AAA.CO-ALA.CM-AT /GFA
	2014	Aug-Sept	23	37	003-2015-ANA-AAA.CO-ALA.CM-AT/GFA
	2016	Mar-Apr	32	50	007-2016-ANA-AAA.CO-ALA.CSCH.FADM
	2016	Nov	34	49	005-2016-AAA I C-O/SDGCRH
	2017	Sept	34	44	045-2017-ANA-AAA.CO-ALA.CSCH-AA/FADM
	2018	Apr	37	32	013-2018-ANA-AAA.CO-ALA.CM-AT/GFA
Quilca-Vitor-Chili	2011	Aug	24	37	002-2012-ANA
	2011	Oct	24	37	108-2011-ANA-AAA I C-O
	2011	Dec	24	37	001-2012-ANA
	2012	Mar	18	40	011-2012-ANA-PMGRH
	2013	Jan-Feb	33	36	001-2013-PMGRH-CUENCA CHILI
	2013	Mar	33	36	08-2014-ANA-AAA.CO
	2014	Jan	27	40	001-2014-PMGRH-CUENCA CHILI
	2014	Mar	17	37	003-2014-PMGRH-CUENCA CHILI
	2014	May	17	37	005-2014-PMGRH-CUENCA CHILI
	2014	Oct-Nov	16	38	004-2015-PMGRH-CUENCA QUILCA CHILI
	2015	Sept	17	45	046-2016-ANA-AAA.CO-ALA.CH/ECA-JCM
	2017	Sept	17	44	006-2018-ANA-AAA.CO-ALA.CH/JCCM
	2018	Apr	23	48	016-2018-ANA-AAA.CO-ALA.CSCH-AA/FADM
Tambo	2013	Oct	44	33	001-2014-ANA-AAA | C-O/ALA T-AT-ALA MOQ/ECRH/VNCA-LVUC
	2014	Mar	44	34	002-2014-ANA·AAA | C-0/ALA T-AT-ALA MOQ/ECRH/VNCA LVUC
	2014	Jul	45	34	005-2015-ANA·AAA | C-0/ALA T-AT-ALA MOQ/ECRH/VNCA LVUC
	2016	Apr	46	27	011-2016-ANA-AAA | C-O/ALA T-AT-ALA MOQ/ECRH/VNCA-LVUC
	2016	Oct-Nov	43	30	001-2017-ANA-AAA | C-O/ALA T-AT/VNCA
	2017	Oct	43	33	260-2017-ANA-AAA | C-O/ALA T-AT
	2018	Apr	45	33	004-2018-ANA-AAA | C-O/ALA T-AT

[1] Example citation: Autoridad Nacional de Agua (ANA). 2013. *Informe del Primer Monitereo Participativo de Calidad de Agua Superficial en la Cuenca del Rio Ocoña*. Report no. 006-2013-ANA-AAA I CO-SDGCRH/JLFZ.

into four groups: physical-chemical, inorganic, organic, and microbiological/parasitological. Physical-chemical parameters are pH, conductivity, and others related to the presence of organic matter in the water such as nitrates, nitrites, ammonia, phosphates, cyanide, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Inorganic parameters include heavy metals; those of most concern in southeast Peru are arsenic, boron, and chromium (Lopez Arisaca 2018; Pinto Paredes 2018). Organics include the BETX (benzene, ethylbenzene, toluene, and xylene), aromatic hydrocarbons, as well as agrochemicals including organophosphates and organochlorines. Microbiological/parasitological parameters include total coliforms and thermotolerant coliforms.

The design of water quality networks started receiving substantial attention in the 1970s, with quantification of the statistical power needed to detect change and optimize station locations to maximize network reliability (Lettenmaier 1978; Telci et al. 2009). Four criteria are usually considered in the design of water quality monitoring networks: goals, parameters, location, and sampling duration and frequency (Strobl et al. 2006; Moreno Tovar et al. 2008; Singh et al. 2018).

Selection of station location is especially challenging for water quality networks and is closely tied to the goal of the network. Strobl et al. (2006) proposed a "critical sampling point" methodology, in which sampling locations are prioritized to maximize the potential load of critical parameters, subject to accessibility and economic constraints. Telci et al. (2009) emphasized two criteria in the design of a monitoring network to protect human health: detection time and reliability of detecting the contaminant. These criteria lead to trade-offs between downstream stations that will maximize flow capture, but have longer detection time and may fail to detect low concentration contaminants. Lettenmaier (1975) found, however, that the location of sample stations was much less important than the number of stations established when monitoring for environmental change.

Based on these considerations, the following criteria were utilized to evaluate the water quality monitoring network in Arequipa:

1. Parameter selection – In order to identify risks, the priority parameters should be related to the local sources of potential contamination. For the Arequipa Department, the primary concerns are the presence of organic contamination due to wastewater effluent, heavy metals from natural or anthropogenic sources, and agrochemicals.
2. Station uniformity – Uniform sampling of already established sites is preferred over stratified sampling for detection of environmental change (Lettenmaier 1978).
3. Station location – Sites should be situated to monitor a substantial proportion of the runoff from a river basin, while also being able to isolate the effects of suspected sources. Consider both the geographic elements that determine the risk of natural contamination and potential discharges from anthropogenic activities (e.g., mining, agriculture, wastewater treatment).
4. Station accessibility – Sample stations should be located so that a single grab sample is representative of average quality for that reach (i.e., samples taken from bridges rather than shore), and should be located to minimize sample transport time and travel requirements (Lettenmaier 1978).
5. Representativeness – Care should be taken to locate samples such that local effects do not indicate spurious trends (e.g., local construction).
6. Sampling frequency and timing – Sample time should take into account the potential for both diurnal and seasonal variation. The minimum magnitude of change that can be detected increases by about 80% with a decrease in frequency from monthly to quarterly, but there is no additional power in sampling less than bi-weekly (Lettenmaier 1978).

