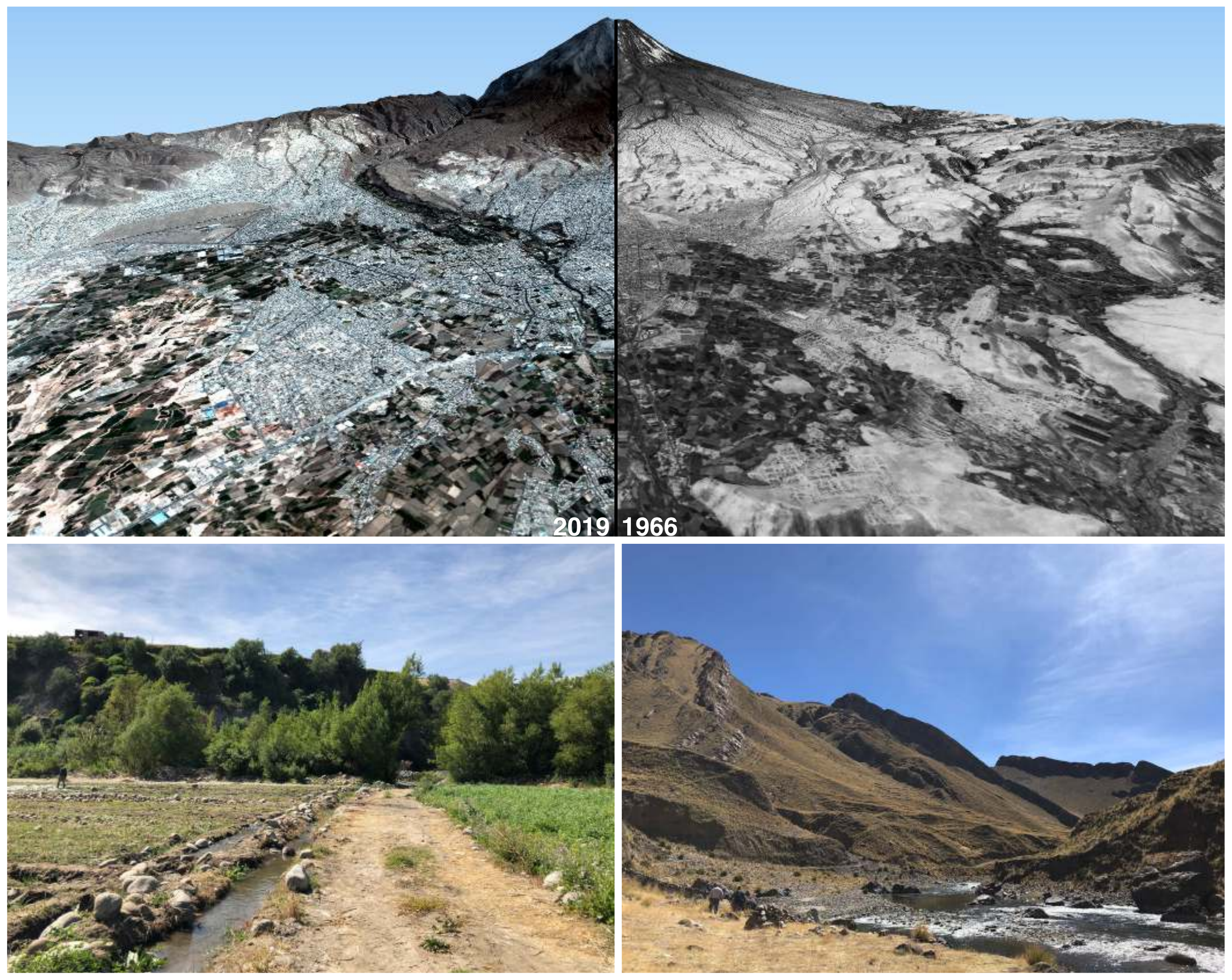
Journal of Contemporary
Water Research & Education

Issue 171
December 2020



Challenges and Opportunities of International University Partnerships to Support Water Management

UCOWR
UNIVERSITIES COUNCIL
ON WATER RESOURCES

A publication of the Universities Council on Water Resources
with support from Southern Illinois University Carbondale

JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION

Universities Council on Water Resources
1231 Lincoln Drive, Mail Code 4526
Southern Illinois University
Carbondale, IL 62901
Telephone: (618) 536-7571
www.ucowr.org

CO-EDITORS

Karl W. J. Williard
Southern Illinois University
Carbondale, Illinois
williard@siu.edu

Jackie F. Crim
Southern Illinois University
Carbondale, Illinois
crimjac@siu.edu

SPECIAL ISSUE EDITORS

Laura C. Bowling
Professor, Dept. of Agronomy
Co-Director, Natural Resources &
Environmental Sciences Program
Purdue University
bowling@purdue.edu

Katy E. Mazer
Sustainable Water Management Coordinator
Arequipa Nexus Institute
Purdue University
kmazer@purdue.edu

John E. McCray
Professor
Civil and Environmental Engineering Dept.
Hydrologic Science & Engineering Program
Colorado School of Mines
jmccray@mines.edu

ASSOCIATE EDITORS

Kofi Akamani
Policy and Human Dimensions
Southern Illinois University
k.akamani@siu.edu

Natalie Carroll
Education
Purdue University
ncarroll@purdue.edu

Mae Davenport
Policy and Human Dimensions
University of Minnesota
mdaven@umn.edu

Gurpreet Kaur
Agricultural Water and Nutrient Management
Mississippi State University
gk340@msstate.edu

Prem B. Parajuli
Engineering and Modeling
Mississippi State University
pparajuli@abe.msstate.edu

Gurbir Singh
Agriculture and Watershed Management
Mississippi State University
gurbir.singh@msstate.edu

Kevin Wagner
Water Quality and Watershed Management
Oklahoma State University
kevin.wagner@okstate.edu

M.S. Srinivasan
Hydrology
National Institute of Water and
Atmospheric Research, New Zealand
MS.Srinivasan@niwa.co.nz

Jonathan Yoder
Natural Resource Economics
Washington State University
yoder@wsu.edu

TECHNICAL EDITORS

Elaine Groninger
Southern Illinois University
Carbondale, Illinois 62901
egroninger@siu.edu

Shelly Williard
Southern Illinois University
Carbondale, Illinois 62901
swilliard@siu.edu

ISSN 1936-7031

Cover photo top: *Arequipa, Peru in 1966 from the KH-40 Corona J-1 Satellite and 2019 from the Sentinel Satellite.* Credit: Zach Brecheisen
Cover photo bottom left: *Irrigation canal in the Uchumayo District, Arequipa, Peru*. Credit: Caelum Mroczek
Cover photo bottom right: *Colca River Valley, Arequipa, Peru*. Credit: Paul Dawley
Back cover photo: Reedy River Falls, Greenville, SC. Credit: Nicolas Henderson, original work, CC BY 2.0
Inside back cover photo: Downtown Greenville. Credit: Timothy J, original work, CC BY 2.0

The *Journal of Contemporary Water Research & Education* is published by the Universities Council on Water Resources (UCOWR). UCOWR is not responsible for the statements and opinions expressed by authors of articles in the *Journal of Contemporary Water Research & Education.*

Journal of Contemporary Water Research & Education

Issue No. 171 **December 2020**

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 1-8, December 2020

Challenges and Opportunities of International University Partnerships to Support Water Management

Edwin F. Bocardo-Delgado[1], Katy E. Mazer[2], and *Laura C. Bowling[2]

[1]Department of Biology, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru
[2]Department of Agronomy, Purdue University, West Lafayette, IN, USA
**Corresponding Author*

Historically water scarce regions such as the Central Andes in South America are particularly vulnerable to changes in water supply and demand and are struggling to adopt a more participatory model of integrated water management. Inclusive engagement principles have been used successfully in many locations to improve agricultural and water management; however, there are several barriers to transference of similar practices to Latin America. For example, collaborative research arrangements between U.S. and Latin American universities are desirable to develop sustained research programs on appropriate integrated water management techniques, but institutional barriers and the lack of a culture of applied research and extension that is responsive to community needs may limit the effectiveness of research partnerships. Additional barriers to participatory management exist at the community level, including traditional limitations such as low institutional capacity, traditional gender roles, and authoritarian structure, as well as emerging issues related to changing rural livelihoods. This article examines opportunities and threats associated with an emergent partnership between Purdue University (Purdue) in Indiana, USA, and Universidad Nacional de San Agustín de Arequipa (UNSA) in Arequipa, Peru. It serves as the introduction to this Special Issue exploring water resources risks in Arequipa, Peru, as well as potential barriers and strategies to support water management adaptation.

Globally, many drivers such as population growth, climate change, and changing income and consumer preferences are dramatically altering water resources management. In water scarce regions that rely on irrigated agriculture in particular, the intrinsic linkage between land and water management (Chen et al. 2018) means new sustainable management frameworks must be developed to minimize environmental impacts on both resources (Brack et al. 2017). However, in some countries the lack of technical knowledge, infrastructure, and human capacity means that well-intentioned sustainable management frameworks do not achieve the expected results in the management of water resources (Maestu 1997; Ortiz Acosta and Romo Aguilar 2016; Rivera-Marquez et al. 2017; Ruiz 2019). In Peru, although a complete revision of the national water policy in 2009 provides a general framework for the proper management of water resources, its application is limited (Robert 2019).

At the same time, Peruvian Canon Law No. 27506 provides a source of funding to enhance Peruvian water management infrastructure (Congreso de la Republica 2001). This law invokes a tax, collected by the State, on the economic exploitation of natural resources. According to Article 6.2, regional and local governments should use funding from this tax exclusively for the financing or co-financing of regional and local impact infrastructure projects, and 20% of the tax can be transferred to public universities to invest in research that enhances regional development.

In response to on-going issues of environmental degradation, UNSA, a Peruvian public university, used the tax-derived financing from mining to establish a partnership with Purdue in the United States. Purdue was approached due to their experience in water resources management, especially for agricultural management, and their history of international extension, to foster applied research in Arequipa, Peru.

This unique collaboration has not been without challenges, but is also showing initial successes, and the purpose of this Special Issue is to provide a clear look at both. Our contributing authors explore not only institutional challenges in the formulation of the partnership, but also social challenges that impact participatory water governance. Collaborations are making technological advances and demonstrating the potential impact of applied research into water-related threats. To start, in this introduction the established legal framework governing environmental management is reviewed. To examine the partnership established between UNSA and Purdue to improve water management capacity in Arequipa, we analyze existing conditions, both internal and external, around which this partnership was developed and establish the opportunities and threats (challenges) which contribute to the implementation, improvement, and achievements of this unique partnership.

Universidad Nacional de San Agustín

UNSA is a public university in Arequipa in southern Peru. The university comprises three campuses, with 17 departments and 45 professional schools in the fields of humanities, natural sciences, social sciences, and engineering. Its mission is "to train competent and ethical professionals, with capacity for research and innovation generating scientific, technological, and humanistic knowledge, contributing to the sustainable development of the region and the country (UNSA 2020)."

Purdue University

Purdue University is the land grant university of Indiana, established through the Morrill Act in 1869, with its main campus in West Lafayette, Indiana, USA. The university is organized into 13 colleges and schools. It offers 200 undergraduate degrees and 70 master's and doctoral degrees. It is known worldwide as a leading research institution. As a land grant university, the Purdue College of Agriculture has a three-part mission for teaching, extension, and research, as follows: "Purdue Agriculture will help make Indiana, our nation, and our world better through: Students prepared to make a difference; Research with purpose, leading to discovery with impact; Engagement/ Extension that strengthens lives and livelihoods; An inclusive culture that supports excellence in all we do (Purdue 2020)."

Arequipa Nexus Institute

To raise technical and human capacity, the UNSA strategic plan included a goal to establish long-term collaborations to address the environmental, agroeconomic, and social challenges that support sustainable management of water, soil, energy, food, and other resources in the Arequipa region, in Peru in general, and throughout Latin America. Thus, a thorough search was carried out throughout the world to identify potential collaborators, with the security of having economic funds from the mining Canon.

Through the work of the Core Foundation, the connection between UNSA and Purdue was achieved with a mission to provide transformative solutions for great challenges in the sustainable management of Arequipa's resources. In 2017, through high-level coordination, Tomas Díaz de la Rubia, Chief Scientist and Chief Executive Officer of Discovery Park at Purdue, and UNSA Rector Rohel Sánchez, laid the foundations for the collaboration. In March 2018, the Arequipa Nexus Institute of Food, Water, Energy and the Environment was launched. The vision of the Nexus Institute is "to be a vibrant, educational, and innovative research ecosystem where transformative solutions to the great challenges facing Arequipa, Peru, and Latin America are explored." Its mission is to "Increase the capacity and strategic collaborations required in the long term to address environmental, agroeconomic, and social challenges that provide support for the development of adaptive, profitable, and sustainable food-energy and water systems in the Arequipa region of Peru." The initial phase resulted in funding ten three-year projects addressing the interdependent topics of food, energy, water, and the environment. The largest of these projects, led by the authors, addresses Sustainable Water Management in the Arequipa Region. Each project involves professionals from both Purdue University and UNSA.

