American Journal of Water Resources, 2025, Vol. 13, No. 2, 51-62
Available online at http://pubs.sciepub.com/ajwr/13/2/3
Published by Science and Education Publishing
DOI:10.12691/ajwr-13-2-3

Arequipa's Water in the Short Future: a Hydrologic Outlook in an Arid Peruvian Andes Region Utilizing Hyperresolution RCM and CREST-VEC Model Simulations Under SSP5-8.5

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Received May 02, 2025; Revised June 03, 2025; Accepted June 10, 2025

Abstract Climate change is anticipated to drastically impact South America differently in different regions. As a climate-vulnerable area, the Peruvian Andes region is projected to have hydrological changes that can potentially devastate the region. Leveraging the output of an existing hyperresolution Regional Climate Model (RCM) and a state-of-art hydrological model (Coupled Routing of Excessive STorage, CREST), this study examines changes in hydrological conditions in 2075-2079 compared to its semi-current state in 2015-2019 in Arequipa region under the Shared Socioeconomic Pathways 5-8.5 (SSP5-8.5) scenarios. The region would face a 19.8% runoff reduction, 83%-86% averaged streamflow reduction, and 37.8 days of wet season duration reduction. The Rio Chili would experience complete "no water" events in 2078 and 2079, and all the 1st order stream reaches would be dry more than 50% of the time between 2075 and 2079 compared to less than 40% of the time in 2015-2019. However, the flood risk would not decrease in the future, with the City of Arequipa expected to face at least one flood event that is more severe than its 2017 and 2019 floods, and Rio Colca would have many more flood events in the future.

Keywords: *Regional Climate Model, Hydrologic model, Peruvian Andes, future streamflow*

Cite This Article: Mengye Chen, Yongjie Huang, Xiao-Ming Hu, Ming Xue, Yang Hong, Hector Mayol Novoa, Elinor R. Martin, Renee A. McPherson, Siyu Zhu, Andres Vitaliano Peraz, José Luis Ticona Jara, and Isaac Yanqui Morales, "Arequipa's Water in the Short Future: a Hydrologic Outlook in an Arid Peruvian Andes Region Utilizing Hyperresolution RCM and CREST-VEC Model Simulations Under SSP5-8.5." *American Journal of Water Resources*, vol. 13, no. 2 (2025): 51-62. doi: 10.12691/ajwr-13-2-3.

1. Introduction

Under the IPCC Shared Socioeconomic Pathways (SSPs 5-8.5) prediction with Coupled Model Inter-comparison Project 6 (CMIP6), South America is projected to experience a 1.9 to 5.0 C surface temperature rise by 2100, compared to the pre-industrial level [1,2]. Climate change affects the region differently based on the location. In some places, there is an increase in extreme precipitations and floods [3], and in other places have increased aridification [4,5]. The Northern Andes glaciers melt at an unprecedented rate and cause a reduction in the local water supply among mountainous communities [6,7]. The El Niño–Southern Oscillation (ENSO) is believed to be affected by Climate Change, especially in the eastern part of the equatorial Pacific, where northern Peru and Ecuador are located. The impacts include increased frequency of extreme precipitation and droughts in the eastern equatorial Pacific area in non-stationary patterns [8,9,10]. When several or all of these climate change impacts happen simultaneously, or sequentially, they are considered cascading risks, which can stress the publication service system and existing infrastructure beyond their capacities [11]. All these climate-change-related impacts can heavily affect the residents living in South America, including livability and public safety [12].

The Global Climate/Circulation Models (GCMs) have been the tool for future climate studies [1,2,13,14], however, typical temporal-spatial resolutions from CMIP6 GCMs are 6 hourly to monthly and 1 – 3 arc degrees, with most members having daily and 1-ish arc degrees resolutions. These coarse resolutions are not ideal for direct applications in Climate Change impact assessments or local mitigation/adaptation decision-making [15]. The Regional climate models (RCMs) became the approach to provide higher temporal and spatial resolutions in future climate projections and historical climate reanalyses [16,17,18,19,20]. The approach assumes that the GCM outputs provide information to the RCM through lateral boundary conditions, and the RCM can simulate subscale information with a smaller domain, which has finer resolution and more accurate physical parameterizations to model the mesoscale atmospheric processes [21]. Statistical downscaling is one of the RCM techniques that extrapolate GCMs data by establishing empirical relationships between the GCMs and local in-situ observations, which requires less computational resources and can produce high resolution data globally [15,22] and regionally [23,24]. Dynamic downscaling requires a numerical modeling core and a set of parameterizations to simulate the evolution of atmospheric dynamics within and between each modeling grid [25], which is limited by computational resources but contains more physical meaning within the simulation if the model can pass the validation. Previous studies [20,26] have validated a hyperresolution South American RCM precipitation result against the NASA Global Precipitation Mission (GPM) Integrated Multi-satellitE Retrievals (IMERG) data and the historical rain gauge (450+ sites) measurements by SENAMHI, Peru. Both studies demonstrated that the RCM-simulated precipitation was a sufficient estimate for ungauged areas, and the performance was comparable to the satellite precipitation products. Other South American RCMs including Coordinated Regional Climate Downscaling Experiments (CORDEX, *Lake & Bukovsky, 2024; Nilsson & Lake, 2025*), and the studies done by Da Silva et al. (2023) and Cabos et al. (2019), all showed promising accuracy, but their horizontal spatial resolutions were larger than 10km. To assess the changes in local hydrology and water resources under Climate Change, the hyperresolution RCM and hydrological models are required.

Mediterranean and arid regions naturally experience floods and droughts regularly due to the consequences of irregular distribution of precipitation and high evapotranspiration [30]. For South America, a large portion of its population is concentrated along the west side of the Andes Mountains and the eastern Pacific Coast [31], which is dominated by the Mediterranean and arid climates [26,32]. Hydrological extremes (flood and drought) can change the water resources availability, and hydrological connectivity, thus impacting the freshwater ecosystem and its eco-services for human livelihoods [33]. While flood is capable of causing devastating damage and fatality to society [34,35,36], drought and hydrological contraction can often cause a decline in water availability, quality, and habitat sustainability, through increases in water temperature, salinity, and toxic cyanobacteria [37,38,39]. Peru is a country that is particularly vulnerable to hydrological extremes [40]. On one hand, Peru has been devastated by flash floods throughout history, caused by ENSO events, the southward migration of the Inter Tropical Convergence Zone (north Peru, *Son et al., 2020*), and Monsoon Convection via easterly aerial rivers (south Peru, *Poveda et al., 2020*). On the other hand, Peru's economy heavily relies on agriculture, of which 31% of the national Economically Active Population (EAP), and 65% of its rural EAP are in agriculture, and 51% of its agricultural land requires precipitation as water sources [42]. A few studies have suggested a pessimistic future for Peruvian hydrology conditions toward the end of the 21st century: Pino-Vargas et al. (2022) used a future snapshot approach and indicated there would be 220% peak flow increases for Devil's Creek at Tacna, Prue under SPS5-8.5 scenario; Brêda et al. (2020) conducted a rather macro hydrological study across the entire South American using the original CMIP5 project members, and the results suggested that the Peruvian Andes would expect increases in streamflow. Wongchuig et al. (2018) managed to dynamically downscale the HadCM3 GCM output and suggested that the Mantaro River Basin, Peru would face a 45% water availability reduction and strong aridification singles under SPS5-8.5. The previous studies have inconsistent findings, which need to be further investigated.