The overall ANA water quality monitoring network is evaluated with respect to sampling frequency and parameters recorded. To evaluate sampling locations, the upper Colca-Majes-Camaná watershed is considered as a case study for identification of critical sampling points.

Results

Assessment of Weather Measurement Infrastructure

Arequipa has 47 active weather stations measuring both air temperature and precipitation, resulting in an average density of 7.4 stations per 10,000 km^2 (Figure 1). The total number of stations in the Arequipa Department increases to 53 when considering the newly established HYDRO stations that only measure precipitation.

Two areas within the Arequipa Department have higher station density (Figure 1): the districts situated in and around the Colca Canyon and the districts in and around the city of Arequipa in the Chili watershed. These two locations represent where the water is most heavily managed in the region and are located between 2500 and 4500 m of elevation (Figure 2 and Table 2). Lower densities coincide with the desert area on the coast and areas over 4500 m of elevation, situated at the northeast and northwest of the Department (Figure 1).

Most of the precipitation measurements started in the 1940s and 1950s (Figure 2a), with only a few of these stations measuring temperature at the time (Figure 2b). The number of stations measuring temperature increased in the 1990s and 2000s. The last decade saw an increase in the number of operational stations (starting in 2013), as well as modernization and automation of stations as AUTO stations with hourly measurements introduced in 2014 and HYDRO stations introduced in 2015.

CRT, CDT, and GSOD stations have on average 5.9% and 6.4% missing observations of precipitation and temperature, respectively, with a few stations missing more than 10% (Figure 2c and d). AUTO stations miss on average 7% of precipitation and 12% of air temperature hourly observations. Two stations were removed from this assessment: Coropuna which had no precipitation measurements, and Visca which was missing 54% of all precipitation measurements. The newer HYDRO stations had on average only 1% missing data.

Seven stations were identified as having the potential to be used for long-term climate trend analysis (Figure 3). These have all been measuring daily precipitation and air temperature extremes since the 1960s, and all have less than 5% missing data. Six of these stations are maintained exclusively by SENAMHI (Aplao, Caraveli, Chivay, Imata, La Joya, and Pampa Blanca), and one comes from the GSOD (Rodriguez Ballon). Metadata from the SENAMHI stations that could be used to aid in adjustments to precipitation and temperature data associated with station relocations, instrument changes, and other factors, has not been located.

Stream Discharge

A total of 40 unique streamflow monitoring

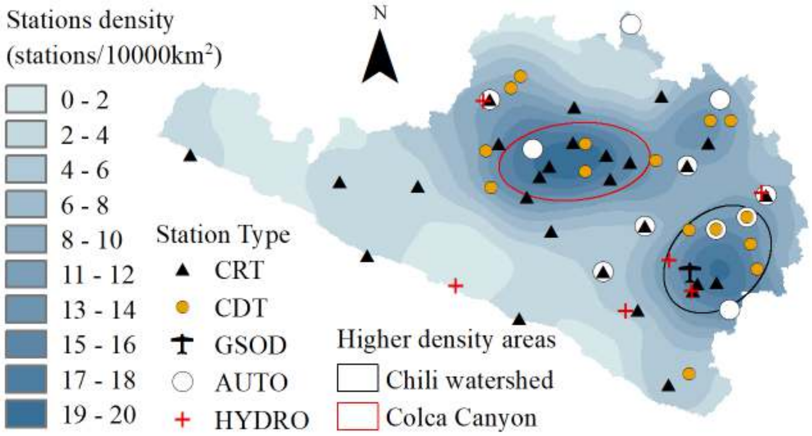

Figure 1. Density of active weather stations measuring at least temperature and precipitation in the Arequipa Department in March 2020 and station types. HYDRO stations were not considered in the density calculation as they only measure precipitation. CRT = conventional stations with real-time data availability (25 stations); CDT = conventional stations with deferred time data availability (15 stations); GSOD = NOAA global summary of the day (1 station); AUTO = automatic stations (11 stations); Hydrology stations (6 stations).