Water Regulation in Peru

In general, water resources management is included in the national environmental policy established for Peru through D.S. No. 012-2009-MINAM (Ministerio del Ambiente 2009). The first objective of this national environmental policy is the protection of biodiversity, due to the richness of flora and fauna in Peru. This does not prevent extraction of all the natural resources in the nation, but criteria must be adjusted to protect biodiversity, consistent with a sustainable development paradigm, which, defined simply, is the use of resources without harming resource use by future generations. In contrast to a nature conservation approach, which prohibits human or economic activity on the land, or a purely resource extraction approach, the sustainable development approach views Peru's natural resources and biodiversity as a public good which can be managed to provide long-term value chains (Nobrea et al. 2016). While achieving true sustainable development may be utopian, this framework establishes minimum values that must be maintained. For example, though it may not be possible to return irrigation water to the same quality and quantity as before using it, environmental standards provide an acceptable threshold for maintaining initial characteristics.

Sustainable development has three principles, which correspond to the economic, the social, and the environmental (Enkerlin Hoeflich et al. 1997; Badii 2004). These principles must be prioritized to maintain balance among them, and the breakdown of this balance can provoke social conflicts. If, for example, the environmental side is prioritized by neglecting the social and economic aspects, there will be protests from groups that are affected by the measures considered.

The Water Resources Law no. 29338 regulates both management of water quantity and water quality (Congreso de la Republica 2009). Use is prioritized as follows: protection of biodiversity, population use, agricultural use, mining and industrial use, and other activities. A water balance is used to determine the amount of water allocated for each purpose. Ecological flow, the minimum amount of water needed to safeguard the biodiversity in a given basin, is used as part of that water balance. The National Water Authority (ANA) is responsible for calculating and maintaining this water balance.

Water quality is regulated through two environmental management policies, the Environmental Quality Standards (ECA; supreme decree 004-2017-MINAM), which establish the maximum amount of a pollutant expected to be present in the water as a receiving medium for different uses. A second instrument is the maximum allowable limits (MPPs), which correspond to the maximum load of contaminants that can be released to receiving waters as point discharges. MPPs are set for each type of release and controlled by the different ministries, so each ministry sets its own permissible ceilings. Of the two management instruments mentioned, the environmental quality standard (ECA) is the most important (Ministerio del Ambiente 2017).

Both ECAs and MPPs set values for various physicochemical, microbiological, heavy metal, and agrochemical parameters. Laboratory or field analyses of water quality samples related to these parameters must be conducted by laboratories that are certified by the National Institute of Environmental Quality (INACAL). These are generally associated with the certification of the international standard ISO 17025.

Methods

A Strength, Weakness, Opportunity, and Threat (SWOT) analysis was applied to analyze the conditions of the partnership established between

UNSA and Purdue to improve water management capacity in Arequipa. SWOT analysis provides a methodology for evaluating what is working well and what is limiting progress in the partnership (Community Toolbox 2020). Both internal factors, i.e. strengths and weaknesses, and external factors, i.e. opportunities and threats, were analyzed, as follows:

- Strengths – Areas of competence which are under the control of the Nexus Institute. These characteristics indicate a high level of performance, providing advantages or benefits and possibilities in the future.
- Weaknesses – Areas of low performance that are under the control of the Nexus Institute and that slow achievement of the objectives.
- Opportunities – Factors over which the Nexus Institute has no direct control, which can contribute to the achievement of objectives.
- Threats – Factors that cannot be controlled directly by the Nexus Institute, but which impair achievement of objectives. Threats pose a risk to the functioning of the partnership.

The SWOT analysis can be used to find interactions between internal and external variables, which inform approaches to continuing the partnership, also known as a TOWS analysis (Dyson 2004). These approaches are as follows:

1. Success approach – using a **strength** to enhance an **opportunity**;
2. Reaction approach – using a **strength** to control a **threat**;
3. Adaptation approach – using an **opportunity** to control or adjust a **weakness**; and
4. Survival approach – mitigating the effect of a **threat** by being aware of a **weakness**.

SWOT Analysis of the Nexus Institute

Strengths

The initial strengths of the Nexus Institute are shown in Table 1. One of its greatest strengths, and the reason that Purdue was approached by UNSA, is the *experience of Purdue faculty members* in conducting and publishing research in the agricultural, food, natural resources, and life sciences. In 2015, Purdue was ranked among the top five universities in the world associated with agriculture and forestry, the categories most related to water management (TOPUNIVERSITIES 2020). The ten Purdue leaders on these projects have over 200 years of combined academic experience, in disciplines ranging from natural resource social science, water, soil and food science, to engineering and technology. They have received numerous recognitions for excellence in research both internal and external to the university, including the 2009 World Food Prize.

Support of university administration allowed for the creation of the Nexus Institute, which provides funding and a collaboration framework for sustainable water management in the Arequipa region for at least three years. An additional strength is that the UNSA mission "to train competent and ethical professionals, with capacity for research and innovation generating scientific, technological, and humanistic knowledge, contributing to the sustainable development of the region and the country" *is aligned with sustainable development* (UNSA 2020**).** Sustainable development is based on the management of natural resources, including water.

Weaknesses

The primary weakness of the collaboration is the *limited involvement of UNSA faculty*. Faculty positions in Arequipa are complex, and many faculty divide their time between more than one position, often serving at multiple universities. To avoid potential conflicts of interest, only faculty working solely at UNSA were eligible to participate in the Nexus Institute. This, together with numerous time constraints and other requirements, greatly limits participation by UNSA faculty. For example, the Sustainable Water Management project includes six faculty from Purdue, but only three UNSA faculty members are officially recognized as part of the project (University Council resolution number 0692-2019).

In addition, *language barriers have limited communication* between professionals at both universities, as very few faculty know both English and Spanish. Language knowledge was not a requirement for proposal submission, and Purdue faculty were told that UNSA faculty would be taking intensive English classes, which has

Table 1. SWOT and TOWS analysis of the Purdue-UNSA partnership.

	Strengths: 1. Experience of Purdue members 2. Support from university administration 3. UNSA mission aligned with sustainable development	**Weaknesses:** 1. Little involvement from UNSA professionals 2. Language barrier 3. Lack of technical experience from UNSA professionals
Opportunities: 1. Canon Law, provides financing 2. Interested government agencies 3. Interested users	**Success:** S1-O1 Developed proposals and received funding from UNSA to develop research on water resources in Arequipa	**Adaptation:** O1-W2 Provide language training to all participants O1–W1/W3 Marketing of technical training for UNSA professionals
Threats: 1. Change of UNSA administration 2. Change in environmental regulations 3. Insufficient access to technology 4. No incentives for UNSA professionals	**Reaction:** S3-T1 Fulfillment of the UNSA mission through the partnership enhances the reputation of the UNSA faculty to their new administration	**Survival:** T3 Train users with available technology T4 Generate economic or other incentives for UNSA professionals

not happened. Furthermore, *UNSA professionals have limited experience* in projects related to water resources management, especially in using computer modeling tools.

Opportunities

Taxes collected from mining as part of the *Peruvian Canon Law* provide a reliable source of research funding for the Nexus Institute and related projects (Congreso de la Republica 2001). This partnership has also received *great interest from government agencies* through agency visits by Nexus members. Both universities have engaged with *groups interested in the development of adequate water management*, and research findings will be shared by developing tools and hosting workshops and trainings to improve water resources management.

Threats

The *term of leadership of the current UNSA administration* ends in December of 2020, which could affect stability and funding of the partnership. Future management of the Nexus Institute will depend on the next elected administration.

In Peru, *environmental regulations have been constantly changing*, putting the design of decision-making tools at risk, especially those that take into account MPPs and ECAs.

There are many locations in Arequipa where we would like to involve users in sustainable water management decisions, but users have *insufficient access to technology*, including the lack of access to smart phones or Internet.

Finally, there are *not adequate incentives for UNSA professionals* to be involved in the project, mainly because collaboration involvement increases workload, but does not provide an increase in compensation.

Approaches - TOWS Analysis

Combining the first strength and opportunity of the Nexus Institute led to initial *success*, which was the development of proposals that received funding from UNSA for water resources research in Arequipa (Table 1). Our strengths also allowed the team to *react* to an external threat, to increase awareness amongst local agencies of the sustainability mission of UNSA, and on-going research efforts to improve sustainability.

However, collaboration weaknesses require the Nexus Institute to *adapt* in two main areas with the help of external opportunities, as highlighted in Table 1. First, a system could be established to encourage the participation of more UNSA faculty in the Nexus Institute. This could include marketing to non-members that technical training is available for UNSA professionals if they participate in the collaboration. In addition, intensive language training should be provided and required for professionals from both universities.

Finally, where team weaknesses intersect with external threats, the collaboration must go into *survival* mode. Better economic incentives and relief from teaching requirements for faculty from UNSA would encourage more participation, thus funding may have to be sought. Also, there is a clear need for training stakeholders to better use technology available and overcome limits to access, which would help fulfill UNSA's mission and engage these groups, particularly in water management.

Evidence of Collaboration Success

This Special Issue documents some of the initial successes that have resulted from the initiation of the Nexus Institute to build research capacity to investigate issues of sustainable water management in Arequipa, Peru. The authors use a range of approaches, incorporating social science concepts, science, and technology, to better understand and address the challenges of water management in the region. This series of papers, all from participants in the Nexus Institute, give those involved in similar international collaborations a resource for identifying potential pitfalls and opportunities for achieving desired outcomes.

In the first paper, Mazer et al. establish a framework of collaboration principles to be used to evaluate international university-led research partnerships, and offer practical guidance on overcoming obstacles early on, amid an imperfect partnership. This work provides practical advice for the establishment of new university-led research partnerships.

Moraes et al. explore the limitations of conducting research in a data poor environment, through an evaluation of the existing water resources monitoring network in Arequipa. The weather, stream discharge, and water quality networks are evaluated with respect to their ability to support water and agricultural management decision making and provides an evaluation of data available for further analysis.

The third and fourth papers give examples of applied research into the use of technology to improve water management. Guevara et al. describe a pilot water irrigation framework utilizing wireless communication and a sensor network for regulating water flow in a drip irrigation system to improve irrigation efficiency in Arequipa. Looking at the water distribution system for public-supply, Dawood et al. developed an assessment framework for potable water systems based on 3D modeling of pipe failure. The developed model can be used by municipal engineers as a screening tool to prioritize maintenance needs. Together, these two papers illustrate the potential of smart technology to improve the sustainability of water management.

An important aspect of water management in a dramatically changing region such as Arequipa is the impact of human-environmental change on people. The next two papers incorporate aspects of stakeholder engagement to address issues of environmental change. Brecheisen et al. incorporate historic imagery dating back to the 1960s into accessible formats to inform public conversation on the environmental impacts of land use change, glacial retreat, and a need for wetland preservation. Also, through analysis of historic change, Mazer et al. develop maps of urban flood hazards in Arequipa to inform municipal agencies and communities on the changing nature of the hazard.

The final paper in this issue discusses the capacity of local citizens and agencies to utilize the technology and information made available to be involved in water management. Popovici et al. describe the challenges associated with coproduction of knowledge, decisions, or policies with local community members in the context of changing rural livelihoods. Utilizing focus groups and semi-structured interviews, they determined that increased migration, market integration, and reliance on regional institutions for water and crop management undermine the effectiveness of coproduction efforts. Not included in this Special

Issue, but in review for publication in JCWRE Issue 172, Bowling et al. discuss the limitations of government agencies tasked with public education in developing, evaluating, and distributing water management information and tools. Based on interviews, focus groups, and small break out groups, they provide a vision for university-led water engagement centers that can provide a venue for applied research and public engagement in Arequipa.

The water resources challenges facing regions such as Arequipa are complex. A legacy of resource extraction and greatly expanded export agriculture threaten water quality and increase competition for scarce water resources. A large gradient between rural and urban livelihoods leads to disparities in access to technology and information, and even the ability to engage in water management decisions, which government agencies do not have the resources to overcome. It is our hope that the cases in this Special Issue provide insight, not only into the challenges facing water resources management, but also highlight some of the ways in which university partnerships can contribute to more effective and sustainable water management globally.

Acknowledgements

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín.

Author Bio and Contact Information

EDWIN BOCARDO-DELGADO is a principal professor in the Department of Biological Sciences and a graduate Environmental Science professor at the Universidad Nacional de San Agustín de Arequipa. He also works as an environmental consultant for several companies and a natural resource management specialist. He can be contacted at ebocardo@unsa.edu.pe or Av. Sánchez Carreón s/n , Cercado Arequipa.

KATY MAZER is coordinator of the Sustainable Water Management team of The Nexus Institute at Purdue University. She engages with stakeholder groups in Arequipa, Peru to coproduce water management decision-making tools. She can be contacted at kmazer@purdue.edu or 920 W. State St., West Lafayette, IN 47907.

LAURA BOWLING (corresponding author) is a Professor of hydrology in the Department of Agronomy at Purdue University. Her research investigates the water resources impact of environmental change across multiple scales, climate regimes, and ecosystems and communicates these findings to stakeholders. She can be contacted at bowling@purdue.edu or 915 W. State St., West Lafayette, IN 47907.

References

Badii, M.H. 2004. Desarrollo sustentable: Fundamentos, perspectivas y limitaciones. *Innovaciones de Negocios* 1(2): 199-227.

Brack, W., V. Dulio, M. Ågerstrand, I. Allan, R. Altenburger, M. Brinkmann, D. Bunke, R.M. Burgess, I. Cousins, B.I. Escher, F.J. Hernández, L.M. Hewitt, K. Hilscherová, J. Hollender, H. Hollert, R. Kase, B. Klauer, C. Lindim, D.L. Herráez, J. Munthe, S. O'Toole, L. Posthuma, H. Rüdel, R.B. Schäfer, M. Sengl, F. Smedes, D. van de Meent, P.J. van de Brink, J. van Gils, A.P. van Wezel, A.D. Vethaak, E. Vermeirssen, P.C. von der Ohe, and B. Vrana. 2017. Towards the review of the European Union Water Framework management of chemical contamination in European surface water resources. *Science of the Total Environment* 576: 720-737.