This study focuses on the Arequipa region where the second largest city of Peru is located. By continuing efforts of a hyperresolution (3-km) dynamically downscaled CMIP6 (multi-members ensemble mean) climate datasets by Y. Huang et al. (2024), we conducted a hydrological analysis for an important political-economic region in Peru. The objective of this study is to examine the projections of future climate under the SSP5-8.5 scenario and its impact on hydrological conditions at hyperresolution (250m, hourly) in the Arequipa region over 5 years from 2075 to 2079, compared to a semi-recent past from 2015 to 2019. This work forecasts the future hydrological outcome in the Arequipa region, including runoff, streamflow, river network contraction/expansion, aridification risk, and flood risk. The rest of this paper is organized as follows. Section 2 describes the study area, the CREST-VEC model, and the RCM dataset as well as other related data for hydrological simulations. Section 3 presents the results in runoff, streamflow, river network changes, and flood risk. Section 4 discusses the major findings from the results. Section 5 concludes and proposes future studies.

2. Ease of Use

2.1. Study Area

Arequipa is situated in southwestern Peru (Figure 1) and is one of the country's 25 administrative regions. The City of Arequipa is the second largest city in the country. It is bordered by the regions of Ica to the north, Ayacucho to the northwest, Apurímac to the west, Cusco to the southwest, Moquegua to the south, and Tacna to the southeast. The Pacific Ocean lies to the southwest of the region. This area has three distinct natural zones: the coastal desert, the Andes Mountain range, and the highland plateau. As shown in Figure 1, the Arequipa basin contains two sub-basins, which are the Río Chili basin (southern) and the Río Colca basin (northern). The elevation of the region has drastic changes from the coast towards the inland, ranging from sea level to more than 6,000 meters. The average slope of the basin is 12° with a maximum of 46° in the Colca Canyon, which is one of the deepest canyons in the world. The Río Chili flows through the city of Arequipa, the capital of the region, and the river is essential for local agricultural activities, so the river is heavily consumed for irrigation. Since irrigation data is not available, and under the scope of this study, irrigation is not included in the simulation and the focus is on the change of water availability between current and future.

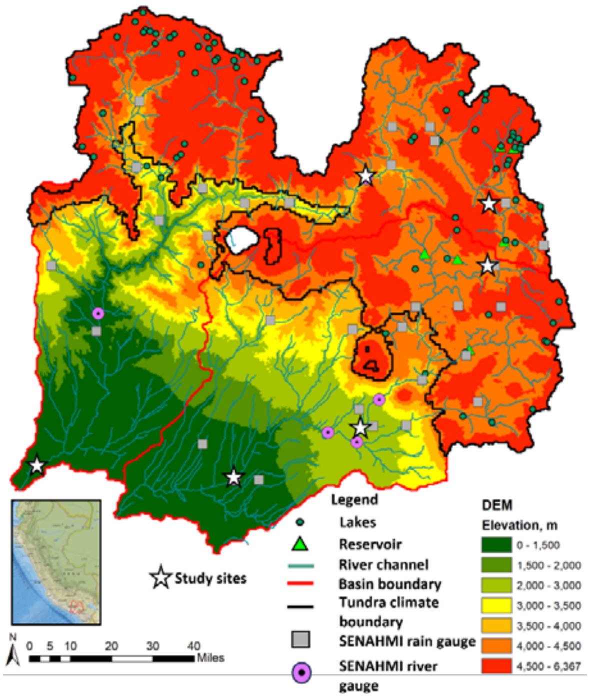

Figure 1. Arequipa region, the study area

2.2. CREST-VEC Hydrological Model

CREST-VEC is the newest advancement of the CREST hydrological model family, which was developed in 2022 [46]. This framework loosely couples three executables of CREST [47,48,49,50], EASYMORE (https:// github.com/ ShervanGharari/EASYMORE), and mizuRoute [51], so it takes advantage of the proven CREST water balance features and the fast computing speed of the vector water routing scheme. The main reason to use the CREST-VEC framework in this study is that the Arequipa region is arid [26], and lakes and mountain snow dynamics are the crucial water storage and sources, respectively, for the local river network. With the lake module included in the CREST-VEC framework [46], the hydrological simulation can be more realistic than using CRESTv3.0.

To set up the model the initial state of all lakes was assumed 60% of their full storage volumes for each of the historical and future simulations. For the reservoirs that have been monitored by Peruvian ANA, we directly insert the discharge time series into the model for both historical and future simulation, which assumes that the reservoir management is the same between 2015-2019 (Past) and 2075-2079 (Future). We also assume that there is no engineering change in the river networks between historical and future simulations, such as new reservoirs/dams, and canals nor aggressive changes in urbanization/suburbanization. To warm up the hydrological model, the WRF simulated climate outputs in 2014 and 2074 are used to force the CREST-VEC model. The hydrological simulations are at the hourly resolution to capture time-sensitive flood events.

2.3. Regional Climate Model and Data

The climate-forcing data for the Past and the Future used in this study are from the Weather Research and Forecasting (WRF) model V4.2.1. The detailed WRF model setup was clearly described in the previous studies [20,52]. To describe the model setup briefly, Hourly data from the fifth major global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ERA5, *Hersbach et al., 2020*); are used for initial and boundary conditions for the simulations. Two one-way nested domains with 15- and 3-km horizontal grid spacings are used, which cover the entire South American and Peruvian central Andes regions, respectively. Both domains are configured with 61 stretched vertical levels, extending up to 20 hPa, employing a Mellor–Yamada–Nakanishi–Niino (MYNN) level 2.5planetary boundary layer (PBL) physics scheme. The historical simulation spanned the period from 2014 to 2019 using the first year as the WRF model spin-up period. This model setup was evaluated in a previous study that produced a precipitation simulation that reasonably approximates the observed precipitation data [52]. For future climate simulations, the model setup is relatively different. As there is no reanalysis nor observation of climate data for the future, the CMIP6 SSP585 bias-corrected multi-model ensemble product [54] was used for the initial and boundary conditions. The WRF simulation for the future is conducted under the SSP585 scenario. The detailed model configuration can be found in the previous study [45], and the future climate simulation period is from 2070 to 2080. The WRF simulation data used for hydrological modeling and analysis are from 2015 to 2019 as the Past and from 2075 to 2079 as the Future. Since the WRF simulated RCM climate data cannot be as accurate as remotely sensed data nor the climate data measured with in-situ methods, we chose not to use the observed climate data for this study.