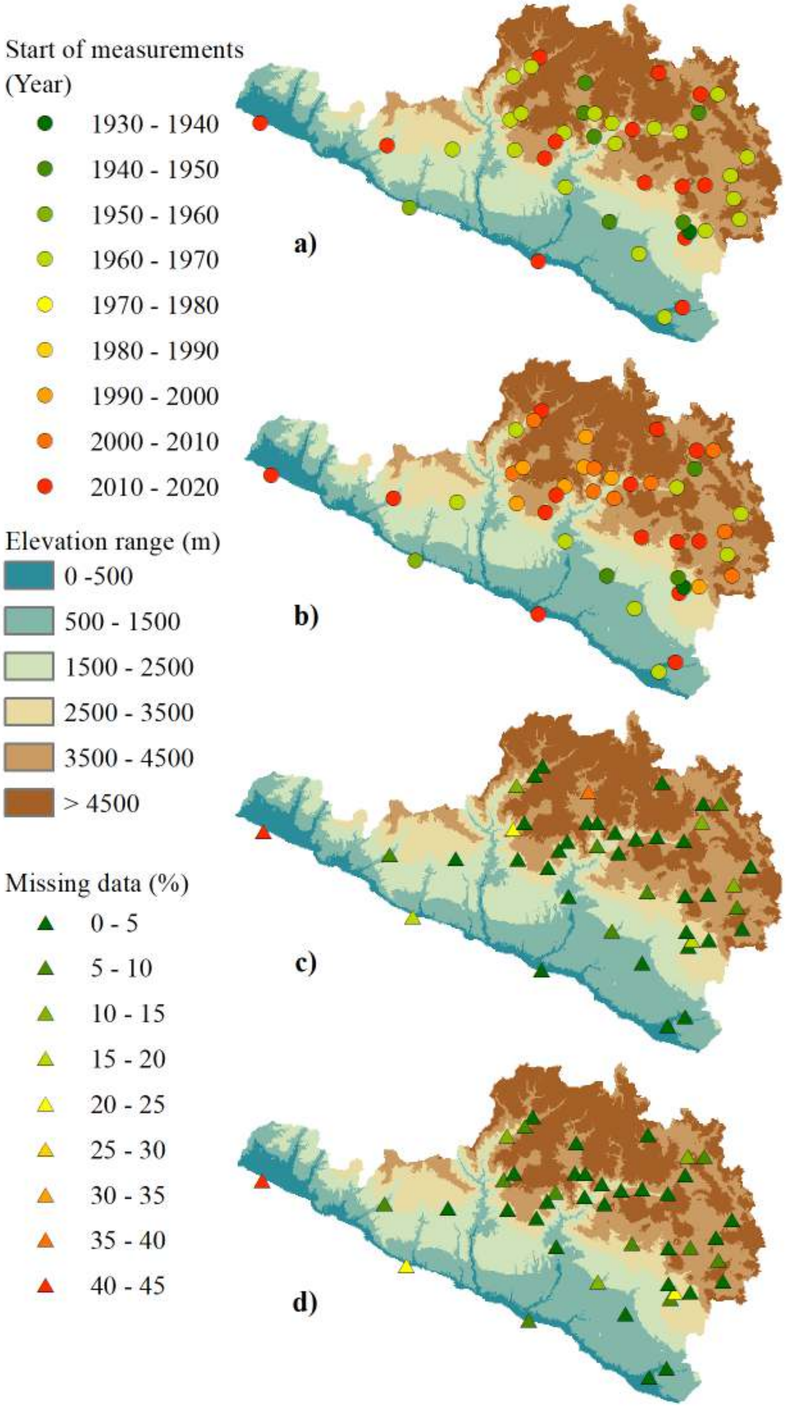

Figure 2. Year when daily a) precipitation and b) air temperature measurements started, c) percentage of missing precipitation, and d) missing air temperature data for the CRT, CDT, and GSOD stations. CRT = conventional stations with real-time data availability (25 stations); CDT = conventional stations with deferred time data availability (15 stations); GSOD = NOAA global summary of the day.

Table 2. Number and percentage of active weather stations (in March 2020) and area per elevation range in the Arequipa Department.

Elevation Range	Stations (n)	Stations (%)	Area (%)
0-500	5	10.4	6.4
500-1500	4	8.3	20.5
1500-2500	6	12.5	17.1
2500-3500	14	29.2	11.8
3500-4500	17	35.4	20.7
>4500	1	2.1	23.0
Total	48	100.0	100.0

locations were identified in seven watersheds overlapping with the Arequipa Department (Figure 3). Twenty-eight of the stations are located in the Quilca-Vitor-Chili and Camana watersheds, which are the main sources of agricultural, industrial, and urban water used in Arequipa (Stensrud 2016). Stream discharge monitoring in Arequipa started with one station in 1923; more consistent streamflow data collection started in the 1960s (Figure 4). Many stations were established to quantify resources in rivers that have since been regulated; these early stations were decommissioned or relocated over time following reservoir construction. As of March 2020, daily stream discharge is actively being monitored in 22 locations in Arequipa. Six of these stations are part of water management infrastructure controlled by AUTODEMA and represent regulated discharge from reservoirs. Nine hourly monitoring stations (three represent new locations; six coincide with existing stations) were installed in 2014 and 2015, but are currently only reporting river stage and cannot be used for hydrologic analysis until a rating curve is established.

These stations were evaluated based on the above criteria to determine their suitability for establishing hydrologic baseline conditions. Thirty stations met the data sufficiency requirement for some portion of their record, but ten were removed from consideration because of significantly modified seasonal cycles or annual flow statistics, with no usable pre-construction records.

Overall, 20 historic reference stations were identified to form a basic understanding of hydrology in the region (Table 3). Nine of these either have a period of record before management or are not managed. The other 11 still have some upstream management, but it was determined to have a minor influence on flow at this location. Record lengths vary from 5 to 53 years (16 years on average), and there is large variation in the years of record, so there is no overlapping climatological period. Drainage areas vary from 143 to 17,097 km^2. Watershed average annual precipitation is inversely proportional to watershed area, since larger watersheds incorporate more desert area on average. Runoff ratios therefore vary with drainage area from 0.7 to 0.17 (mean = 0.33), but these numbers are all dependent on delineated drainage area, which is highly uncertain for several watersheds.

Peak flow, MAF, and 7-day low flow rates increase with increasing drainage area (Figure 5), but the runoff rate tends to be lower for larger watersheds. Low flow varies from 27 to 309 m^3 day^{-1} km^{-2} and MAF varies from 179 to 1259 m^3 day^{-1} km^{-2}. ANOVA showed that a simple regional regression for the 100-year flood based on drainage area alone performed just as well as a model that included precipitation, probably because of the strong correlation between average precipitation and drainage area. The final regional regression shown in Figure 5 is statistically significant (p-value = <0.001; $R^2 = 0.793$).