Chen, B., M.Y. Han, K. Peng, S.L. Zhou, L. Shao, X.F. Wu, W.D. Wei, S.Y. Liu, Z. Li, J.S. Li, and G.Q. Chen. 2018. Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Science of the Total Environment* 613-614: 931-943.

Community Toolbox. 2020. Section 14. SWOT Analysis: Strengths, Weaknesses, Opportunities, and Threats. Available at: https://ctb.ku.edu/en/table-of-contents/assessment/assessing-community-needs-and-resources/swot-analysis/main. Accessed February 22, 2020.

Congreso de la Republica del Perú. 2001. Ley del Canon Minero N° 27506. Lima, Peru. Available at: https://www.mef.gob.pe/es/por-instrumento/ley/6055-ley-n-27506/file. Accessed December 16, 2020.

Congreso de la Republica del Perú. 2009. Ley de Recursos Hídricos N° 29338. Lima, Peru. Available at: https://leyes.congreso.gob.pe/Documentos/Leyes/29338.pdf. Accessed December 16, 2020.

Dyson, R.G. 2004. Strategic development and SWOT analysis at the University of Warwick. *European Journal of Operational Research* 152(3): 631-

640. Available at: https://doi.org/10.1016/S0377-2217(03)00062-6. Accessed June 4, 2020.

Enkerlin Hoeflich, E.C., G. Cano Cano, R.A. Garza Cuevas, and E. Vogel Martinez. (Eds.). 1997. *Ciencia Ambiental y Desarrollo Sostenible*. I.T.P., Latin America.

Maestu, J. 1997. Dificultades y oportunidades de una gestión razonable del agua en España: La flexibilización del régimen concesional. *De La Economía del Agua en España* 121-140.

Ministerio del Ambiente. 2009. Política Nacional del Ambiente. D.S. 012-2009-MINAM, Lima, Perú.

Ministerio del Ambiente. 2017. Estandar de Calidad de Agua. D.S. 004-2017-MINAM. Lima, Perú.

Nobrea, C.A., G. Sampaiob, L.S. Bormac, J.C. Castilla-Rubiod, J.S. Silvae and M. Cardosoc. 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *PNAS* 113(39): 10759-10768.

Ortiz Acosta, S.E. and M.D.L. Romo Aguilar. 2016. Socio-environmental impacts of water management in the protected natural area of Cuatro Ciénegas, Coahuila. *Region and Society* 28(66): 195-230.

Purdue University. 2020. Purdue University College of Agriculture Strategic Plan 2015-2020. Available at: https://ag.purdue.edu/plan/Pages/Preamble.aspx. Accessed June 28, 2020.

Rivera-Márquez, J., M. de Lourdes Hernández-Rodríguez, I. Ocampo-Fletes, and A. María-Ramírez. 2017. Factores condicionantes de la buena gestión del servicio de agua potable en doce comunidades del altiplano mexicano. *Agua y Territorio* 9: 105-116.

Robert, J. 2019. (De) construcción de gobernanza del agua urbana en Lima. La experiencia del Consejo de Recursos Hídricos. Medio. *Ambiente y Urbanización* 90(1): 83-110.

Ruiz, D.G.C. 2019. Reflexiones en torno a la iniciativa sobre la cancelación de la participación privada en la gestión del agua. *Pluralidad y Consenso* 8(37): 140-147.

TOPUNIVERSITIES. 2020. Purdue University. QS Quacquarelli Symonds Limited. Available at: https://www.topuniversities.com/universities/purdue-university/more. Accessed April 16, 2020.

Universidad de San Agustín (UNSA). 2020. Misíon. Available at: https://www.unsa.edu.pe/mision/. Accessed April 20, 2020.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 9-26, December 2020

Creating a Collaboration Framework to Evaluate International University-led Water Research Partnerships

*Katy E. Mazer[1], Anna Erwin[2], Ruxandra Popovici[2], Edwin Bocardo-Delgado[3], Laura C. Bowling[1], Zhao Ma[2], Linda S. Prokopy[2], and Carlos Zeballos-Velarde[4]

*[1]Department of Agronomy, Purdue University, West Lafayette, IN, USA; [2]Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN, USA; [3]Department of Biology, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; [4]Department of Architecture, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; *Corresponding Author*

Abstract: In a globalized world, universities are forming partnerships to solve today's water-related challenges, such as increasing water scarcity and diminished water quality. Over the past 20 years, international university-led water research partnerships have been growing in number, including between the U.S. and countries in the Global South. While there are several examples of guidelines and best practices for executing collaborations, none focus on this type of partnership. Additionally, many international collaborations are formed between universities that have little previous experience in developing these types of partnerships. Often, critiques of partnerships happen after initiation and point to structural barriers and best practices for future collaborations, but few offer practical guidance on overcoming obstacles early on, amid an imperfect partnership. In this paper, we created a flexible collaboration framework which can be used as an evaluative tool. To model this, we conducted an internal evaluation of the Sustainable Water Management team of the Arequipa Nexus Institute, a collaboration designed to build research capacity at the Universidad Nacional de San Agustín to address local issues related to agriculture, natural resource management, and environmental change. Results highlighted project strengths and weaknesses and offered strategies to address challenges that many collaborations face. This strategy identification can serve as a guideline for improving the implementation of new or existing international university-led water research partnerships and help partners as they confront challenges at every stage of the partnership. The evaluation shows the effectiveness of using a collaboration framework as an assessment tool for international university-led water research partnerships.

Keywords: *collaboration principles, international university partnerships, water management, assessment, improvement strategies*

Environmental and socioeconomic issues around the globe are putting pressure on water resources. These stressors include climate change, pollution, and population growth (Bergstrom and Randall 2016). While many of these issues are global, they disproportionately affect the Global South for a multitude of reasons (Vörösmarty et al. 2000; Alcamo and Henrichs 2002). Threats to water security can require large investments and infrastructure-building for which many countries in the Global South do not have the resources (Vörösmarty et al. 2010).

Historically, countries in the Global North have intervened with foreign aid to alleviate some of these disparities. However, the benefits of this aid have been questioned, and researchers and practitioners have advocated for a more sustainable model (Bob 2017). In recent years, international research collaborations have been expanding rapidly (Kolesnikov et al. 2019). Such collaborations include formal partnerships, in which many universities in the U.S. have partnered with institutions abroad, including host country universities, government agencies, and medical institutions (Kolesnikov et al. 2019). However, relationships between academic organizations are the most common type of educational collaboration (Ponds 2009; Kolesnikov et al. 2019). These partnerships, referred to here as international university-led research partnerships, are often mission-based and include the establishment of research centers in the host country (Kolesnikov et al. 2019). Many include other components, like education and entrepreneurship, but in this paper, we focus on the research aspect (Pfotenhauer et al. 2016).

Though similar in principle, international university-led research partnerships vary from one another in their purpose and development method. The four most common formation mechanisms of these partnerships are 1) strategic planning by the visiting university, 2) a host country strategy aimed at capacity-building, 3) those developed over time from individual research partnerships, and 4) partnerships formed because of a specific need expressed by the host country (Kolesnikov et al. 2019). Though varied, main characteristics of a formal partnership over an informal collaboration include the presence of director(s), administrative support, and a multi-year commitment for research projects from both partners (Youtie et al. 2017). Pfotenhauer et al. (2016) provided structural organizational methods and typologies for collaboration that can be applied across partnership types.

There have been criticisms of North/South research partnerships because scholars from the Global North often dominated the global agenda of collaborative research and have extracted data from research sites in the Global South. That model of research did not provide training for host country researchers or local resources for addressing research challenges (Wilmsen 2008; Kouritzin and Nakagawa 2018). Additionally, extractive research fails to adequately address local perspective and is dominated by external ideologies (Kouritzin and Nakagawa 2018). While there are still some power differences in university research partnerships between the Global North and Global South, some projects have placed value on research conducted by local people who understand cultural backgrounds, perceptions, and pertinent challenges (Mahuika 2008; Wilmsen 2008; Kouritzin and Nakagawa 2018). Locally-driven research can re-center the focus of research initiation, benefits, representation, legitimacy, and accountability on local interests (Bishop 2011). Consideration of ethics of international university-led research partnerships is an essential aspect of collaboration that can provide partners with more equal footing and define expectations of both groups (Morris 2015).

Part of the ethical considerations in developing these partnerships is the establishment of collaborative principles, which serve to enhance equity and collaborative success in a partnership. Several frameworks for collaboration principles have been published. Bryson et al. (2006, 44) created a set of 21 principles for cross-sector collaboration, which are those that involve "government, business, nonprofits and philanthropies, communities, and/or the public as a whole," that highlight indicators of success. Similar principles and guidelines for collaboration have been developed for some other circumstances, including collaborative governance, transdisciplinary research in sustainability science, and collaborative ventures (Ariño and de la Torre 1998; Emerson et al. 2012; Lang et al. 2012). This literature, however, does not completely capture the necessary nuances of international university-led water research partnerships. The international component increases complexity, potentially involving different cultures, language challenges, and geographic distance between partners. Also, these partnerships are specifically between two universities, which include different participants and thus different considerations than cross-sector collaborations. Water-related research does, however, often involve considering policies or stakeholders involved in cross-sector collaborations, though the research collaboration is more limited both in its objectives and its interactions with outside groups. To increase likelihood of success of formal international research partnerships, a set of research principles is needed to guide collaboration formation and execution, especially when many partnerships do not have a strategic plan going into the partnership.

Many universities in the U.S. have formed partnerships with universities in the Global South to address water-related challenges, including water resources in Ethiopia (EIWR 2020), research on ecosystems and environmental change in China (Gentry 2013), and agricultural water in Chile (UC Davis Chile 2020). However, few have provided details on the development of their partnerships, best practices, or challenges faced. Information on partnership success is limited, where a few instances report students educated and joint papers published, but these metrics lack consideration for broader impacts or project sustainability (Gentry 2013; Xiamen University and University of Delaware 2013; EIWR 2020). For example, Pfotenhauer et al. (2013) emphasized the importance of host country participants' ability to publish on their own or as first authors and increase their collaboration networks. However, few partnership websites discuss details of how capacity was increased or provide evidence that the university trained gained publication independence. The U.S.-Pakistan Centers for Advanced Studies in Water (USPCAS-W 2020) provided one of the few available self-critiques, and their lessons learned included the need to create and assess impacts of applicable solution-based research, the need for goal setting, and the importance of adaptive management.

While these takeaways are useful for other universities forming similar partnerships, a formal structure does not exist to guide which components to include, nor for how to evaluate and make adjustments when needed. Additionally, lessons learned provide insight on what should have been done, making them more applicable to the *next* collaboration rather than focusing on how problems can be addressed in the moment, or when it is most relevant (Bammer 2008; Spooner et al. 2016; Woldegiyorgis et al. 2018).

In this paper, we combine existing collaborative frameworks to identify and adapt a set of collaboration principles relevant to international university-led water research partnerships. To exemplify the use of these principles, we conduct an internal evaluation of a project focused on sustainable water management within an international university-led water research partnership between Purdue University in the U.S. and the Universidad de San Agustín de Arequipa (UNSA) in Peru using these collaboration principles. Results provide a rich description of the challenges and opportunities associated with an international university-led water research partnership as an example using a collaboration framework as an evaluative tool. This process provides a model for scholars either interested in conducting a similar assessment or combining collaboration frameworks to study their unique collaborations. We conclude by suggesting strategies for overcoming challenges encountered in these types of partnerships to showcase opportunities for using a collaborative framework to improve ongoing partnerships.

Background and Methods

The Nexus Institute and the Sustainable Water Management Team

Purdue University's Discovery Park is a multidisciplinary research park formed to support the creation of solutions to today's problems. UNSA is a public university in Peru that has traditionally focused on teaching but has a four-part mission that also includes research and university in extension. In 2017, the two created a partnership to build research capacity at UNSA and address environmental sustainability challenges in the region. The Department of Arequipa, where UNSA is located, is a hyper-arid region with elevations ranging from 0 to 6400 meters, with water allocation and mining-related water quality concerns that dominate the political landscape. The two universities together formed the Arequipa Nexus Institute for Food, Water, Energy, and the Environment (the Nexus Institute), a collaboration that includes 21 research project teams and over 100 researchers from both Purdue and UNSA. The mission of the Nexus Institute is "to build capacity and collaborations needed to address key environmental, agronomic, and social challenges to support adaptive and sustainable growth in the Department of Arequipa (ANI 2020)." Of these 21 projects, there are at least nine teams conducting water-related research, including our project, the Sustainable Water Management (SWM) team. Topics addressed by water-related projects span water quality, improving data on water availability and water sources, and equitable water availability. The Nexus Institute, as well as individual project teams, have equivalent structures at both universities, with co-directors and co-principal investigators (PIs) working together in leadership roles (Figure 1).

The SWM team is one of the largest groups within the Nexus Institute and is composed of 11 professors, five postdoctoral researchers, and a project coordinator, with a total of nine women and eight men. Several undergraduate students have also been involved from both UNSA and Purdue. Four project members are from UNSA and 13 are from Purdue University. Project member expertise spans agronomy, biology, agricultural and biological engineering, environmental engineering, landscape architecture, and natural resources social science. Because of the nature of the formation of the Nexus Institute, a formal evaluation framework was never created. The SWM team, in an effort to create an unbiased internal evaluation, utilized existing collaboration frameworks to create their own evaluation tool for project success.