Other data used in this study include the Digital Elevation Model (DEM) and Global Lake data from HydroSheds (https://www.hydrosheds.org, Lehner et al., 2008), at 15 arc-second resolution. The river network data from MERIT Hydro [56]. The local reservoir discharge data was collected through the Peruvian National Water Authority (autoridad nacional de agua, ANA) and its Data Analysis and Statistical Water Resources (Análisis de Datos y Recursos Estadísticos del Agua, ANDREA) system (https://snirh.ana.gob.pe/ANDREA/). The land use data was obtained from the European Space Agency (ESA) WorldCover project, for its WorldCover 2021 v200 product at 10-meter resolution that represents the land cover and land use conditions around the year 2020 [57].

3. Results

3.1. Overall Water Availability

The previous study [45], concluded that there was an increase in the annual average and intensity of precipitation in most of the Peruvian Andes region, including most of Peru and the western part of the Brazilian Amazon. However, in arid regions, like Arequipa, the daily average precipitation will be reduced in the Future (2075-2079) by roughly 30%. On the other hand, the same study indicated that the variability of precipitation increases in the Future, and the frequency of extreme precipitation events (99.9th percentile) increases by 16.9% compared to the Past (2015-2019) in the area including the study area in this work.

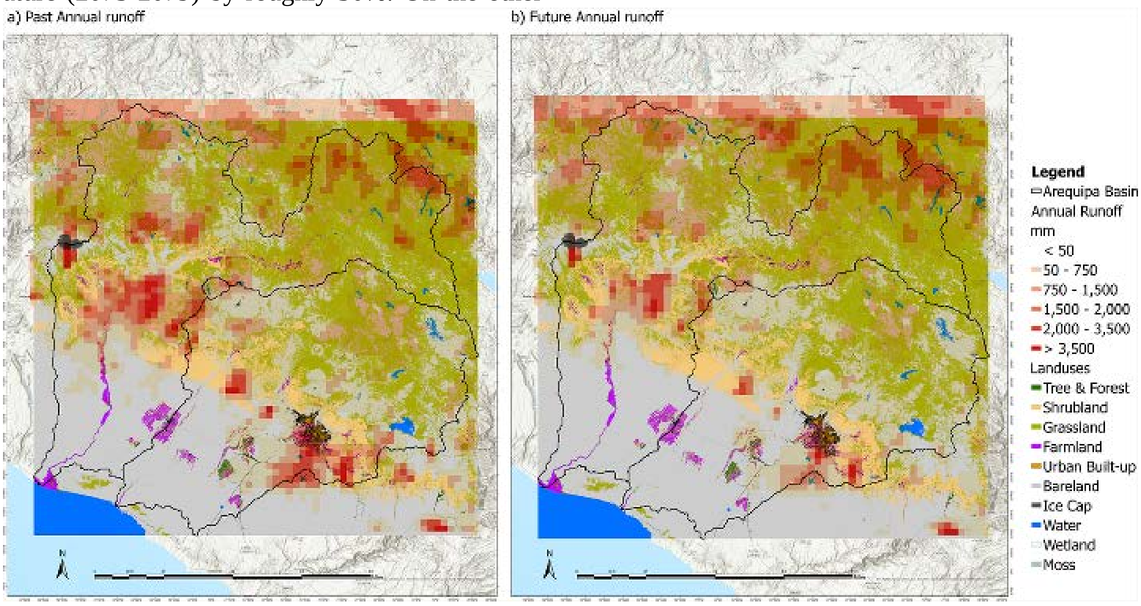

Figure 2. The 5 years accumulative runoff in the Past (a) and the Future (b). Overlaid with landuse/landcover

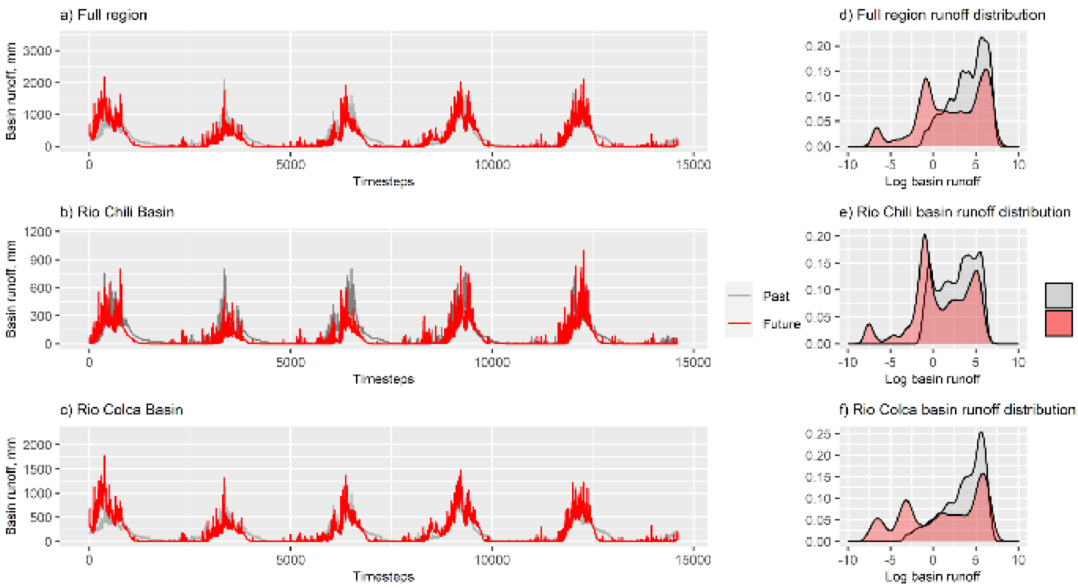

Figure 3. The basin total runoff for the entire region (a), Rio Chili (b), Rio Colca (c), and their corresponding log-runoff density distributions (d-f)

Consequentially, in Figure 2, the surface runoff of the study area showed a shift toward the north and toward the mountains in the Future. Especially the Río Chili basin (southern) appears to have many more ‘blank’ pixels, which means the 5-year averaged annual runoff is less than 50 mm and the higher value pixels are less in the south. As the surface runoff moves north into the Andes Mountains, this means that the cities and developed areas that are built off the mountains will have much less water in the future. For example, the City of Arequipa and its downstream agricultural region are expected to receive much less surface runoff in the Future. This means that the human establishments and the agricultural activities in the Arequipa basin will become more dependent on the stream water. Figure 3 shows the surface plus subsurface runoff changes over the 5-year courses for the Past and the Future in the Arequipa basin and its sub-basins.