Of the 20 stations identified as HRHN stations, seven are still in operation and have not had significant flow modification (The Sibayo station stopped reporting discharge in 1993, but stage data are available to present.). Of the 10 stations that failed the monthly data sufficiency test, two (Bella Union and Ocona) are still in operation and are believed to be free from upstream diversion and may be included as part of the future reference network, following a more complete evaluation of hydrologic modification. The hourly stage stations (Cuyau, Bolladero, and Socosani) installed in new locations in 2015 can potentially serve as reference stations following a more complete evaluation of hydrologic modification and publication of rating curves.

These 12 stations are proposed for inclusion in a FHRN. The stations vary in elevation from 23 to 3,880 m, with drainage area varying from 1,101

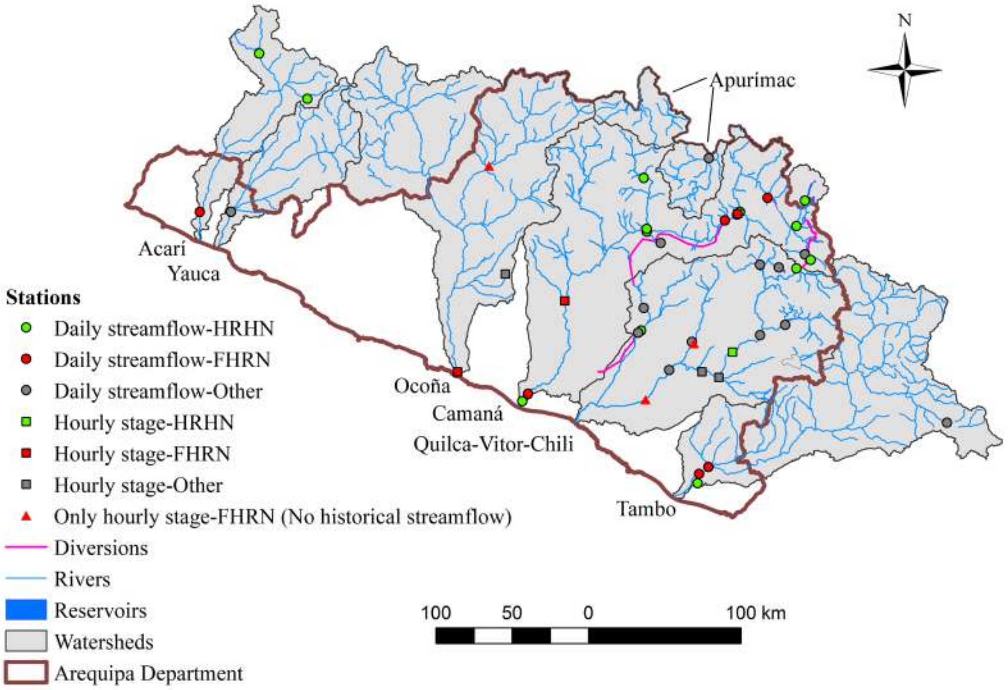

Figure 3. Locations of stream discharge monitoring stations in the Arequipa Department of Peru. Locations are marked by frequency and type of measurement (daily flow or hourly stage), and whether they meet the requirements to be part of the historic or future hydrologic reference network (HRHN and FHRN, respectively). Rivers, major diversions, and reservoirs are also identified on the map.

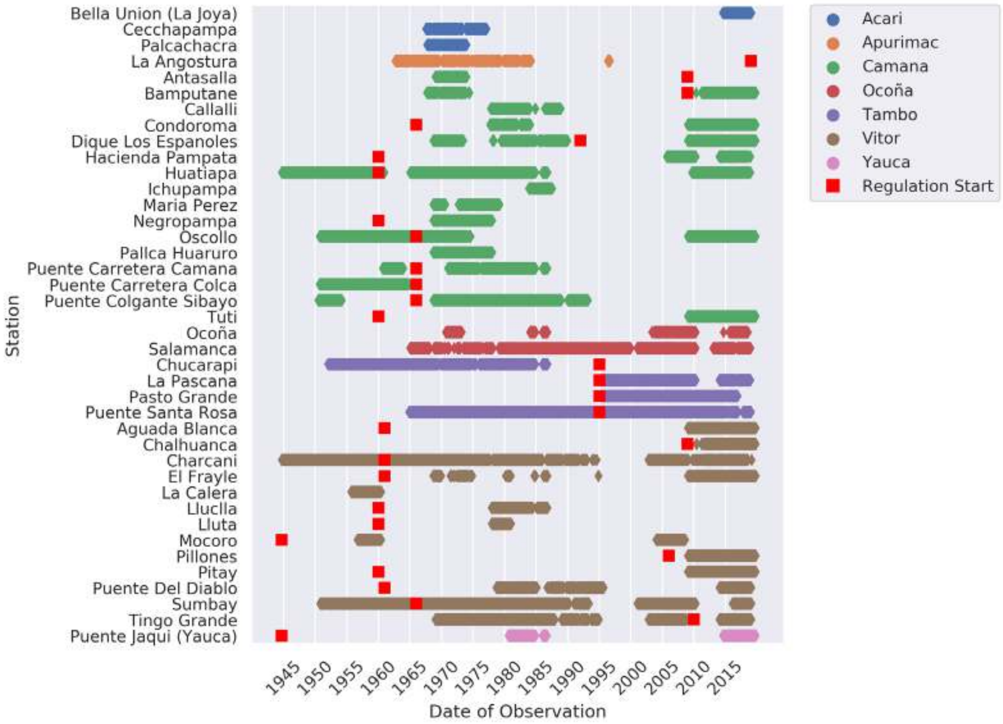

Figure 4. Dates of observations for all streamflow stations in the Arequipa Department of Peru. Color indicates the river basin in which each station is located. Start of upstream regulation (based on earliest regulation for stations downstream of multiple structures) is indicated for each station by a red square. If the start of regulation pre-dates 1944, then it is plotted as occurring in 1944 so that it appears on the figure.