Developing a Collaborative Framework for International University-led Water Research Partnerships

In order create a framework to examine the SWM project, we first conducted a literature review which mined scholarship on collaborative frameworks, especially those relevant and applicable to international university-led water research partnerships. Because of the complexity and breadth of partnerships that involve water management, we studied frameworks spanning multilevel management and transboundary policies. Scholarship included cross-sector, collaborative governance, transdisciplinary research, and international collaborations (Winer and Ray 1994; Ariño and de la Torre 1998; Thomson and Perry 2006; Babiak and Thibault 2009; Emerson et al. 2012; de Jong et al. 2019).

After conducting the literature review, we created a framework that includes components from multiple cross-collaborative assessments. First, we chose Bryson's et al. (2006) cross-sector collaborative framework because not only does water management research often involve cross-sector exchange, but the principles were easily adaptable and applied to many collaboration types. Second, we included principles from the transdisciplinary research in the sustainable science collaborative framework because it shared many aspects with our partnership, particularly in involving external actors, though it lacked an international perspective (Lang et al. 2012). Third, the broad guidelines provided by Archer and

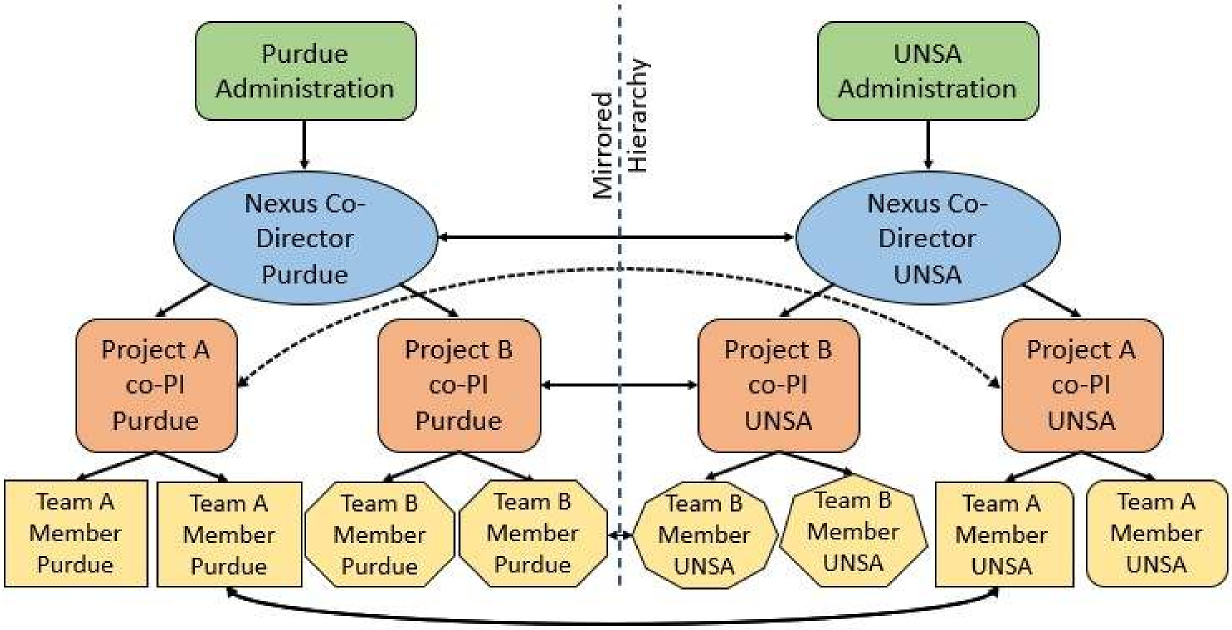


Figure 1. The Nexus Institute is structured with a parallel hierarchy on both sides of the collaboration, with shared leadership responsibilities for all levels of the partnership. Expertise among team members within groups was not always a perfect match. The SWM team was one of many projects within this structure.

Cameron (2009) were also useful when accounting for the flexibility needed when working with diverse partners. More detailed principles, showing collaboration competencies, were also useful for understanding relationships within the partnership and were applied for critical evaluation (Getha-Taylor 2008). Finally, we incorporated some principles from Ansell and Gash (2007) because they were useful in understanding the outward facing aspect of water research, which in our case included stakeholder engagement at multiple scales. Principles that were outside the scope of this partnership or that did not equate to actionable steps in a partnership were discarded.

The framework was next divided into categories, which reflect aspects of a project and considerations that are important for collaboration (Figure 2). The **initial structure** and **initial phases** are foundational to the collaboration development, and other phases of a partnership can be built upon them (Bryson et al. 2006; Lang et al. 2012). **Fostering growth** and **maintenance** are both dependent on previous stages of collaboration and coexist at equal importance (Archer and Cameron 2009; Lang et al. 2012). In water research, there is often **external involvement**, where some interaction with the public and governmental agencies is needed, but these interactions cannot be approached until there is a stable working relationship (and previous stages of the collaboration) between the two partner institutions (Bryson et al. 2006). A sound relationship both improves the ability of the public to have a positive perspective and provides an adequate framework for outside organizations to participate (Lang et al. 2012).

Remaining principles were then placed into appropriate categories based on when in the collaboration process they were most applicable. Frequently occurring principles and those most applicable to the SWM team were selected as parts of the collaboration framework. While this paper is focused on a bilateral partnership, this model can be utilized for expanding the partnership, allowing the partnership to work with other entities, or duplicating the partnership at other universities.

This collaborative framework was used to conduct an internal evaluation of the Nexus Institute's SWM project. As the members of the SWM team were both authors and those that were sharing their experiences, we did not conduct formal interviews. However, because of the multidisciplinary and international nature of our team, our joint experiences created evidence to evaluate our progress. By applying our created framework as an evaluation, we recognize that we are the same entity creating and utilizing the assessment tool, and that because of this, inherent biases may exist in our evaluation. However, utilizing several existing frameworks and reconciling their many nuances makes this framework more robust and

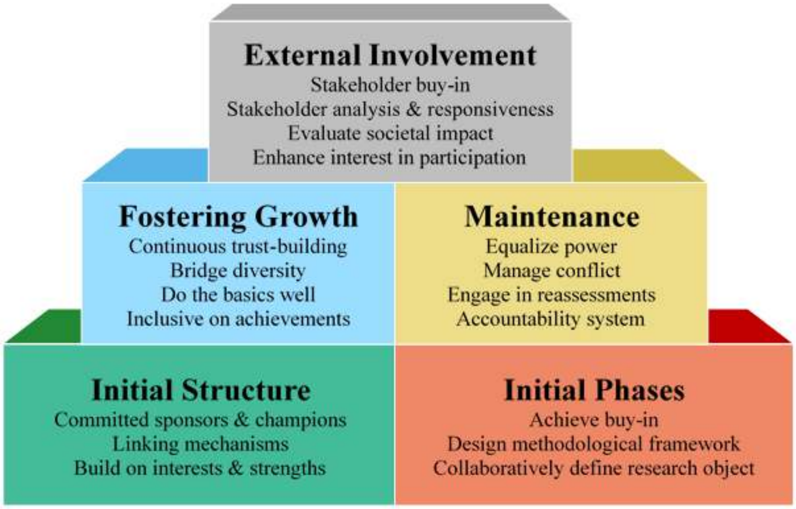


Figure 2. These five categories of collaboration - initial structure and phases, fostering growth, maintenance, and external involvement - are important aspects of international university-led research partnerships for water management that build on one another, and they can be used to better understand individual principles.

subject to self-reflexivity, where direct comparison with other frameworks would reveal gaps (Tracy 2010). Additionally, the internal evaluation assessed not only successes, but also weakness or challenges in this partnership. This suggests that this collaborative framework is functional and was created with sincerity, where the goal was to reveal areas of improvement rather than be boastful. We also recognize that as only one set of projects was assessed with this framework, there may be specific aspects to other projects that would not be addressed using these principles. To that end, the process we modeled in this paper can also be used to modify ours and other similar frameworks to include or exclude principles as necessary.

Results: Using the Collaborative Framework for an Internal Evaluation

In this section, we share the results of an internal evaluation of the SWM project of the Nexus Institute using these collaboration principles as an assessment tool. Factors affecting success came both from within the project team (internal) and from the entire Nexus Institute, the two universities, and from the two countries (external). We considered both internal and external influences and made suggestions to overcome encountered challenges, both from project experience and from the literature. The SWM team's experiences of the collaboration in relation to the principles, as well as strategies to address challenges that could be implemented during the project, are in Tables 1-5 and are discussed in the sections below.

Initial Structure

The initial structure of the SWM project was heavily influenced by the Nexus Institute (Table 1), which was largely based on existing conditions and ideals held by both universities, as well as the efforts of key individuals within the partnership. A key strength of the SWM team was that there were committed champions at many levels who were able to advocate for its creation and establishment. This has proved useful for the duration of the collaboration and will be useful as inevitable changes in the administration (particularly at UNSA) and in researchers occur. A large amount of linking mechanisms existed at formation, including interests in addressing water resources issues and the desire for international recognition, which provided substantial motivations for each university to collaborate and provided a foundation for building a relationship (Bryson et al. 2006). The SWM partnership focused on building on self-interests and characteristic strengths, like cultivating local knowledge or insights about the Water Resources Law of 2009 (Popovici et al. 2020a), the guiding policy for water governance in Peru. This approach provided incentive for collaboration and a need for project involvement for both partners (Bryson et al. 2006). Research direction was tailored to the existing expertise of UNSA team members, which included investigating water availability for agriculture and the use of macroinvertebrates as water quality indicators (Bryson et al. 2006).

Initial Phases

The initial phases of collaboration allowed for more direct decision-making by the SWM team, though procedures were still heavily influenced by rules implemented on the level of the Nexus Institute (Table 2). The short project term (< 3 years) limited opportunities for the team members from both universities to collaboratively build a framework, which is important for setting expectations (Archer and Cameron 2009). However, the SWM team was one of few teams to include social scientists who gathered information on local perceptions and needs to inform project direction in water management decision-making. The social science data were invaluable in directing the research and producing locally relevant research products. The research object for the team, which is meant to provide guidance for putting a vision into action, was not initially defined collaboratively (Lang et al. 2012). Rather, it was outlined by Purdue researchers, with UNSA researchers adding to the team after project creation. This created confusion for both Purdue and UNSA project members because the initial research topic was established based on the Purdue team's limited knowledge of research needs and local circumstances affecting Arequipa. Being very aware of this limitation, building mutual understanding and bringing in the expertise and knowledge of UNSA colleagues

Table 1. Collaborative principles for initial structure.

Collaboration Principle	Nexus SWM Experience*	Strategies to Improve
Committed sponsors and effective champions (Bryson et al. 2006)	+ UNSA and Purdue administrators, as well as many SWM project members, were committed to the partnership (Ex) + Committed postdocs and project coordinator, who were hired to work on Nexus projects only (In) − Frequent administration changes at multiple levels at UNSA (Ex) − Postdocs often hold a contracted (temporary) position (In) − PIs often split among various projects or responsibilities (In/Ex) − Hiring Purdue graduate students was not allowed (Ex)	• Incorporate champions that can ensure stability during transitions as project develops (e.g., bring in a management specialist for implementation details and evaluation) (Ivery 2010) • Create space for sharing and negotiations among project teams (Morton 1983) • Formalize induction of new project members to follow specific norms (Morton 1983)
One or more linking mechanisms exist at formation (Bryson et al. 2006)	+ Desire to solve problems + Desire to conduct cutting-edge research + Desire for international recognition (Ex) + Interest in water resources as an issue − Differences in annual calendars − Differences in language, culture, and location − Difference in views among administration of what aspect of writing papers is important (Ex)	• Provide language classes or stricter language requirements for participation • Set up norms for how to deal with different calendars where the universities have different course schedules and vacation times
Build on individuals' and organizations' self-interest and each sector's characteristic strengths while minimizing, overcoming, and compensating for each sector's weaknesses (Bryson et al. 2006)	+ UNSA – access to funding (Ex) + Purdue – R1 university seeking new research opportunities (Ex) + UNSA – knowledge of local needs and direction (In/Ex) + Purdue – publishing experience, ideas for techniques not yet used in Arequipa (In) + UNSA – proximity to study area (In/Ex) + UNSA – local connections (In) + Purdue – access to advanced equipment and software (In) + SWM team identified expertise of all members to utilize for research and project goals (In) − Lack of partner social scientists at UNSA (In/Ex)	• Conduct a SWOT (strengths, weaknesses, opportunities, and threats) analysis • Ask each project member to outline their individual goals within the larger project (i.e., publish papers in peer-reviewed journals) • Ask each member to identify areas where they need resources or support from the PIs

*Factors considered for the Nexus SWM experience were both internal (In) and external (Ex) to the SWM team. The "+" refer to elements that contributed to a positive experience and the "−" refer to obstacles in the collaboration.

Table 2. Collaborative principles for initial phases.