In total, the cumulative runoff of the Arequipa region from the 5-year period in the Future reduces by about 19.8% from 3,438 meters to 2,759 meters in the Future. In the Rio Chili Basin, where the city of Arequipa is located and has more human activity, the reduction of cumulative runoff reached 39.9% in the Future compared to the Past, which is expected to experience more water reduction. In the Rio Colca Basin, which is less developed, the reduction of cumulative runoff was 9.3% in the Future compared to the Past. Overall, the entire Arequipa region will receive less water in the Future, but the more developed basin, the Rio Chili Basin, will experience much more reduction, which can devastate local human activities and agriculture. In Figure 3 d-f, the distribution of the basin-total runoff for the whole study region (d), Rio Chili Basin (e), and Rio Calco Basin (f) all showed increased time when the runoff is less than 1 mm (0 at log scale) and decreased time when the runoff is more than 100 mm (2 at log scale) in the Future compared to the Past. Especially for the Rio Chili Bain, the time for the basin-total runoff greater than 1 mm dramatically decreased in the Future compared to the Past. The previous study [45] emphasized the increase in the frequency of intensive precipitation could potentially cause more flooding in this study area, which would lead to infrastructure damage and economic losses. However, the increase in the frequency of intensive precipitation does not directly translate to an increase in the frequency of intensive surface runoff. In Figure 3e, the frequency of extreme (10^7 mm) basin-total runoff did not increase in the Future compared to the Past, which matters more since the Rio Chili Basin is where the urban development is located and most human activities occur. The frequency of extreme (10^7 mm) basin-total runoff slightly increased in the Rio Colca Basin in the Future compared to the Past, which is more underdeveloped, and the potential flood hazard in the Future could threaten the local tourism and remote communities living in the mountains.

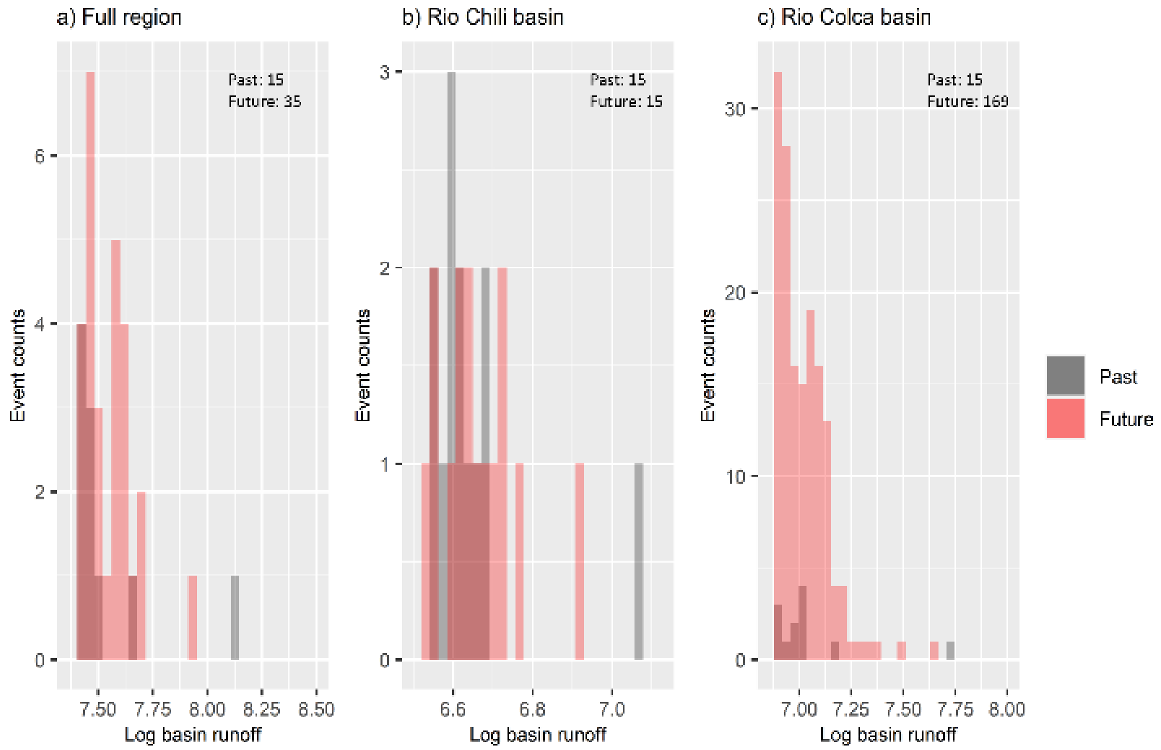

Figure 4. The extreme runoff event histogram and event counts for the entire region (a), Rio Chili (b), and Rio Colca (c)

To further investigate the runoff intensity changes in the Future, we plotted the events histogram that are greater than 99.9% percentile events in the Past in each region (Figure 4). At the 99.9% percentile, there are only 15 events (4-month events for 5 years of data) in the Past for the entire region, Rio Chili, and Rio Colca. In the Future (2075-2079), the 99.9% percentile events increased from 15 to 35 events for the entire region and 169 events for the Rio Colca Basin. The results indicate that the extreme events will increase in the Future, where the 4-month event in the Past becomes the 2-month event in the Future for the entire region. Fortunately, the increase in the frequency of extreme events will be mostly concentrated in the Rio Colca Basin, where the likelihood of 99.9% percentile events increases over 11 times in the Future. Rio Colca basin is less developed with minimal urban built-up, which means that the increase of extreme runoff events might cause less economic damage in the area. On the other hand, the more developed basin, Rio Chili Basin, shows no change in extreme event frequency between the Past and the Future. The climate change under SSP5-8.5 will not post more flood threat for the City of Arequipa. This observation also proves the runoff-shifting phenomena that are displayed in Figure 2.

Table 1. The average difference of the wet season in the Future starting and ending time compared to the Past

Future-Past	Start (days)	End (days)	Duration (days)
Rio Chili Basin	-3.3	-43.5	-46.8
Rio Calca Basin	0.3	-28.2	-27.9
Entire region	-0.4	-37.2	-37.6

The other observation from Figure 3 is that the transition from the wet season to the dry season is much more pronounced in the Future compared to the Past. By analyzing the wet/dry seasons for the Arequipa region for the Past and Future, the results in Table 1 indicate that, on average, the wet reason for the Future is 37.6 days shorter than the Past. In particular, the wet season for the Rio Chili Basin was estimated to reduce by 46.8 days in the Future, and the wet season for the Rio Colca Basin was estimated to reduce by 27.9 days on average compared to the Past. The starting times of the wet seasons are relatively the same for the Past and the Future, however, the Future wet seasons ended much earlier. The end of the wet season is usually not when agricultural activities have the highest water demand, however, the shortened wet season for such an arid region can be very destructive for the local economy and ecosystem in the Arequipa region.