Table 3. Summary of stream gauges that passed the assessment criteria for inclusion in a Reference Hydrologic Network for Arequipa. Includes dates of useful record, drainage area, suitability for use in the Future Hydrologic Reference Network (FHRN), and information on known upstream regulation.

Station Name	River Name	Years for Historic Reference	Drainage Area (km^2)	Suitability for FHRN	Upstream Regulation (Construction Date)
			Acari River Basin		
Cecchapampa	Rio Yanamayo	1969-1974	203	No, not active	None
Palcachacra	Rio San Jose	1968-1973	829	No, not active	None
			Camaná River Basin		
Bamputane	Rio Jaguary	1968-1973	143	No, modified flow	Bamputane (2009)
Dique Los Espanoles	Rio Colca	1969-1989	276	No, modified flow	Los Espanoles (1992)
Hacienda Pampata	Rio Camana	2006-2016	17039	Yes	Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009), Tuti Diversion (1960)
Huatiapa	Rio Majes	1944-2018	12834	Yes	Tuti Diversion (1960), Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009)
Maria Perez	Rio Molloco	1969-1978	683	No, not active	None
Negropampa	Rio Molloco	1969-1977	5690	No, not active	Tuti Diversion (1960), Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009)
Oscollo	Rio Negrillo	1951-1966	202	No, modified flow	El Pane (1966)
Pallca Huaruro	Rio Molloco	1969-1977	1580	No, not active	None
Puente Carretera Camana	Rio Camana	1961-1986	17097	No, not active	Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009), Tuti Diversion (1960)
Puente Carretera Colca	Rio Colca	1951-1964	4074	No, not active	Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009)
Puente Colgante Sibayo	Rio Colca	1950-1992	4074	Yes	Condoroma (1985), Los Espanoles (1992), El Pane (1966), Bamputane (2009)
Tuti	Rio Colca	2009-2019	4322	Yes	Los Espanoles (1992), El Pane (1966), Bamputane (2009), Condoroma (1985)
			Quilca-Vitor-Chili River Basin		
Charcani	Rio Chili	1944-1961	4193	No, modified flow	El Frayle (1961), Aguada Blanca (1971), Pillones (2006), Chalhuanca (2009), Canal Zamacola water transfer (1966)
Lluclla	Rio Sihuas	1978-1986	1466	No, not active	Tuti Diversion (1960)
Sumbay	Rio Sumbay	1951-1966	721	No, modified flow	Canal Zamacola water transfer (1966)
			Tambo River Basin		
Chucarapi	Rio Tambo	1952-1986	13005	No, not active	Pasto Grande (1995)
La Pascana	Rio Tambo	1998-2015	11878	Yes	Pasto Grande (1995)
Puente Santa Rosa	Rio Tambo	1965-2018	12891	Yes	Pasto Grande (1995)

to 17,039 km^2. The earliest record started in 1944 (although there are only 47 years of data) and the latest began in 2015.

Water Quality

Water quality monitoring has been overseen by a number of agencies as well as through short-term academic studies; however, official monitoring of water quality in Arequipa by ANA started in 2011. Although these earlier and smaller scale monitoring efforts are potentially useful for specific purposes, this study focuses on the current, regional-scale monitoring infrastructure.

Currently, water quality sampling does not occur at fixed, uniform station locations; instead, stratified sampling is conducted in different river basins for a period of time. This results in differences in the number of samples taken during a campaign (from 16 to 46), and differences in the number of parameters recorded (from 32 to 50) (Table 1). Samples have been collected from approximately 210 measurement locations across Arequipa focusing on the four major river basins that pass through the Department (Figure 6). Sampling frequency is as little as once in four years, and at most four times per year (in the Quilca-Vitor-Chili watershed in 2014). There is also variation in the timing of the sampling, with no consistency in the months when sampling is conducted within a watershed.

ANA's water quality network sampling locations are sparse and well distributed in all of the evaluated watersheds (Figure 6), with the exception of a cluster of sampling locations located around the city of Arequipa. Monitoring locations are tied to places with easy access to the river and landmarks that are easily identified to promote repeat sampling (see e.g., ANA 2013). The spatial distribution of existing sampling sites captures flow from major tributaries of the river networks. This network seems to focus on identifying local sources of contamination, such as city waste dumps, mining, agriculture, and known sources of natural contaminants. The reports do not provide a thorough explanation of how the sampling locations were chosen, but do provide detailed information about each location and discuss the possible sources of contaminants, when those are found in the samples (see e.g., ANA 2013).