Collaboration Principle	Nexus SWM Experience*	Strategies to Improve
Achieving “buy-in” (Ansell and Gash 2007)	+ Project members interested in advancing research through partnership (In) + Many excited to work with international partner (In) + In-person meetings early on were critical (In) − Misunderstanding of project goals (In) − Frustration by many project members regarding the slow project pace (Ex) − Limitations for some faculty to participate (Ex) − Few incentives for UNSA faculty to participate, difficult time commitment (Ex)	• Establish needs and identify rewards and motivations • Create clear expectations and process for dealing with success (Leider 1999) • Increase awareness and understanding of collaboration (Thomson et al. 1999) • Emphasize common values to find shared motivation (Morton 1983)
Building the framework (Archer and Cameron 2009)	+ Included assessment of local perceptions (In) + Multidisciplinary team enhanced learning (In) + Ongoing in-person meetings (In) + Protocol for inviting co-authors and identifying research sub-teams (In) + Joint discussion on large project decisions (In) − Unrealistic time expectations (Ex) − Many overlapping projects and repeated content but disjointed communication (Ex) − No equivalent to postdocs at UNSA (Ex)	• “It seems important to more carefully craft the project goals and to employ an adequate research methodology for evidence-based transfer and outreach.” (Wiek et al. 2012, 19) • Create line of sight for direction and purpose (Getha-Taylor 2008)
Collaboratively define research object, objectives and specific research questions, and success criteria (Lang et al. 2012)	+ Re-evaluation of project goals and project member roles (In) + Initially vague research objectives (In) + Research pursued based on interest of project members (In) − Proposals were written only by Purdue (In/Ex) − Lack of consensus in understanding the term “environmental management” across languages − Isolation of proposal development (Ex) − UNSA project members were assigned (Ex) − Little vetting for project funding (Ex) − Lack of transparency for building (assigning) project teams (Ex)	• Discuss project vision and mission and how they aligned with individual goals • Use a simple symbol/phrase as a reminder of the core (Heath an Heath 2007) • Create SMART (specific, measurable, achievable, relevant, time bound) goals for short and longer term within project timeframe

*Factors considered for the Nexus SWM experience were both internal (In) and external (Ex) to the SWM team. The “+” refer to elements that contributed to a positive experience and the “−” refer to obstacles in the collaboration.

was a priority when the project first started. Because objectives within the original proposal were general, the Purdue-UNSA team was able to discuss, identify, and focus on research aspects that were relevant and important to project members at both universities; for example, mapping of hazards related to flash floods in the city's ephemeral streams helped achieve buy-in from project members, which ensured commitment to the group (Ansell and Gash 2007).

Fostering Growth

In comparison to other collaborative phases, the SWM team had more control over meeting collaborative principles in the fostering growth phase (Table 3). One of their main successes was that trust-building activities, a key aspect for building relationships and preparing partnerships for challenges, were continuous between partners at the two universities (Bryson et al. 2006). Although, new, non-established relationships caused the project to progress very slowly at the beginning, and initial trust building that was unaccounted for in the proposed project timeframe led to misjudgment of a project timeline. Additionally, cultural differences, professional norms, languages, and research backgrounds created additional obstacles for bridging diversity that slowed progress. Bilingual project members and leaders on the SWM team were key in bridging diversity and building trust within the partnership. Specifically, a bilingual water scientist was recruited into the research team to serve as the overall project coordinator. This individual was invaluable in many ways, but her Spanish communication capacity (speaking and writing) and ability to translate all meetings and key project material was critical to promoting discussion among team members who did not have the language capacity, leading to increased trust and collaborative relationships among team members. Both trust-building and bridging diversity collaborative principles were thus vital steps in the project, which allowed the group to do the basics well by building a solid working rhythm. These foundational relationships acted as cornerstones when challenges were encountered (Archer and Cameron 2009). The SWM team valued transparency and allowed for an inclusive perspective on achievements, which acknowledges all group members, by making requirements for inclusion in credit-giving, providing easy to follow guidelines to maintain motivation of efforts (Getha-Taylor 2008). For example, an authorship agreement was developed, discussed, and adapted to meet the fairness standard of different team members between universities and across disciplines.

Maintenance

Project maintenance was a stabilizing mechanism and allowed for consistent readjustment when the SWM team encountered difficulties (Table 4). However, the bulk of the maintenance challenges faced by the SWM team (and others) were external factors, imposed by the Nexus Institute. Internally, the SWM team was relatively deft in identifying and addressing problems , often translation miscommunications, as they arose. They utilized open communication to manage conflict early, as well as a central project coordinator to ensure accountability and maximize resiliency in the team. Equalizing power, which helps prevent mistrust, was one of the most consistently difficult challenges, where the UNSA also served as the funder and thus, made more rules and decisions (Huxham and Vangen 2005; Bryson et al. 2006). Within the project, funds were only directly available to Purdue, which created a power imbalance, though the decision to distribute funds to Purdue alone was made by UNSA. To mitigate this issue within the SWM team, project members were transparent about project costs and fund usage. The project team was also unique in their ability to have equal input and respect across genders, with equal distribution of male and female co-PIs, which was a more difficult challenge for other groups. The Nexus Institute as a whole also failed to include regular reassessments, which should be implemented to address issues early and make timely improvements (Bryson et al. 2006). This missing evaluation limited knowledge of progress and success of the collaboration as a whole, and the SWM team has compensated by conducting one informally via this internal evaluation. An accountability system, which provides guidance and expectations for participants, was limited to ensuring the successful completion of proposed deliverables, i.e., decision support tools for water

Table 3. Collaborative principles for fostering growth.

Collaboration Principle	Nexus SWM Experience*	Strategies to Improve
Trust-building activities are continuous (Bryson et al. 2006)	+ Transparency high priority (In) + Frequent virtual communication (In) + Periodic, but limited visits (In) + Inclusion of perspective of project members (In) + Periodic technical training available (In/Ex) + Process transparency (In) + Data sharing and division of work (In/Ex) + Annual workshop (In/Ex) − Some one-sided decision-making (In) − Connectivity issues (In) − Non-flexible rule changes mid-project (Ex)	• Build trust with vague goals and low expectations before clear goals with high expectations (Butler and Gill 1995; taken from Vangen and Huxham 2003) • Use small trust gained to build bigger trust and implement practices of sharing credit, balance of power, etc. (Vangen and Huxham 2003) • More frequent face-to-face interactions
Bridge diversity (Getha-Taylor 2008)	+ Some bilingual group members (In) + Cultural liaison (Ex) − Language challenges (In) − Lack of knowledge of other culture (In) − Difficulty in accommodating work norms for both groups (In) − Some one-sided procedures felt colonial (Ex)	• Cultural/diversity training • Recognize similarities, recognize and accept cultural limitations, utilize differences as strengths (Brodsky and Faryal 2006) • Get to know each other's skills, weaknesses, and needs for support, and use them to your advantage (Archer and Cameron 2009) • Adopt a fusion model of collaboration (Janssens and Brett 2006)
Do the basics well (Archer and Cameron 2009)	+ Training for basic research topics (submitting papers, grant writing) (In) + Open communication through various platforms like email, video chat, and messaging (In) − Difficulty in consolidating multiple ideas and interests of all project members (In) − Leads to divided effort, lack of consensus (In)	• Collaboration training • Role clarity for each project member (Archer and Cameron 2009) • Commitment to a positive strategy of empowerment and representation of weaker or disadvantaged project members (Ansell and Gash 2007)
Inclusive perspective on achievements (Getha-Taylor 2008)	+ Transparent process for gaining authorship (In) + Inclusive authorship perspective (In)	• Acknowledgement of effort as deserved (Vangen and Huxham 2003) • One project member synthesizes group successes (Bammer 2008) • Expand measures of success that reflect and reward important work and collaborative nature (Goring et al. 2014)

*Factors considered for the Nexus SWM experience were both internal (In) and external (Ex) to the SWM team. The "+" refer to elements that contributed to a positive experience and the "−" refer to obstacles in the collaboration.

Table 4. Collaborative principles for collaboration maintenance.

Collaboration Principle	Nexus SWM Experience*	Strategies to Improve
Partners use resources and tactics to **equalize power** effectively (Bryson et al. 2006)	+ Mirrored Nexus hierarchy and leadership structure (In/Ex) – Differences between university power structures (In) – One-sided distributor of project funds (Ex) – One-sided holder of project funds (In/Ex) – Bureaucracy both within UNSA and in Peruvian government (Ex)	• Explore external funding options • Foster reciprocity for both collaboration and competition (Bammer 2008) • Altruistic perspective on resource sharing (Getha-Taylor 2008)
Partners use resources and tactics to **manage conflict** effectively (Bryson et al. 2006)	+ Project coordinator to balance opinions/needs (In) + Open communication to foster trust for conflict ease (In) – Information distributed unequally to each university (Ex)	• Collaborative conflict resolution (Getha-Taylor 2008) • Create a no-blame culture (Archer and Cameron 2009; Lloyd-walker et al. 2014) • Solve problems quickly, as they arise (Archer and Cameron 2009) • Be aware of limitations (funding, time, etc.) that will constrain boundaries (Bammer 2008) • Identify and understand organizational types (Archer and Cameron 2009)
Engage in regular reassessments (Bryson et al. 2006)	+ Open communication (In) + Feedback from special events (In/Ex) + Biannual reports can include project challenges (Ex) + Collaborative principles assessment (In) – No formal feedback process (Ex) – No formal monitoring and evaluation program (Ex)	• Start evaluation program • Conduct assessments at the level over which you have control • Build capacity in the importance and process of evaluation (Conlin and Stirrat 2008)
Accountability system that tracks inputs, processes, and outcomes (Bryson et al. 2006)	+ Group research updates and tracking of progress (In) + Periodic deadlines for required checkpoints (In) + Accountability in progress in biannual reports (Ex) – Emphasis on deliverables, which can sacrifice the science (Ex)	• Minimize ambiguity (Schwartz 2001) • Point person for compiling progress (Ryan and Walsh 2004)

*Factors considered for the Nexus SWM experience were both internal (In) and external (Ex) to the SWM team. The "+" refer to elements that contributed to a positive experience and the "–" refer to obstacles in the collaboration.

management, with inflexible guidelines and no consideration for less tangible, but equally valuable, outputs and outcomes (Bryson et al. 2006).

External Involvement

Because of the SWM team's focus on understanding local water-related institutions and their efforts in using stakeholder input to produce tools for decision-makers, their ability to navigate external involvement was largely positive (Table 5). UNSA project members were key in developing relationships with and achieving project buy-in, which improves likelihood of project impact, from agencies and individual stakeholders (Ansell and Gash 2007). Research and product development for water management support tools were heavily based on stakeholder analysis and feedback, both through interviews and focus groups (see Popovici et al. 2020b). By following cultural norms and ensuring responsiveness to key stakeholders, the SWM team enhanced capabilities for and interest in participation for partnerships in the future and assured that research outcomes would be useful to users (Bryson et al. 2006). The SWM team has also led coordination among other Nexus Institute projects to create a formal plan to reduce burden on external actors, like local water user associations. In other projects at the Nexus Institute, the process for creating new partnerships has already started, including Memorandums of Understanding (MOUs) signed with a partner water management agency in Peru. With good in-country press and project success among participating members, interest in collaboration has increased for other UNSA faculty, as well as faculty from other institutions, which allows for greater reach of the partnership for the future (Lang et al. 2012).

Discussion

The SWM internal evaluation provided a detailed example of a functioning international university-led water research partnership, as well as an example of implementation of this collaborative framework as an assessment tool for this partnership type. This method can be used by other similar partnerships to assess project success and provide guidance for project direction. The need for insight on collaboration principles and project evaluation is increasing, as international university-led water research partnerships are rapidly growing (Kolesnikov et al. 2019). In this internal evaluation, many positive attributes of the partnership in the SWM project of the Nexus Institute were identified. Many of the challenges identified are associated with the opportunistic formation of this partnership, where early aspects were one-sided, as well as the lack of certain rules and structures. Because of the complexities of this partnership and the newness of the collaboration, this is expected because most collaborations are exceedingly difficult to execute successfully (Bryson et al. 2006). It is important that the issues identified be addressed, both by the SWM team itself, and by the Nexus Institute. Still, with similarities and many positive attributes of collaboration principles, this partnership has been viable, effective, and beneficial for both universities.

Assessing the SWM team within the Nexus Institute using a set of collaboration principles was an informative way for identifying challenges and providing insight on addressing these challenges. Strategies enacted in the project, as well as many suggested in the literature, created opportunities for improving the partnership as they occurred (Tables 1-5). Utilizing an attentive and proactive problem-solving approach, strategies can be implemented quickly and be effective. Because many of these partnerships are nascent (Kolesnikov et al. 2019), they must be careful to implement strategies to overcome differences, understand each other, and gain support (Bammer 2008). The evaluation of a project team within a larger partnership also provides a case example of how to make improvements inside an imperfect partnership, without having power to address all challenges. While this is limiting in some regards, it also empowers members of an already established project to learn to work within the space at which they can enact change.

When identifying challenges and considering improvement strategies, our collaboration framework is also useful in identifying a trajectory to overall project improvement. Because of its structure, implementation of principles farther along in the process may be dependent on successful implementation of principles from earlier stages

Table 5. Collaborative principles for including external involvement.