Table 2. The 5 years accumulative total runoff that lands on each landuse type

Landuse	Past (meters)	Future (meters)	Change
Tree & Forest	20.5	10.6	-48.2%
Shrubland	435.4	283.6	-34.9%
Grassland	965.3	674.9	-30.1%
Farmland	82.3	60.1	-27.0%
Urban Built-up	25.1	15.7	-37.3%
Bareland	1,405.3	1,307.5	-7.0%
Ice Cap	20.0	13.7	-31.6%
Water	124.4	111.4	-10.4%

Table 2 demonstrates the 5 years accumulative runoff changes based on different land uses in the Arequipa region. As an arid region, the study area is covered by vast bareland based on the ESA WorldCover 2021 v200 product classification. Consequentially, the bareland also receives the most runoff (1,405.3 m) compared to other land types over the 5 years period in the Past, and the changes of accumulative runoff in the Future was about 7% reduction, which was the least changed among all landuse/landcover types. All other landuse/landcover types that are related to human activities and local ecosystems show around 30% runoff reduction. A few land types that have significant reductions are Tree & Forest (48.2%), Urban Built-up (37.3%), Shrubland (34.9%), Ice Cap (31.6%), Grassland (30.1%), and Farmland (27.0%). The reduction of runoff in the urban area can reduce the stormwater management burden and reduce the risk of urban flooding in general. However, the forest and grass/shrubs can have significant ecological impacts from vegetation reduction to decreases in biodiversity. The runoff reduction for farmland in the Future would increase the water dependence from streams withdrawing for irrigation. The reduction of runoff from the Ice Cap in the future could be a more severe issue since snowmelt from the Andes is the major water source for this region, not rainfall. The runoff reduction from the Ice Cap in the Future can directly impact the water supply in the region. The reduction of water runoff and the spatial shift from low altitude to high altitude is a classic aridification phenomenon [58,59,60] that occurs in the Arequipa region in the Future.

3.2. Streamflow Reduction and River Network Contraction in the Future

Table 3. The median streamflow in the Past and Future at each study sites for Rio Chili and Rio Colca

Streamflow, m^3/s		Downstream	Midstream	Upstream	Full River
Rio Chili	Past	17.55	0.22	0.069	1.86
	Future	3.15	0.0016	0.00020	0.26
Change		-82.06%	-99.29%	-99.71%	-86.15%
Rio Colca	Past	6.77	49.34	22.47	5.03
	Future	0.95	9.46	4.03	0.85
Change		-86.04%	-80.83%	-82.09%	-83.02%

Three points of each Rio Chili and Rio Colca were selected for stream flow analysis (Figure 1), representing the downstream, midstream, and upstream. Figure 5 demonstrates the Past and Future streamflow at each timestep in 5-year spans in Rio Chili and the flow distribution. Table 3 shows the median flowrate at each selected point of both rivers and the whole river averaged flowrate. The full river averaged flowrate is calculated by averaging the flowrate over all reaches of the river at each timestep, which weights the value more towards the mainstems of the river, then finding the median value from the time series. The median value is chosen as the metric since the rivers in the Arequipa region have high volatility and from the water resource management perspective, the flow that is sustained most of the time in a river is more critical. The reason for weighing towards the mainstems of the river is that most of the water drawing activities in Arequipa are located in the mainstems.

From Figure 5, the reduction of streamflow during the drying periods (falling limbs) was clear, and the basin-averaged median streamflow reduction for Rio Chili was 86.15%. The upstream showed more reduction, where the median streamflow at Sumbay station in the Future is as low as 0.0002 m^3/s, which is lower than many commercial stream gauges' minimum detection level. Since the median is the value that has a 50% probability in the sample, the finding indicated that at Sumbay station, half of the time from 2075 to 2079 or more, the streamflow would be too small to be detected. The almost 100% median flow reduction at Sumbay indicates that the upstream of Rio Chili had serious river degradation, and the local ecosystem would be at risk. Moreover, the midstream of Rio Chili, where the City of Arequipa is located, had a 99.29% median streamflow reduction, which would negatively impact the city's livelihood.

Figure 6 demonstrates the streamflow comparison between the Past and Future at the Rio Colca basin. As explained in section 3.1, the runoff shifted from the south towards the Andes Mountains in the Arequipa region, the streamflows at 3 sites along the Rio Colca reflected the findings, where on many occasions the flow in the Future is greater than the flow in the Past during the wet season. However, the transition from wet to dry season was more rapid in the Future, which was the same as the Rio Chili. The median flow reduction for the Rio Colca was 83.02%, which was less severe than Rio Chili but it was still a significant reduction. Both the midstream (Tuti) and upstream of Rio Colca are in the mountains and had less flow reduction than the downstream, which indicated that the desert region, where the Rio Colca downstream (Hecienda) is located, would experience more intensive aridification. The streamflow distribution of both rivers showed a significant increase in low flow in the Future, which indicated that the river would get drier more often.

By setting 0.0003 m^3/s as the threshold of "no flow", we were able to compute the percentage of time that the river reaches above the "no flow" level, which is defined as Occurrence in this study. Figure 7 displays the occurrence of both rivers in the Past (a) and the Future (b). The first observation is that the high occurrence of river reaches (85+% of the time in 5 years) was dramatically reduced in the Future, which means that the river networks in the Arequipa basin contracted smaller and more frequently in the Future during dry seasons. The river reaches that have 50% to 75% occurrence were uncommon to see in the Past became the majority in the Future, especially for Rio Chili. This finding was synchronized with the findings in section 3.1, which that Rio Chili experienced more runoff reduction in the Future. However, the Rio Colca which had less runoff reduction also showed extensive river network reduction in occurrence in the Future. The more time the river stays dry, the greater risk poses to the local ecosystem, which is another indication of aridification as the local ecosystem becomes more fragile due to the lack of water. Table 4 displays the average river reach occurrences based on stream orders for the Arequipa region in the Past and Future. For Rio Chili, first, second, and third-order streams all faced over 20% reduction in occurrences in the Future, while Rio Colca only had its first-order streams that had over 20% reduction in occurrences. Moreover, Rio Chili's second and third-order streams showed more reduction in occurrences (about 5%) than the first-order streams, which could indicate future river cut-off at second and third-order streams. The fifth-order streams have the most river reaches flows into them, so the reduction in occurrences was limited. However, in the Past, the fifth-order streams were always 100% occurrence in all basins, which meant all time from 2014 to 2019 the streamflow was greater than 0.0003 m^3/s, so it was concerning to find that even the stream reaches that received water from many others faced no-flow times in the Future. For the entire Arequipa region, the first-order river reaches had less than 50% of occurrences in the Future, which indicated that the upstream of the Arequipa basin would be dry more than half of the time in the Future.