The Colca River was chosen as a case study to evaluate the water quality network design because it is an important local water supply for residential

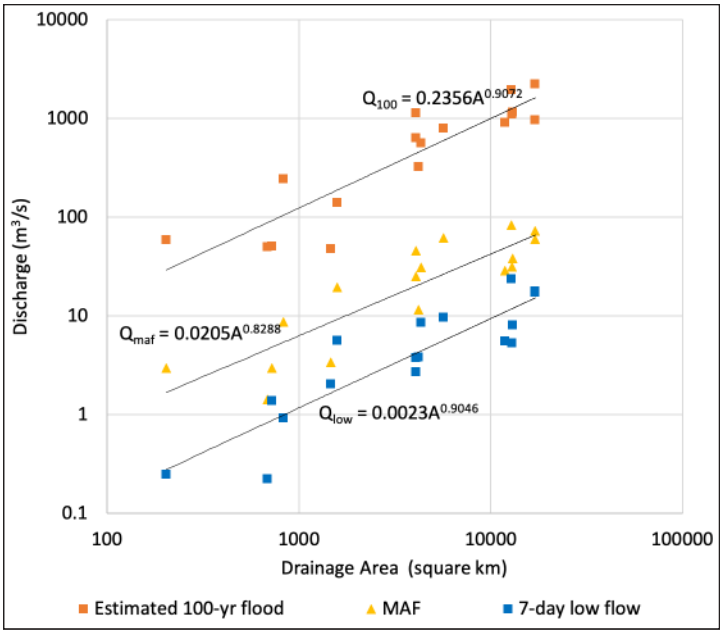

Figure 5. Baseline hydrology for the Arequipa Department of Peru, including the estimated 100-year flood based on a fitted EVI distribution, 7-day mean low flow, and mean annual flow based on 21 Historic Reference Stations with different reference years (see Table 2), using the historic reference years identified in Table 2.

use and agricultural activities, as well as a tourism destination (Garcia Quijano 2018). Additionally, the Colca River is an important conduit for water transferred from the headwaters to the Siguas River to supply the Majes irrigation district.

For this network design case study, we considered the water quality results from the monitoring campaigns carried out by ANA in 2013 and 2014 and the presence of geographic elements that represent risks of natural and/or anthropogenic contamination. In the 2013 and 2014 campaigns, ANA sampled six locations in the Colca watershed in October 2013, March 2014, and August 2014 (Figure 7). With respect to location, ANA 1, 2, and 3 correspond to the inflow and the outflow of the Condoroma reservoir, upstream of any suspected sources of anthropogenic contamination (pH was higher than normal and thermotolerant coliforms are present), and a proposed water transfer from the Apurimac basin (Figure 7). ANA 4, on the main stem of the Colca River before the intake for the Tuti diversion, has a drainage area of approximately 4,300 km^2, with high values of arsenic and thermotolerant coliforms. There are two potential sources of contamination upstream of this point on the Pulpera River. Point of interest (POI) 1 is downstream of a lime factory, while POI 2 is a solid waste dump in the Callalli district, which is located only 80 m from the river. Monitoring sites at POI 3 and 4 would allow a baseline measurement for attributing water quality changes to the reservoir or to potential sources located further downstream. At ANA 5, under the Tapay Bridge, high values of arsenic, cadmium, and thermotolerant coliforms were detected. Between ANA 4 and 5, there is potential contamination from solid waste dumps located near the river, actively eroding gorges (quebradas) and active agricultural areas (POIs 5-8). This includes wastewater treatment from the town (population 6,500) that is set along the Colca River and one of its tributaries. ANA 6 is at the exit of the Mamacocha Lagoon, which then flows into the Colca River. In this location, no parameters exceed the established standards; however, thermotolerant coliforms have not been analyzed.

Discussion

Climate Monitoring Infrastructure

Arequipa is a region of significant topographic variability and climatic extremes, including being heavily influenced by El Niño cycles (Dore 2005; Meehl et al. 2005). While climate observations for some locations started as early as the 1930s, stations have traditionally been sited closer to population centers where they can be maintained than the higher altitude regions that are more sensitive to climate shifts. Additionally, the regional network

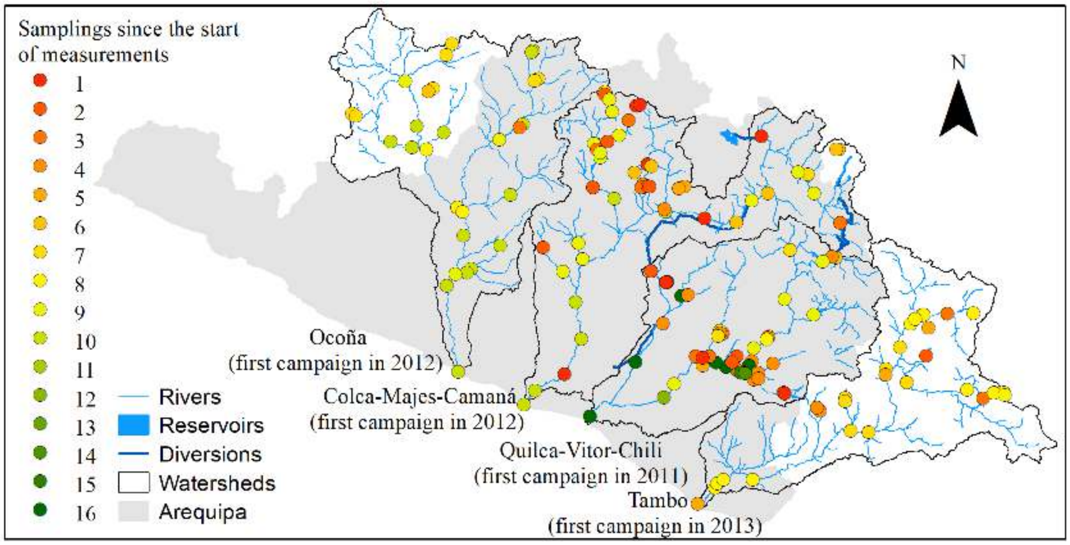

Figure 6. Spatial distribution of water quality measurements performed by the National Water Authority (ANA) from 2011 to 2019 in the four main watersheds in the Arequipa Department. Points represent locations and fill color represents the number of samplings done since the start of measurements.