Collaboration Principle	Nexus SWM Experience*	Strategies to Improve
Achieve buy-in from outside stakeholders, other interested groups (adapted from Ansell and Gash 2007)	+ Interactions with many groups through interviews and focus groups (In) + Development of relationships through previous contacts (In) – Disconnected message, overlapping asks to agencies among groups (In/Ex) – Slow to build stakeholder understanding of project and partnerships (In/Ex)	• Hire on-the-ground research coordinator to maintain constant contact with stakeholders • Additional connections with groups outside of water management, like non-governmental organizations (NGOs), schools, and businesses • Create committee on community engagement to outline standard procedures • Clear strategy as to how participation benefits local stakeholders
Use stakeholder analysis, and emphasize responsiveness to key stakeholders (Bryson et al. 2006)	+ Coproduction process to include stakeholder input (In) + Qualitative data collection from many stakeholders (In) + Extension efforts (In and Ex) – Lack of in-depth knowledge of community needs (Ex) – Ever-changing agency officials (Ex)	• Add UNSA social scientists to work with the Purdue social scientists on the SWM team • Establish alternative strategies for receiving input from stakeholders (see Popovici et al. this issue)
Evaluate societal impact (Lang et al. 2012)	+ Plans to create extension centers (In/Ex) + Creating consumer products based on research with user input (In) – No current plan for impact assessment (In) – Short project timeframe (In/Ex)	• Incorporate narrative with qualitative and quantitative data (Donovan 2011) • Utilize document analysis and engage with decision-makers for feedback (Hanney et al. 2000) • Include a variety of impacts, including indirect, in assessment (van der Weijden et al. 2012)
Enhance capabilities for and interest in participation (Lang et al. 2012)	+ MOUs signed with agencies (Ex) + Project progress attracted future potential partners (In) + Purdue faculty seminars at UNSA (In) + Used established organizations to engage community (Ex) + Many press releases for public engagement (Ex) + Active social media (In/Ex) + SWM has fostered some faculty partnerships beyond Nexus collaboration (In) – No unified message to stakeholders among projects (In)	• Open call for participation at both universities

*Factors considered for the Nexus SWM experience were both internal (In) and external (Ex) to the SWM team. The "+" refer to elements that contributed to a positive experience and the "–" refer to obstacles in the collaboration.

and require that these more foundational principles be satisfied before addressing other principles. For example, some strategies for managing conflict, like collaborative conflict resolution, are much more challenging when trust-building activities are not continuous and a foundation of trust between groups has not been created (Kelmen 2005). Though there have been no large conflicts within the SWM team, continuous trust-building activities and relationships built among project members have enhanced communication and minimized misunderstandings that often lead to conflict (Kelly et al. 2002). These foundations have also been established to manage conflicts that could occur. Likewise, focusing on collaboration principles from earlier phases and reiterating them can lead to development or enhancement of other principles further along. For example, developing a joint understanding of the research goal can help keep the group's focus, provide motivation, serve for a measure of assessing progress, and is more likely to draw in outside interest when the message is unified (Christenson and Walker 2004; Heath and Heath 2007). Thus, in addressing challenges in a collaboration, it is important to work backwards in the framework of principles to identify the root cause of the problem (Vaaland 2004). Additionally, our assessment suggests that beginning with basic improvement measures can build foundations that will both address core issues and improve abilities to address more nuanced ones.

Conclusions

Based on our experience with and evaluation of an international university-led water research partnership, this type of collaboration is a viable option for developing sustainable research and can be beneficial for both universities. Developing these research partnerships can build research capacity at universities without those capabilities, provide important information to local populations, and contribute to the body of knowledge on global issues. Additionally, these opportunities can improve rankings and provide new sources of funding for universities in the U.S. (Kolesnikov et al. 2019).

This internal evaluation highlights how international university-led water research partnerships can use collaborative frameworks as an assessment tool to ensure success. In this case study, the partnership vision is simple and clear and provides a permanent stable basis off which to build an institution with Purdue's Discovery Park and UNSA as partners. Stability is enhanced by a consistent funding source. After establishment of a solid foundation and achieving small successes that build both rapport and confidence between universities, there is an opportunity for growth within this partnership. Additionally, because of the nature of the research and the involvement of stakeholders throughout the research project, the SWM team and the Nexus Institute have provided a pathway to creating actionable research that can be applied to policy and have impacts on water management outside the confines of the two-university partnership.

While international university-led water research partnerships are a useful collaboration option, they should be approached thoughtfully, as there are many nuances that make them unique. The collaboration framework and the process to create it described in this paper can be used as guidance for structuring and building a partnership, from the initial structure and phases, to fostering growth and maintenance, and providing a solid foundation to extend research ideas and practices to include or impact local stakeholders. These characteristics and structures can then provide opportunities to replicate partnership within and across other institutions, especially in an international context. Even with already-established partnerships, these principles can serve as an assessment framework for finding weaknesses and making adjustments to improve them. Although evaluations are more effective if designed and monitored from the start, performing an evaluation at any point can provide some insight into partnership success.

Likewise, within existing partnerships, there is opportunity to make ongoing changes that can be implemented as soon as the need is identified. Using this framework, a simple process is in place for identifying challenges, and with this methodology, areas for improvement can be prioritized. Our findings suggest that there are many sources of strategies for improving during different phases of the partnership, and these can be implemented without having to wait for the next iteration or funding opportunity. Acting quickly and being adaptable are important aspects of any international partnership, especially those recently created.

This was an internal evaluation of an international university-led water research partnership from one project within the collaboration, but there is need for a larger-scale evaluation of the entire partnership, including interactions among teams and at different leadership levels. Likewise, more studies of the collaboration success of these types of partnerships are needed.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín.

Author Bio and Contact Information

Katy Mazer (corresponding author) is coordinator of the Sustainable Water Management team of The Nexus Institute at Purdue University. She engages with stakeholder groups in Arequipa, Peru to coproduce water management decision-making tools. She can be contacted at kmazer@purdue.edu or 920 W State St., West Lafayette, IN 47907.

Anna Erwin is a Postdoctoral Research Associate in the Purdue University Department of Forestry and Natural Resources. Dr. Erwin is an interdisciplinary social scientist and environmental justice scholar who studies how people perceive and respond to social ecological change and investigates how organizations and policies respond to those changes. She can be contacted at erwin9@purdue.edu or through www.annaerwin.com.

Ruxandra Popovici is a Postdoctoral Researcher in the Department of Forestry and Natural Resources at Purdue University. Her work focuses on environmental governance, where she researches the various rules and norms through which people on the ground manage their natural resources. She can be contacted at rpopovi@purdue.edu or 195 Marsteller St., West Lafayette IN 47907.

Edwin Bocardo-Delgado is a principal professor in the Department of Biological Sciences and a graduate Environmental Science professor at the Universidad Nacional de San Agustín de Arequipa. He also works as an environmental consultant for several companies and a natural resource management specialist. He can be contacted at ebocardo@unsa.edu.pe or Av. Sánchez Carreón s/n , Cercado Arequipa.

Laura Bowling is a Professor of hydrology in the Department of Agronomy at Purdue University. Her research investigates the water resources impact of environmental change across multiple scales, climate regimes, and ecosystems and communicates these findings to stakeholders. She can be contacted at bowling@purdue.edu or 915 W. State St., West Lafayette, IN 47907.

Zhao Ma is a Professor of Natural Resource Social Science in the Department of Forestry and Natural Resource at Purdue University. Her research examines how individuals and organizations make natural resource decisions in the context of social-ecological change. She can be contacted at zhaoma@purdue.edu or 195 Marsteller Street, West Lafayette, IN 47907-2033, USA.

Linda Prokopy is a Professor in the Department of Forestry and Natural Resources at Purdue University. She conducts research on the social dimensions of watershed management. She can be contacted at lprokopy@purdue.edu or 195 Marsteller St., West Lafayette IN 47907.

Carlos Zeballos-Velarde is an architect, urban planner, and professor at the Faculty of Architecture and Urbanism at the Universidad Nacional de San Agustín in Arequipa, Peru. He conducts GIS analyses about various topics related to environmental urban planning and works in several research projects about participatory risk management with different communities. He can be contacted at czeballos@unsa.edu.pe or Urb. Las Begonias F-1, JLByR. Arequipa, Peru.

References

Alcamo, J. and T. Henrichs. 2002. Critical regions: A model-based estimation of world water resources sensitive to global changes. *Aquatic Sciences* 64: 352-362. Available at: https://doi.org/10.1007/PL00012591. Accessed March 13, 2020.

Ansell, C. and A. Gash. 2007. Collaborative governance in theory and practice. *Journal of Public Administration Research and Theory* 18(4): 543-571. Available at: https://doi.org/10.1093/jopart/mum032. Accessed December 10, 2019.

Archer, D. and A. Cameron. 2009. *Collaborative Leadership: How to Succeed in an Interconnected World*. Butterworth-Heinemann, Jordan Hill, Oxford, UK.

Arequipa Nexus Insitute (ANI). 2020. Arequipa Nexus Institute for Food, Energy, Water, and the

Environment. Available at: https://www.purdue.edu/discoverypark/arequipa-nexus/en/index.php. Accessed November 6, 2020.

Ariño, A. and J. de la Torre. 1998. Learning from failure: Towards an evolutionary model of collaborative ventures. *Organization Science* 9(3): 306-325. Available at: https://www.jstor.org/stable/2640225. Accessed December 6, 2019.

Babiak, K. and L. Thibault. 2009. Challenges in multiple cross-sector partnerships. *Nonprofit and Voluntary Sector Quarterly* 38(1): 117-143.

Bammer, G. 2008. Enhancing research collaborations: Three key management challenges. *Research Policy* 37(5): 875-887. Available at: https://doi.org/10.1016/j.respol.2008.03.004. Accessed January 3, 2020.

Bergstrom, J.C. and A. Randall. 2016. *Resource Economics: An Economic Approach to Natural Resource and Environmental Policy*. 4th ed. Edward Elgar, Northampton, Massachusetts.

Bishop, R. 2011. Freeing ourselves from neo-colonial domination in research. In: *Transgressions: Cultural Studies and Education* (Freeing Ourselves, Vol. 66), S. Steinberg and J.L. Kincheloe (Eds.). Sense Publishers, pp. 1-30.

Bob C. 2017. Foreign government support for threatened civil societies: Helpful or harmful? In: *Partnerships in International Policy-Making: Civil Society and Public Institutions in European and Global Affairs (International Series on Public Policy)*, R. Marchetti (Ed.). Palgrave Macmillan, London, pp. 257-273.

Brodsky, A.E. and T. Faryal. 2006. No matter how hard you try, your feet still get wet: Insider and outsider perspectives on bridging diversity. *American Journal of Community Psychology* 37(3-4): 191-201. Available at: https://doi.org/10.1007/s10464-006-9015-x. Accessed February 14, 2020.

Bryson, J.M., B.C. Crosby, and M.M. Stone. 2006. The design and implementation of cross-sector collaborations: Propositions from the literature. *Public Administration Review* 66(s1): 44-55. Available at: https://doi.org/10.1111/j.1540-6210.2006.00665.x. Accessed December 4, 2020.

Butler, R. and J. Gill. 1995. Learning and knowledge in joint-ventures: The importance of trust. In: *paper presented to the British Academy of Management annual conference.* Sheffield, UK.

Christenson, D. and D.H.T. Walker. 2004. Understanding the role of "vision" in project success. *Project Management Journal* 35(3): 39-52. Available at: https://doi.org/10.1177%2F875697280403500306. Accessed April 3, 2020.

Conlin, S. and R.L. Stirrat. 2008. Current challenges in development evaluation. *Evaluation* 14(2): 193-208. Available at: https://doi.org/10.1177/1356389007087539. Accessed March 10, 2020.

de Jong, K., U. Daellenbach, S. Davenport, J. Haar, and S. Leitch. 2019. Giving science innovation systems a 'nudge'. *Technlology Innovation Management Review* 9(10): 51-61. Available at: http://doi.org/10.22215/timreview/1275. Accessed January 3, 2020.

Donovan, C. 2011. State of the art in assessing research impact: Introduction to a special issue. *Research Evaluation* 20(3): 175-179. Available at: https://doi.org/10.3152/095820211X13118583635918. Accessed March 10, 2020.

Emerson, K., T. Nabatchi, and S. Balogh. 2012. An integrative framework for collaborative governance. *Journal of Public Administration Research and Theory* 22(1): 1-29. Available at: https://doi.org/10.1093/jopart/mur011. Accessed December 10, 2019.

Ethiopian Institute of Water Resources (EIWR). 2020. Graduate Programs. Addis Ababa University, Ethiopia. Available at: http://www.aau.edu.et/iewr/programs/. Accessed October 28, 2020.

Gentry, R. 2013. Special issue on impacts of land use and climate change on hydrological processes in China. *Journal of Hydrologic Engineering* 18(4): 377.

Getha-Taylor, H. 2008. Identifying collaborative competencies. *Review of Public Personnel Administration* 28(2): 103-119. Available at: https://doi.org/10.1177/0734371X08315434. Accessed December 5, 2019.

Goring, S.J., K.C. Weathers, W.K. Dodds, P.A. Soranno, L.C. Sweet, … and R.M. Utz. 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. *Frontiers in Ecology and the Environment* 12(1): 39-47. Available at: https://doi.org/10.1890/120370. Accessed January 2, 2020.

Hanney, S., T. Packwood, and M. Buxton. 2000. Evaluating the benefits from health research and development centres: A categorization, a model and examples of application. *Evaluation* 6(2): 137-160. Available at: https://doi.org/10.1177/13563890022209181. Accessed March 10, 2020.

Heath, C. and D. Heath. 2007. *Made to Stick: Why Some Ideas Survive and Others Die*. Random House, New York.

Huxham, C. and S. Vangen. 2005. *Managing to Collaborate: The Theory and Practice of Collaborative Advantage*. Routledge, New York.

Ivery, J.M. 2010. Partnerships in transition: Managing organizational and collaborative change. *Journal of Human Behavior in the Social Environment* 20(1): 20-37. Available at: https://doi.org/10.1080/10911350903256648. Accessed December 12, 2019.

Janssens, M. and J.M. Brett. 2006. Cultural intelligence in global teams: A fusion model of collaboration. *Group & Organization Management* 31(1): 124-153. Available at: https://doi.org/10.1177/1059601105275268. Accessed February 14, 2020.