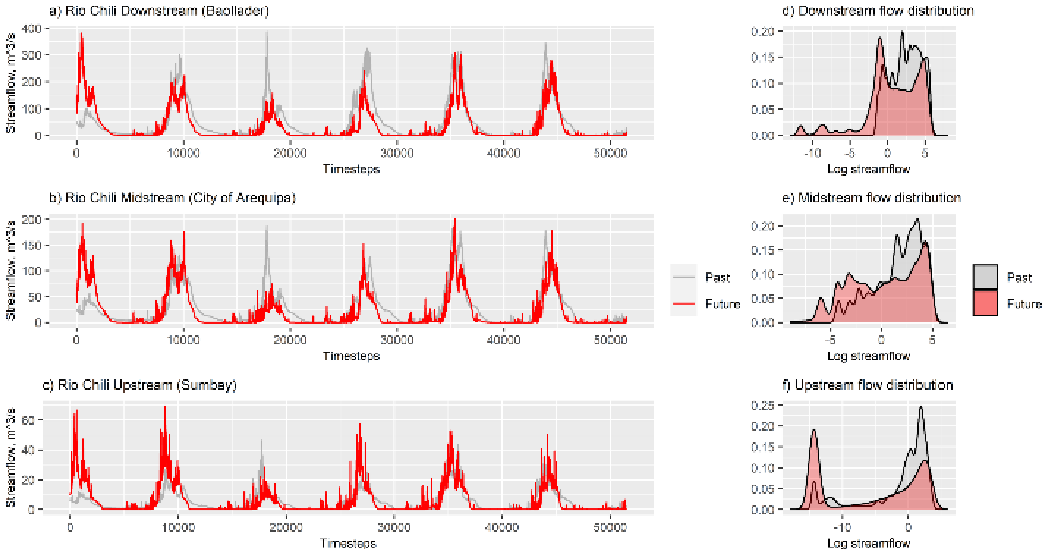

Figure 5. The hydrographs of Rio Chili at study sites of downstream (a), midstream (b), upstream (c), and their corresponding log-streamflow distributions (d-f)

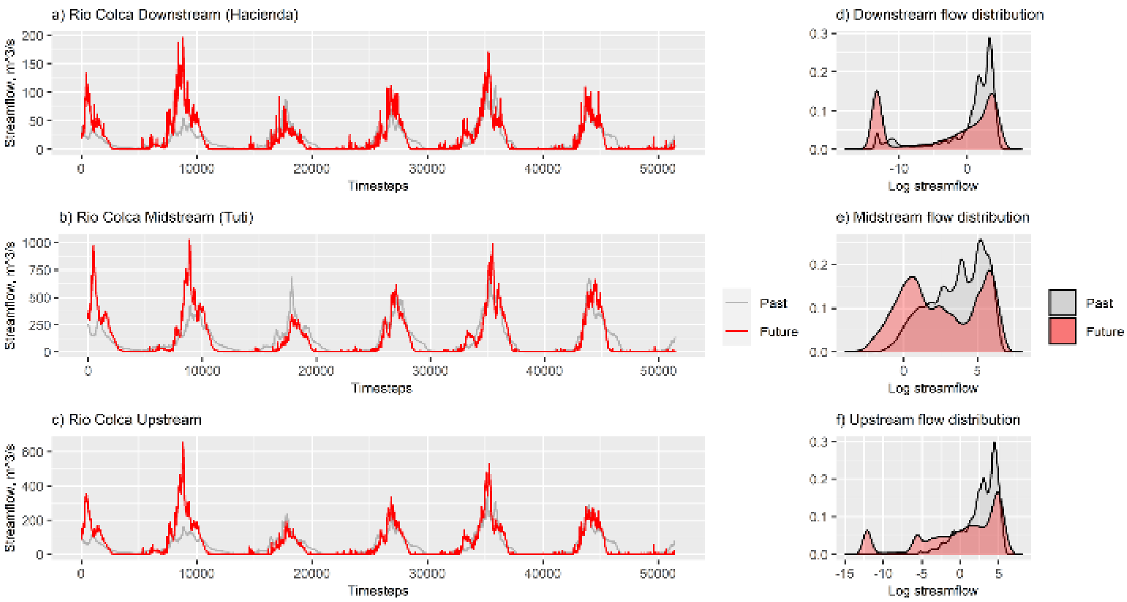

Figure 6. The hydrographs of Rio Colca at study sites of downstream (a), midstream (b), upstream (c), and their corresponding log-streamflow distributions (d-f)

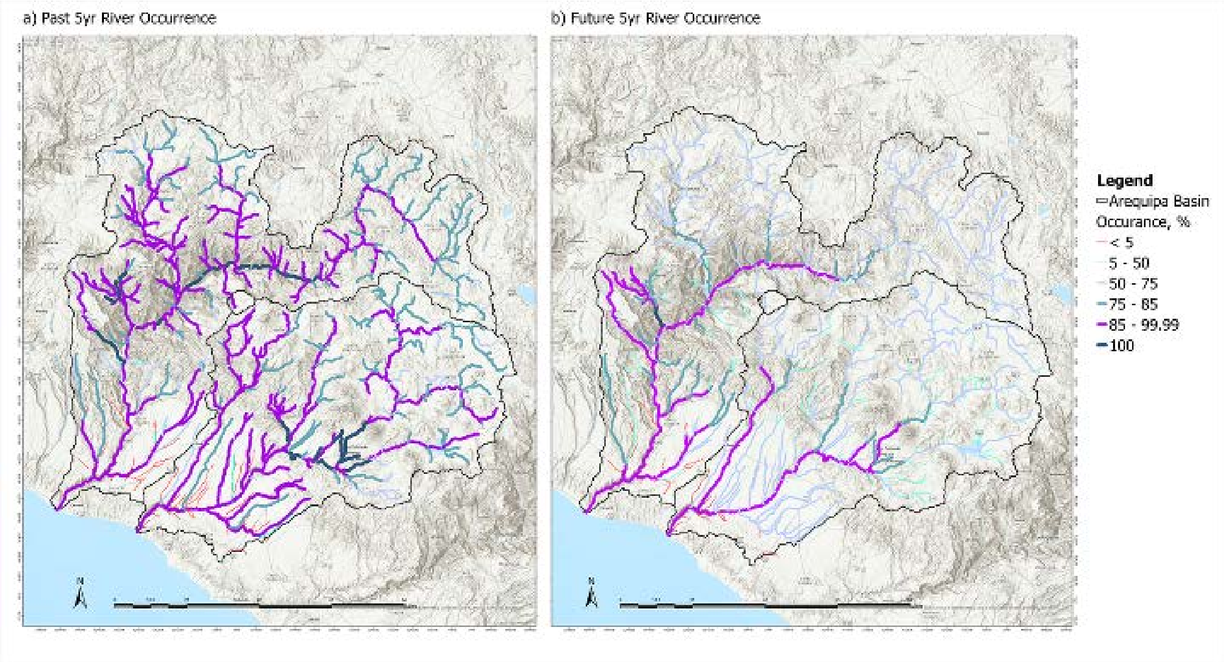

Figure 7. River network % occurrence over the 5-year period in the Past (a) and Future (b)