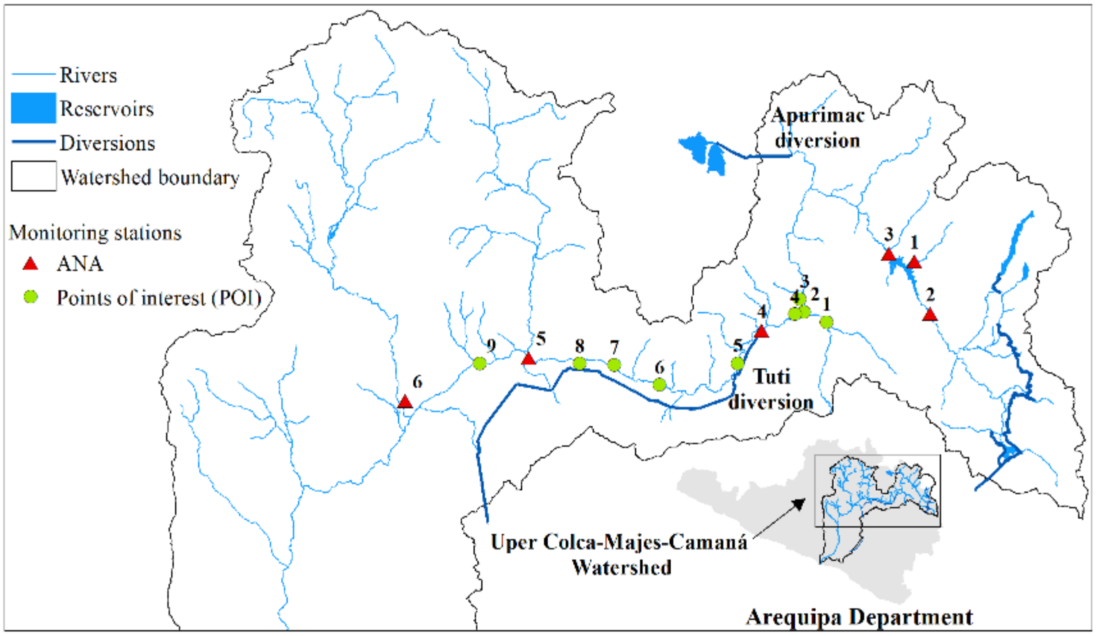

Figure 7. Proposed monitoring network for the upper Colca-Majes-Camaná watershed. ANA – monitoring locations where the National Water Authority has sampled previously. Points of interest – locations for future measurements.

is hampered by data collection problems, and a lack of publicly available metadata.

The Arequipa Department has low weather station density (7.4 stations per 10,000 km^2), especially when considering the great climatic and topographic variability of the region. For comparison purposes, the average station density in the United States (stations measuring air temperature and precipitation) is approximately 33.3 stations per 10,000 km^2 (MADIS 2020). A lower station density in the desert area can potentially represent the climatic characteristics of the region given its very consistent climate; however, most of the stations in the area are either on the coast or surrounded by massive irrigation projects. Stations on the coast are significantly influenced by the ocean (Daly et al. 2002; Daly 2006), while the large irrigation projects have a cooling effect on the local climate, which significantly impacts Tmax (Kueppers et al. 2007; Lobell and Bonfils 2008; Kueppers and Snyder 2012). The increased evaporative cooling around the irrigation districts may influence local weather conditions causing the formation of localized microclimates that increase the need for more weather stations to provide better data for irrigation management.

Areas of increased station density are mostly located in and around population centers. This is likely due to ease of access, lower installation and maintenance costs, and community interest in local conditions, but this trend in placement can lead to a bias in the homogeneity of the network (Arsenault and Brissette 2014). According to Moraes et al. (2019), precipitation in the region increases significantly with altitude. Because most measurements are in the valleys, it is likely that regional precipitation is being underrepresented by the current measurement network. Areas over 4,500 m of elevation represent 23% of the Department's area and the majority of the water supply, but there is only one station, at an altitude of 5,800 m (Table 2) monitoring that environment.

The city of Arequipa has often witnessed devastating flooding events (Cacya et al. 2013; Thouret et al. 2013) that are potentially being intensified by climate change, especially in El Niño years (Dore 2005; Meehl et al. 2005). These strong precipitation events can be very localized and are often not detected by the current station network. For example, during an event that occurred on January 8, 2013, the La Pampila station measured 124.5 mm, while the two nearest neighboring stations (both within 10 km) measured less than

6 mm on the same day. More specifically, there is no weather station on the slopes of Misti, the volcanic mountain that towers over the city of Arequipa. Flash floods in the ravines on Misti's slopes are a significant concern (Mazer et al. this issue). Another shortcoming is the lack of high temporal resolution data, especially precipitation. High temporal resolution precipitation data are necessary for precipitation intensity calculations, one of the most important factors influencing runoff and flooding extensions (Bronstert and Bárdossy 2003).

SENAMHI has increased the number of weather stations and modernized its station network in the last decade with the addition of automatic stations. Prior to 2013, most of the weather stations in the Department relied on manual readings of temperature and precipitation. Quality data from manual networks rely on the skill, training, equipment, and support provided to the observers (WMO 2018), and observer errors are a well-known source of uncertainty (Hunziker et al. 2017). Only seven stations in Arequipa have data from the 1960s and less than 5% missing data; however, the overall percentage of missing data is reasonably low and consistent through time. Quality issues can also arise during the transmission of data, such as the mobile phones used by some Peruvian stations (Hunziker et al. 2017). According to Fiebrich and Crawford (2009), the automatization of a network results in a clear increase in data quality, although the automated stations in the region (AUTO and HYDRO) were found to have the greatest range in missing data percentage. This indicates that simply automating a station network will not guarantee better data quality as many other problems such as poor maintenance, technical defects, thievery, or vandalism, may arise. Automation of climate stations is on-going, and we also have observed an evolution in the SENAMHI website over the last couple of years that has facilitated access to the data. This recent investment in climate measurements will hopefully decrease data inconsistencies and increase access to metadata in the future.