Kelly, M.J., J. Schaan, and H. Joncas. 2002. Managing alliance relationships: Key challenges in the early stages of collaboration. *R&D Management* 32(1): 11-22. Available at: https://doi.org/10.1111/1467-9310.00235. Accessed April 3, 2020.

Kelman, H.C. 2005. Building trust among enemies: The central challenge for international conflict resolution. *International Journal of Intercultural Relations* 29(6): 639-650. Available at: https://doi.org/10.1016/j.ijintrel.2005.07.011. Accessed April 3, 2020.

Kolesnikov, S., S. Woo, Y. Li, P. Shapira, and J. Youtie. 2019. Mapping the emergence of international university research ventures. *The Journal of Technology Transfer* 44: 1134-1162. Available at: https://doi.org/10.1007/s10961-017-9640-6. Accessed January 3, 2020.

Kouritzin, S. and S. Nakagawa. 2018. Toward a non-extractive research ethics for transcultural, translingual research: Perspectives from the coloniser and the colonized. *Journal of Multilingual and Multicultural Developmen*t 39(8): 675-687. DOI: 10.1080/01434632.2018.1427755.

Lang, D.J., A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, … and C.J. Thomas. 2012. Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science* 7: 25-43. Available at: https://doi.org/10.1007/s11625-011-0149-x. Accessed January 28, 2020.

Leider, H.L. 1999. Gaining physician buy-in for disease management initiatives. *Disease Management and Health Outcomes* 6: 327-332. Available at: https://doi.org/10.2165/00115677-199906060-00003. Accessed March 10, 2020.

Lloyd-walker, B.M., A.J. Mills, and D.H.T. Walker. 2014. Enabling construction innovation: The role of a no-blame culture as a collaboration behavioural driver in project alliances. *Construction Management and Economics* 32(3): 229-245. Available at: https://doi.org/10.1080/01446193.2014.892629. Accessed February 17, 2020.

Mahuika, R. 2008. Kaupapa Māori theory is critical and anti-colonial. *MAI Review* 3(4): 1-16. Available at: https://www.researchgate.net/publication/26569994_Kaupapa_Maori_theory_is_critical_and_anti-colonial. Accessed March 13, 2020.

Morris, N. 2015. Providing ethical guidance for collaborative research in developing countries. *Research Ethics* 11(4): 211-235. Available at: https://doi.org/10.1177/1747016115586759. Accessed January 28, 2020.

Morton, G.H.A. 1983. Become a project champion. *International Journal of Project Management* 1(4): 197-203. Available at: https://doi.org/10.1016/0263-7863(83)90048-0. Accessed March 10, 2020.

Pfotenhauer, S.M., J.S. Jacobs, J.A. Pertuze, D.J. Newman, and D.T Roos. 2013. Seeding change through international university partnerships: The MIT-Portugal Program as a driver of internationalization, networking, and innovation. *Higher Education Policy* 26(2): 217-242.

Pfotenhauer, S.M., D. Wood, D. Roos, and D. Newman. 2016. Architecting complex international science, technology and innovation partnerships (CISTIPs): A study of four global MIT collaborations. *Technological Forecasting and Social Change* 104: 38-56. Available at: https://doi.org/10.1016/j.techfore.2015.12.006. Accessed January 3, 2020.

Ponds, R. 2009. The limits to internationalization of scientific research collaboration. *Journal of Technology Transfer* 34: 76-94. Available at: https://doi.org/10.1007/s10961-008-9083-1. Accessed March 13, 2020.

Popovici, R., A. Erwin, Z. Ma, L.S. Prokopy, L. Zanotti, E.F. Bocardo Delgado, ... and G.R. Arce Larrea. 2020a. Outsourcing governance in Peru's integrated water resources management. *Land Use Policy*. Available at: https://doi.org/10.1016/j.landusepol.2020.105105. Accessed November 4, 2020.

Popovici, R., K.E. Mazer, A. Erwin, Z. Ma, J.P. Pinto Caceres, … and L.S. Prokopy. 2020b. Coproduction challenges in the context of changing rural livelihoods. *Journal of Contemporary Water Research and Eduction* 171: 111-126. Available at: https://onlinelibrary.wiley.com/journal/1936704x. Accessed December 22, 2020.

Ryan, C. and P. Walsh. 2004. Collaboration of public sector agencies: Reporting and accountability challenges. *International Journal of Public Sector Management* 17(7): 621-631. Available at: https://doi.org/10.1108/09513550410562284. Accessed April 3, 2020.

Schwartz, R. 2001. Managing government-third sector collaboration: Accountability, ambiguitiy, and politics. *International Journal of Public Administration* 24(11): 1161-1188. Available at: https://doi.org/10.1081/PAD-100105234. Accessed March 10, 2020.

Spooner, C., C. Lavey, C. Mukuka, and R. Eames-Brown. 2016. Multi-institution research centers: Planning and management challenges. *Journal of Research Administration* 47(2): 32-48.

Thomson, A.M. and J.L. Perry. 2006. Collaboration processes: Inside the black box. *Public Administration Review* 66(s1): 20-32. Available at: https://doi.org/10.1111/j.1540-6210.2006.00663.x. Accessed December 10, 2019.

Thomson, K., L. de Chernatony, L. Arganbright, and S. Khan. 1999. The buy-in benchmark: How staff understanding and commitment impact brand and business performance. *Journal of Marketing Management* 15(8): 819-835. Available at: https://doi.org/10.1362/026725799784772684. Accessed March 3, 2020.

Tracy, S.J. 2010. Qualitative quality: Eight “big-tent” criteria for excellent qualitative research. *Qualitative Inquiry* 16(10): 837-851.

UC Davis Chile. 2020. Research & Development. UC Davis Chile Life Sciences Innovation Center. Available at: https://chile.ucdavis.edu/en/research-development. Accessed October 27, 2020.

U.S.-Pakistan Centers for Advanced Studies in Water MUET Jamshoro (USPCAS-W). 2020. Final Report: 12 Dec 2014 - 11 Dec 2019. Cooperative Agreement No. AID-391-A-15-00003. Available at: http://water.muet.edu.pk/wp-content/uploads/2020/05/Final-Report-USPCAS-W-MUET.pdf. Accessed October 28, 2020.

Vaaland, T.I. 2004. Improving project collaboration: Start with the conflicts. *International Journal of Project Management* 22(6): 447-454. Available at: https://doi.org/10.1016/j.ijproman.2003.11.003. Accessed April 3, 2020.

van der Weijden, I., M. Verbree, and P. van den Besselaar. 2012. From bench to bedside: The societal orientation of research leaders: The case of biomedical and health research in the Netherlands. *Science and Public Policy* 39(3): 285-303. Available at: https://doi.org/10.1093/scipol/scr003. Accessed March 10, 2020.

Vangen, S. and C. Huxham. 2003. Nurturing collaborative relations: Building trust in interorganizational collaboration. *The Journal of Applied Behavioral Science* 39(1): 5-31. Available at: https://doi.org/10.1177/0021886303039001001. Accessed December 12, 2020.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289(5477): 284-288. Available at: https://doi.org/10.1126/science.289.5477.284. Accessed April 3, 2020.

Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, … and P.M. Davies. 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555-561. Available at: https://doi.org/10.1038/nature09440. Accessed April 2, 2020.

Wiek, A., B. Ness, P. Schweizer-Ries, F.S. Brand, and F. Farioli. 2012. From complex systems analysis to transformational change: A comparative appraisal of sustainability science projects. *Sustainability Science* 7(1): 5-24. Available at: https://doi.org/10.1007/s11625-011-0148-y. Accessed November 17, 2020.

Wilmsen, C. 2008. Extraction, empowerment, and relationships in the practice of participatory research. In: *Towards Quality Improvement of Action Research: Developing Ethics and Standards*, B. Boog, J. Preece, M. Slager, and J. Zeelen (Eds.). Sense Publishers, Rotterdam, The Netherlands, pp. 135-146.

Winer, M. and K. Ray. 1994. *Collaboration Handbook: Creating, Sustaining, and Enjoying the Journey*. Amherst H. Wilder Foundation, St. Paul, Minnesota.

Woldegiyorgis, A.A., D. Proctor, and H. de Wit. 2018. Internationalization of research: Key considerations and concerns. *Journal of Studies in International Education* 22(2): 161-176. Available at: https://doi.org/10.1177/1028315318762804. Accessed January 3, 2020.

Xiamen University and University of Delaware. 2013. Collaboration Across the Seas. Joint Institute for Coastal Research and Management. Available at: https://www.joint-crm.org/. Accessed October 28, 2020.

Youtie, J., Y. Li, J. Rogers, and P. Shapira. 2017. Institutionalization of international university research ventures. *Research Policy* 46(9): 1692-1705. Available at: https://doi.org/10.1016/j.respol.2017.08.006. Accessed January 3, 2020.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 27-48, December 2020

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

*André Geraldo de Lima Moraes[1], Edwin Bocardo-Delgado[2], Laura C. Bowling[3], Fariborz Daneshvar[1], José Pinto[4], Alec Hale Watkins[1], and Keith Aric Cherkauer[1]

*[1]Agricultural & Biological Engineering Department, Purdue University, West Lafayette, IN, USA; [2]Biology Department, Universidad Nacional de San Agustin, Arequipa, AR, Peru; [3]Agronomy Department, Purdue University, West Lafayette, IN, USA; [4]Agronomy Department, Universidad Nacional de San Agustin, Arequipa, AR, Peru; *Corresponding Author*

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)	Sampling Date (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

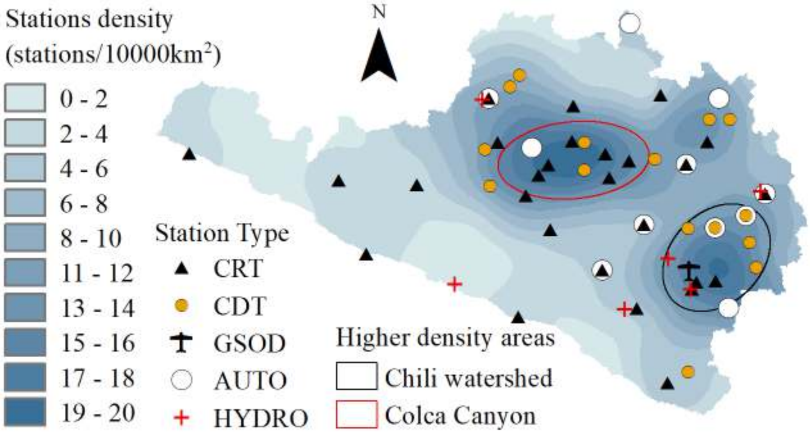


Figure 1. Density of active weather stations measuring at least temperature and precipitation in the Arequipa Department in March 2020 and station types. HYDRO stations were not considered in the density calculation as they only measure precipitation. CRT = conventional stations with real-time data availability (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).

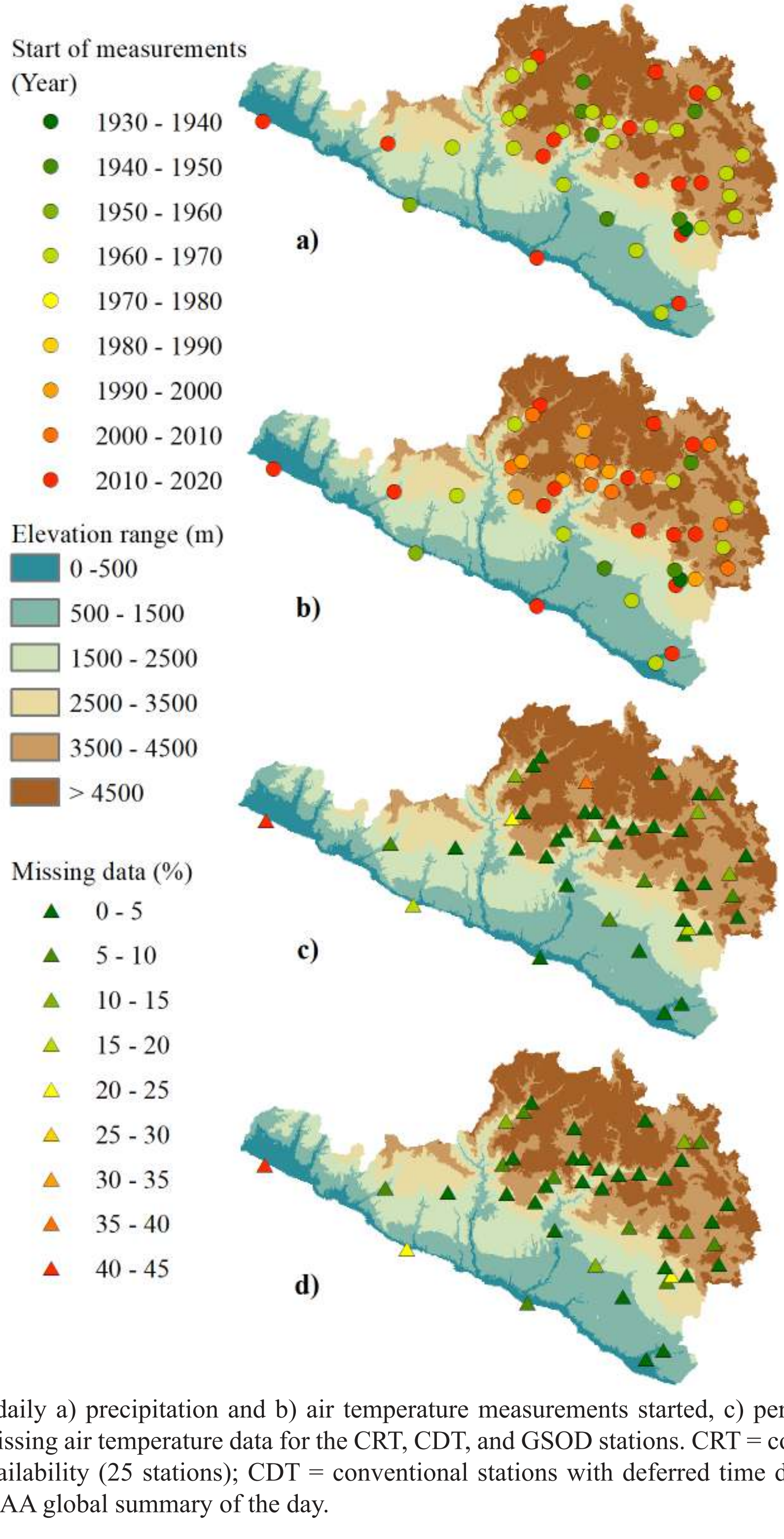


Figure 2. Year when daily a) precipitation and b) air temperature measurements started, c) percentage of missing precipitation, and d) missing air temperature data for the CRT, CDT, and GSOD stations. CRT = conventional stations with real-time data availability (25 stations); CDT = conventional stations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