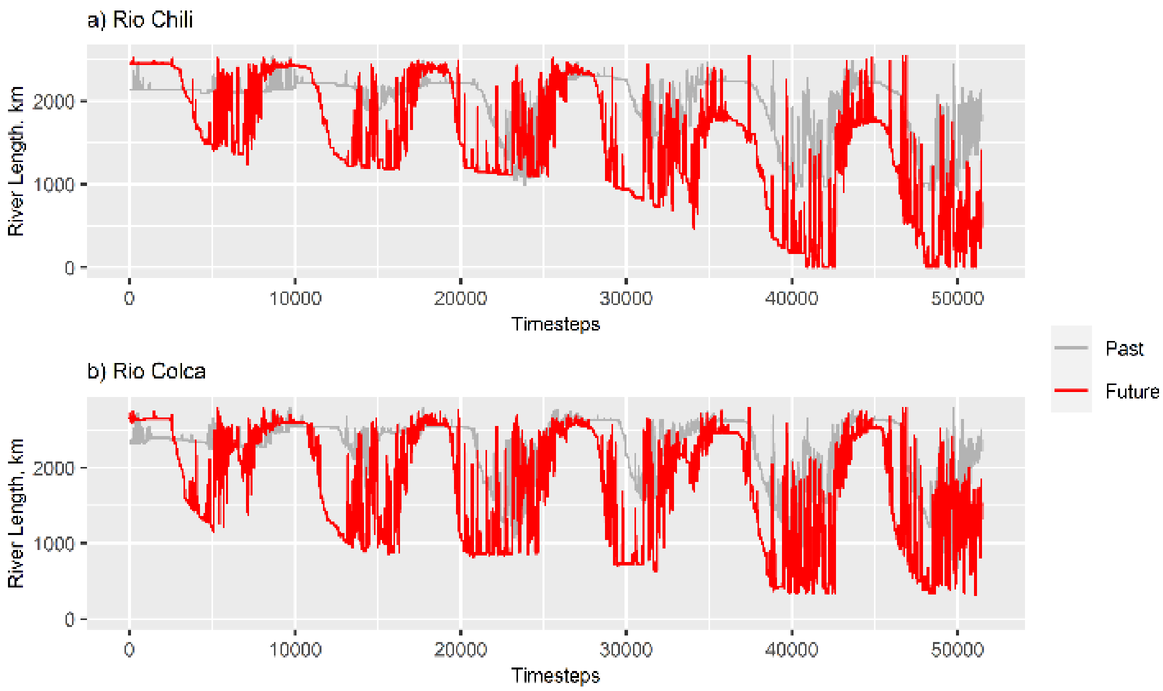

Figure 8. The total river length changes over the 5-year period in the Past and Future for Rio Chili (a) and Rio Colca (b)

Table 4. The average river reach % occurrence in the 5-year period in the Past and Future for different river orders

	Full Region			Rio Chili			Rio Colca		
Order	P	F	Δ	P	F	Δ	P	F	Δ
1	69.20	47.87	-21.33	67.04	46.64	-20.40	70.85	48.92	-21.93
2	82.63	62.23	-20.40	83.34	59.31	-24.03	82.09	64.45	-17.65
3	91.56	73.25	-18.31	92.95	69.32	-23.63	89.75	78.36	-11.39
4	96.93	81.62	-15.31	96.29	80.06	-16.23	97.18	82.24	-14.94
5	100.0	97.03	-2.97	100.0	95.42	-4.58	100.0	99.07	-0.93

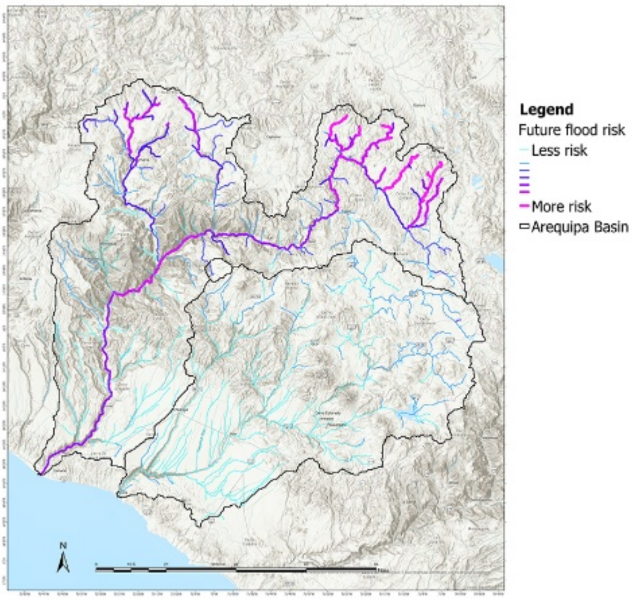

Figure 9. The river flood risk for the Arequipa region, the thicker and brighter purple river reaches indicates higher flood risk, and thinner and light blue river reaches indicates lower flood risk

Figure 8 shows the time series of corresponding total river length changes throughout the 5-year period in the Past and Future. The Future river length changes showed much shorter river lengths during the dry season compared to the Past, and the Rio Chili showed selective events that the total river length became 0 km, which meant the river completely dried out during these events in 2078 and 2079. The river lengths in the future showed more dramatic changes in the Future compared to the Past, which indicated the strong river contraction and expansion phenomena in the Future. The comprehensive understanding of river contraction and expansion's effects on aquatic chemistry and aqua-biology is not fully studied, but the preliminary studies have exposed such phenomena would help transform the local ecosystem to adapt to more arid climate conditions [61,62,63]. The full dry-out events of the Rio Chili in 2078 and 2079 under SSP 585 would be devastating to the local agriculture and economic activities, and the City of Arequipa should consider more water conservation methods, as well as inter-basin water transfer projects in the future to prevent this projection from happening.