Hydrology Monitoring Infrastructure

The short span of data collection and high percentages of missing data, and flow alterations caused by upstream regulations, limit the potential for long-term hydrological analysis in Arequipa. It is generally recommended that reference stations have 20 to 25 years of data for evaluation of environmental trends (Bradford and Marsh 2003; Whitfield et al. 2012). Here, we included stations with records as short as five years in order to estimate baseline hydrology. Only three of the active stations identified have record lengths greater than 20 years.

The overall station density shown in Figure 3 is reasonable, but stations were either installed to estimate flow potential for later reservoir construction, or to monitor current water transfer through the system. No active stations were identified with a drainage area less than 1,000 km^2. Small natural upland gauged catchments are needed in order to distinguish climate-driven changes in the frequency and magnitude of floods or droughts from those due to more immediate and direct anthropogenic causes (Bradford and Marsh 2003). As mentioned above, flash floods are a concern in many areas around Arequipa, but there have been no gauging stations historically that can help to quantify flood hazard in these <100 km^2 watersheds (Mazer et al. this issue).

The discharge monitoring network also suffers from a lack of transparency and metadata. Station locations reported on the SNIRH website often only include a degrees-minute precision, resulting in significant uncertainty in site location. Even official water resources publications do not include drainage area or precise descriptions of the station locations (see e.g., ANA 2013). For the main stream stations, the gauging location is relatively clear, but for the smaller watersheds, the delineated drainage areas used as a basis for summary statistics are highly uncertain.

Water Quality Monitoring Infrastructure

The monitoring network presented by ANA shows a reasonable spatial coverage in the four watersheds. Monitoring campaign results from 2011 to 2019 serve as exploratory research for identification and confirmation of contaminant sources; however, the low sampling frequency and inconsistent timing cannot represent the effect of seasonal hydrology on water quality (Ouyang et al. 2006; Rodrigues et al. 2018). There is also a lag between when the time samples are collected and when lab analysis has been completed and certified, so the network has no real-time ability to report on water quality conditions that may pose a risk to humans. The mean seasonal discharge cycle shows the dominant influence of the monsoon climate with high flows from January to April and an extended low flow period from July to October. The Colca sampling campaigns in October, March, and August were well-positioned to capture the beginning and end of the dry season, and the peak of the wet season.

The motivation for stratified sampling campaigns with different locations, dates, and number of parameters measured in each campaign is not reported, but presumably there is some attempt to maximize station density and identify key parameters. Ramos-Herrera et al. (2012) reported that a long-term water quality monitoring network for the Tabasco River in Mexico was troubled by changes in the precision and accuracy of measurements over time, but has still proven to be an important source of information regarding the quality of water used by the inhabitants of the areas surrounding the Tabasco River. For a long-term monitoring network to detect environmental change, however, it is preferable to establish a regular, frequent sampling strategy at fewer sites, with the same set of indicator parameters (Lettenmaier 1978).

The network's spatial density is suitable for monitoring long-term change in water quality; however, to identify the source of specific human health hazards, a more focused water quality sampling network may need to be established in specific locations. For example, the proposed densification of the monitoring network for the upper Colca-Majes-Camaná watershed presented here as a case study for potential future modifications of the Department wide sampling network, is focused on attributing water quality contaminants to specific potential sources. New locations may need to be selected to help identify possible sources of contamination not captured in the ANA sampling regime, and placement of additional sites should factor in an improved ability to attribute contaminants to the correct source. Finally, informal mining is a significant problem in the region, and any monitoring network attempting to identify the source water quality contaminants must have the flexibility to add or remove locations when something like a large informal mine is identified and residents raise concerns.

Conclusions and Recommendations

Evolution of the weather monitoring infrastructure in the last decade is clear, with an increasing number of stations, better quality control, and ongoing modernization of equipment for measurement and data access. We recommend the following focus areas for future improvement: 1) the addition of stations in areas over 4,500 m of elevation and at the northwest of the Department would increase spatial representativeness of climate events of hydrology importance and reduce the bias of the measurements network in areas affected by canyons; 2) the addition of sub-daily, automated stations to the region, but specifically on the slopes of Misti, could increase the representativeness of and response time to destructive precipitation events; and 3) continued support for data collection and access, and the publication of up-to-date metadata for all stations.

It seems clear that the early discharge monitoring network was established to evaluate the feasibility of large-scale water infrastructure projects, and current monitoring quantifies water distribution throughout the system. In order to improve understanding of hydrologic change in the region, and improve flood hazard warnings, we recommend the following: 1) rating curves should be published for stage only stations and real-time reporting should be established; 2) the identified reference stations should be maintained to provide regular, daily measurements; 3) additional stations should be installed on small, unregulated, tributary watersheds; and 4) access to metadata should be improved, including improved station coordinates and drainage area information.

The evaluated infrastructure is relatively new and reflects the growing effort dedicated to water quality assessments in the last decade. Despite having several inconsistencies, the evaluated infrastructure can be used as the basis for the development of a more permanent network. We make the following recommendations: 1) establish regular, repeated monitoring stations, that are visited at least twice per year, with a shortened list of parameters selected based on local concerns; 2) identify locations to provide a balance between vicinity to sources and reliability in detection; and 3) results of water quality analysis should be made more accessible.

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