3.3. Flood Risk

Table 5. The accumulative time that the Future streamflow is beyond the 5-yeard event in the Past at each study sites

Accumulative days beyond 5 yr event		
	Rio Chili	Rio Colca
Downstream	0.00	33.42
Midstream	0.42	40.58
Upstream	8.51	45.88

Strong flow and occurrence reductions in the Arequipa region do not exempt the area from flood risk. Table 5 summarizes the cumulative days that the stream flow rate selected in section 3.2 in the Future was greater than the 5-year event in the Past. The two river basins showed distinct differences in high flows in the Future greater than the 5-year event in the Past. For Rio Chili, the upstream site (Sumbay) was expected to have accumulated 8.51 days out of 5 years the streamflow was greater than the Past 5-year event in the Future. In the city of Arequipa (midstream of Rio Chili), the cumulative time of the streamflow greater than the Past 5-year event was less than a half-day (10 hours), which happened in two separate events in 2075 (3 hours) and 2078 (7 hours). In the Future, the city of Arequipa had no significant increases in flood risk compared to the Past, however, the prediction indicated that the city would at least have a severe flood event in 2078. The downstream (Baollader) of Rio Chili in the Future had its streamflow always lower than the 5-year event in the Past, mostly due to the flow reduction and contraction in the entire river network, as well as the local climate was lack of precipitation. On the other hand, Rio Colca at all three locations showed an accumulation of extensive time in the Future that had greater streamflow than the 5-year event in the Past, which means that Rio Colca would have much higher flood risk in the Future. The upstream of Rio Colca had more time (45.88 days) when its streamflow was greater than the Past 5-year event than the downstream (33.42 days). The finding is synchronized with the findings in section 3.1, which state that the runoff in the region shifted towards the Andes in the Future.

If defining the cumulative time of the streamflow in the Future is greater than the Past 5-year event, as the Future flood risk, the Future flood risk map was plotted for each river reach of the Arequipa region in Figure 9. The bright purple color represents the higher flood risk in the Future, mostly located upstream of Rio Colca close to the Andes, which indicates possible more mountain flooding in the Future. The main stem of the Rio Colca in the Future was also exposed to higher flood risk, which collects the increased extreme runoff from the mountains. In contrast, Rio Chili in general would not have increased flood risk in the Future, except for a few first and second-order river reaches in the mountain would have a marginal increased flood risk.

Overall, the Arequipa region was projected to have significant aridification signals from 2075 to 2079 under SSP585, including reductions in runoffs, streamflow, wet season duration, and river length in dry seasons (river contraction). However, the aridification would not exempt the region from flooding compared to the Past (2015 to 2019), and the flood risk would increase in the Future, but mostly concentrated in Rio Colca. The city of Arequipa was expected to have 1 flood event in 2078 from the Rio Chili that would be more severe than its 2016 and 2019 floods, meanwhile, the same river was projected to be completely dry for a few moments in 2078 and 2079.

4. Discussion

This study is based on the SSP5-8.5 and dynamically downscaled WRF and CREST-VEC simulations, which are typically considered the ‘worst-case scenario’ that the world is heading towards further globalization, fast technology innovations, and heavy fossil fuel consumption [14]. In this scenario, South America was projected to see 4.0 °C temperature increases by 2079 [2]. For an arid region like Arequipa, the increased 8.5 mW/m^2 forced radiation input (by definition of SSP5-8.5), would accelerate the hydrological cycle including evapotranspiration, snowmelt, etc. The findings in section 3.1 showed that the runoff is shifting toward the Andes in the Arequipa region could be a result of the raised radiation and temperature. The increased snowmelt leads to more runoff in the mountainous regions, and the combination of reduced precipitation [20,45] and increased evapotranspiration causes a significant reduction of runoff in the low-altitude regions. Unlike the Santa Ana Winds, which have been well-studied for their future diminishing trends [64], the similar hot and dry wind in the western Andes called the Puelche wind [65] has not been studied for its future pattern under Climate Change projections. It is unclear if the Puelche wind would be more intensive in the Future or its impact on the local hydrology, which will require further investigations. The WRF simulated outputs used in this study were validated with precipitation data but not wind data [20], therefore the model captured the change in the Puelche wind in the future is in question.

The Arequipa region has 6 major reservoirs upstream that control the flow of Rio Chili and Rio Colca, and there are heavy agricultural activities downstream of both rivers. In this study, the reservoir operations were considered the same for the Past and the Future. Meanwhile, the downstream agricultural water consumption was also considered the same for the Past and Future. However, these assumptions can hardly become a future reality, considering such a dramatic water availability reduction, human behavior should change accordingly. The following study involves agricultural modeling and water management sensitivity analysis [66] would provide more insights into the impact of aridification in the Arequipa region.

5. Conclusions

The dynamically downscaled future climate projections for South America motivate this study to explore Climate Change impacts on hydrology on the west side of the Andes Mountains, where rapid human activities and development occur. The local stakeholders can be better informed by estimated hydrological conditions including streamflow, runoff, flood probabilities, etc., in the projected future for decision-making. This study analyzes and estimates the runoff and streamflow in 2075-2079 (Future) and compares with the same data in 2015-2019 (Past) under SSP585, to find the following key conclusions: (i) the Arequipa region is projected to have strong aridification in the Future including reductions in runoffs, streamflows, wet season durations, and increases in river contraction compared to is hydrological conditions in the Past; (ii) the runoff clusters are projected to shift toward the Andes and the landcover related to human activities face significant runoff loss in the Future; (iii) the flood risk increases in the Future, mostly in Rio Colca and mountainous regions, even under severe aridification.

The present study is one of the first to explore the changes in “close-up” hydrological conditions in the Peruvian Andes in the future using dynamically downscaled hyperresolution climate data. These are important results for an already water-scarce region to look into one possible future outcome and for local stakeholders to prepare their water management plan and policies in the next 50 years. The findings have indicated that Climate Change would impact human activities in the Arequipa region under the SSP585 scenario. While the uncertainty of the future climate persists and this study only provides the “worst-case scenario”, immediate efforts to adapt to the negative impacts of other water stressors in Arequipa need to be promoted. With such a drastic water loss as projected in this study, more adaptive management of water resources is crucial for the local ecosystem’s existence, and not to lose the critical ecosystem services.

This study opens up a few future research paths based on the presented results, including future water management analysis, future Puelche wind in Arequipa and fire hazard projections, and future ecosystem development/degradation projections under the SSP585 scenarios. The water resource in Peru under Climate Change needs to be further studied and attract attention locally and internationally as the report indicated the water crisis in Peru could potentially destabilize the region [12].

ACKNOWLEDGEMENTS

This project was primarily supported by grant no. 20163646499 from the Universidad Nacional de San Agustin of Peru.

Availability of Data and Materials

The CREST-VEC model is archived at GitHub (https://github.com/chrimerss/CREST-VEC.git, [46]). The CREST-VEC simulated outputs are archived at HydroShare (http:// www.hydroshare.org/ resource/ 647b268538424d82b25bf8c5daa8cb65, [67]).

The RCM data are permanently hosted in the OU Supercomputing Center for Education & Research and can be accessed and downloaded through Globus Public collections (Past: https:// app.globus.org/ file-manager?origin_id=50059a6c-1e40-433e-b051-70d790108352 &origin_path=%2F; Future: https:// app.globus.org/ file-manager?origin_id=04d9456b-4e40-4856-8fe8-6f8d3f10ca3d&origin_path=%2F).

The data analytic codes and scripts are available from GitHub (https:// github.com/ mchen15ouedu/ EF2025_analysis.git)

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