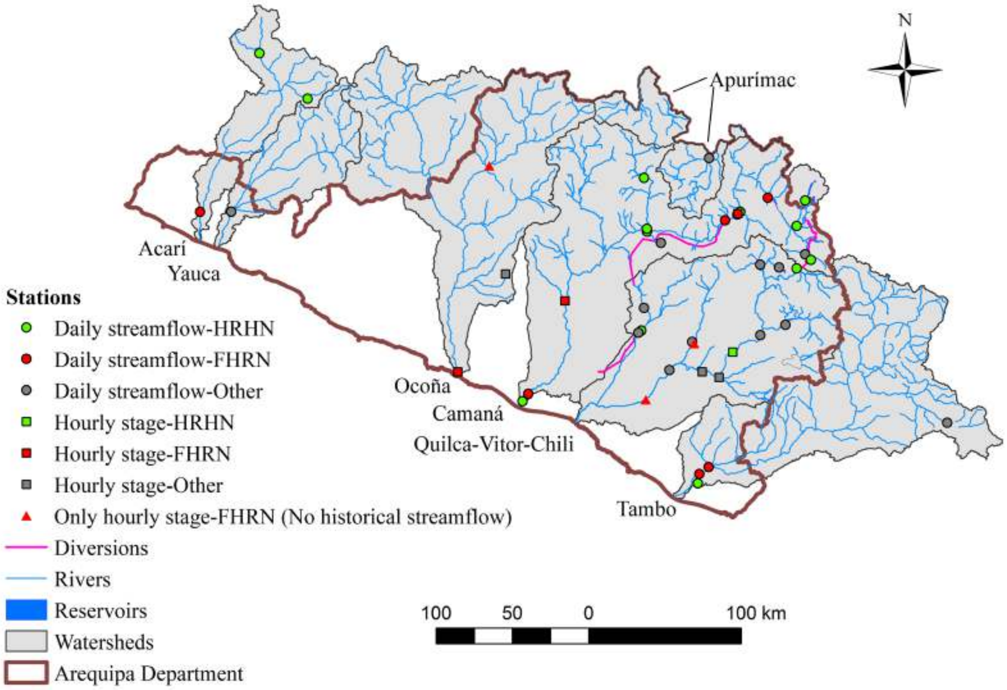


Figure 3. Locations of stream discharge monitoring stations in the Arequipa Department of Peru. Locations are marked by frequency and type of measurement (daily flow or hourly stage), and whether they meet the requirements to be part of the historic or future hydrologic reference network (HRHN and FHRN,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

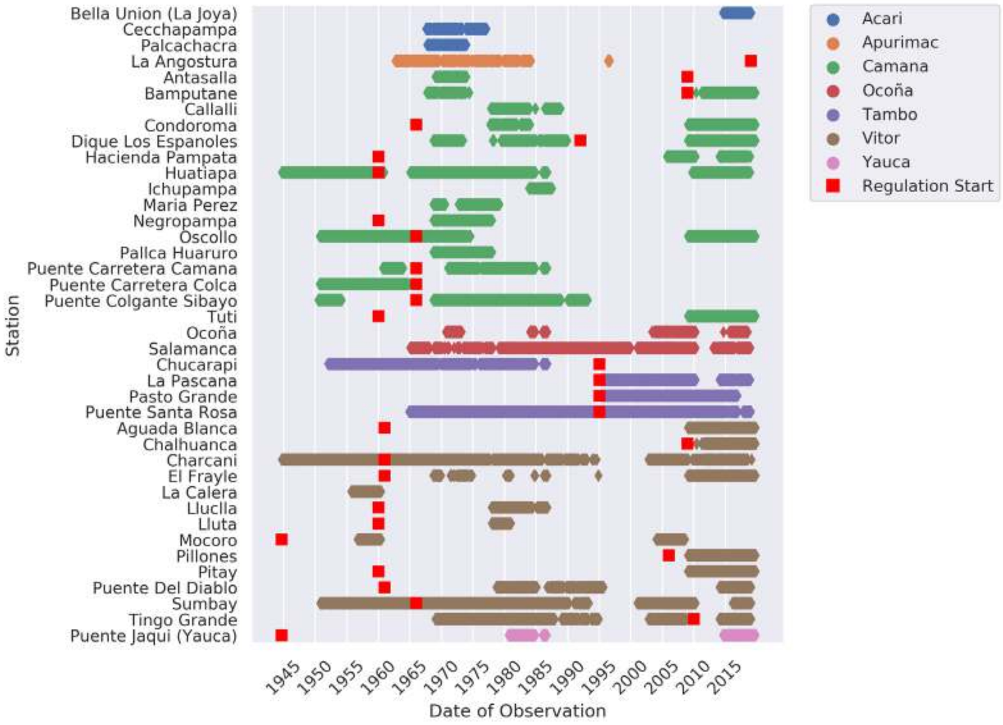


Figure 4. Dates of observations for all streamflow stations in the Arequipa Department of Peru. Color indicates the river basin in which each station is located. Start of upstream regulation (based on earliest regulation for stations downstream of multiple structures) is indicated for each station by 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

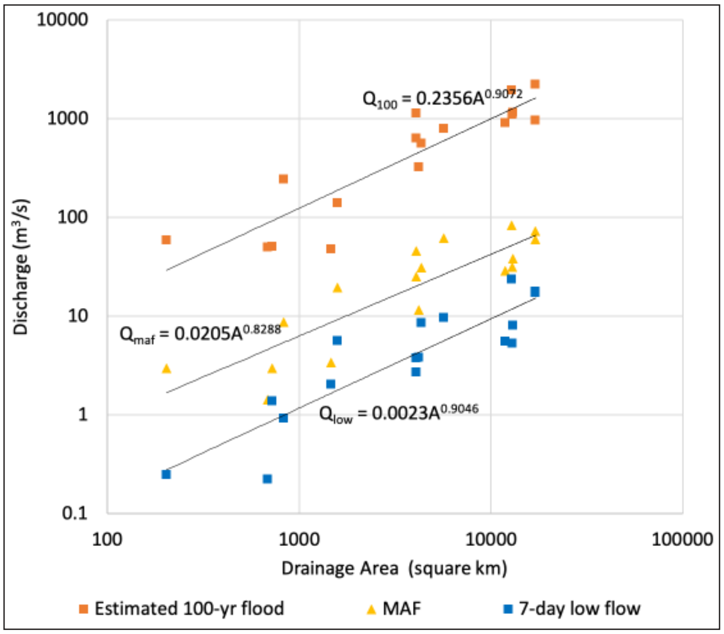


Figure 5. Baseline hydrology for the Arequipa Department of Peru, including the estimated 100-year flood based on a fitted EVI distribution, 7-day mean low flow, and mean annual flow based on 21 Historic Reference Stations with different reference years (see Table 2), using the historic reference years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

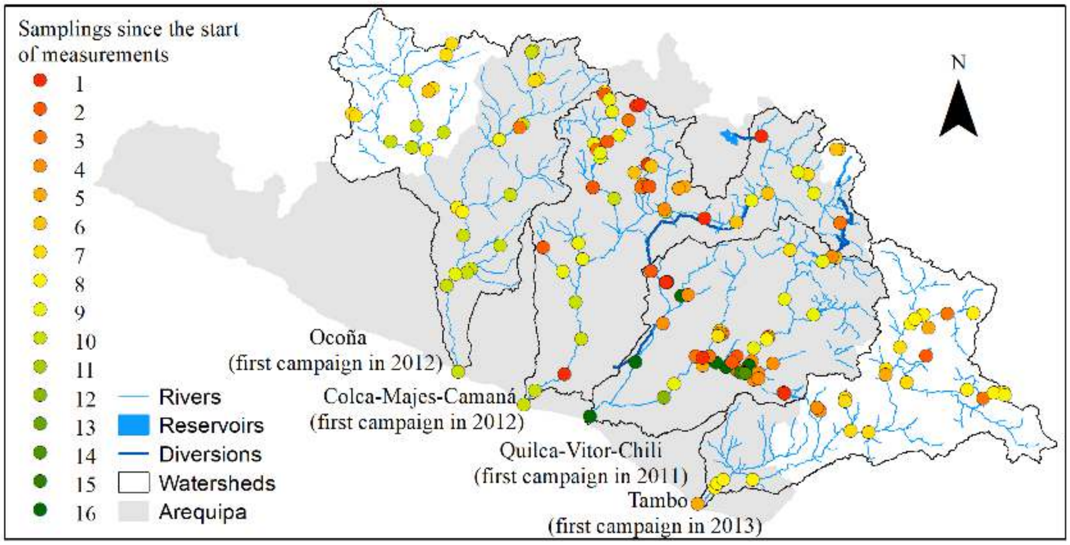


Figure 6. Spatial distribution of water quality measurements performed by the National Water Authority (ANA) from 2011 to 2019 in the four main watersheds in the Arequipa Department. Points represent locations and fill color represents the number of samplings done since the start of measurements.

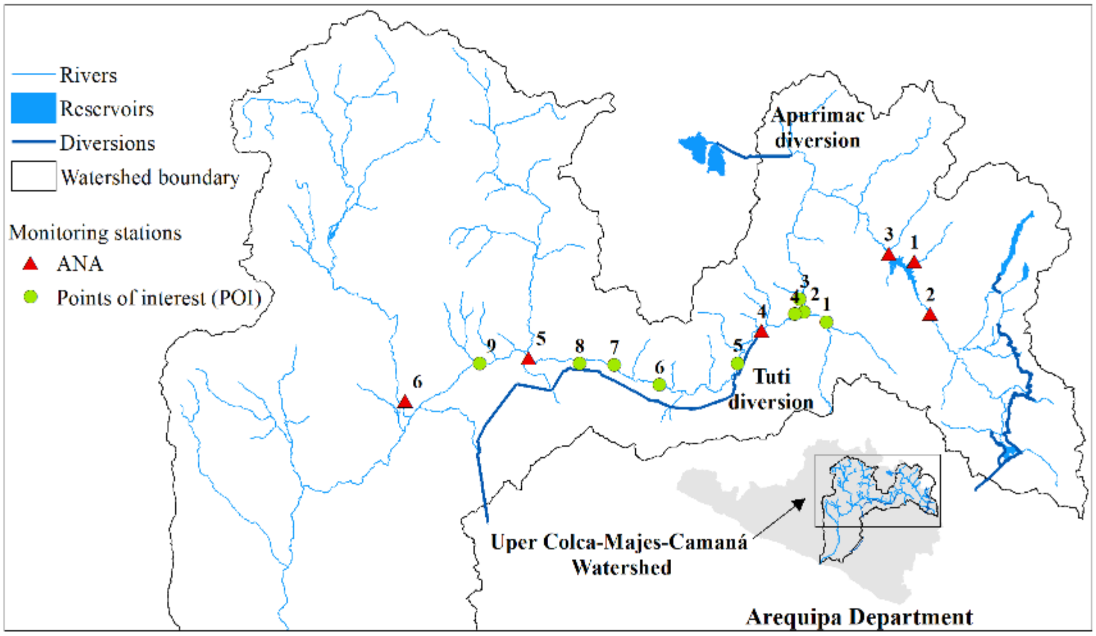


Figure 7. Proposed monitoring network for the upper Colca-Majes-Camaná watershed. ANA – monitoring locations where the National Water Authority has sampled previously. Points of interest – locations for future measurements.

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.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustin.

Author Bio and Contact Information

André Geraldo de Lima Moraes (corresponding author) was born in Muzambinho, Minas Gerais, Brazil, and concluded his bachelor's degree in Agronomy (2011), Masters (2013), and Ph.D. (2018) in Agronomy-Soil Science (CPGA-CS) at the Federal Rural University of Rio de Janeiro (UFRRJ). Currently, he is a postdoc at the Agriculture and Biologic Engineering (ABE) Department at Purdue University. Research interests include soil management and conservation, genesis, morphology, survey, classification, digital soil mapping, erosion and infiltration spatial modeling, climate mapping, climate trend analysis, and general applications of remote sensing and GIS. He can be contacted at adelimam@purdue.edu or 225 S. University St., West Lafayette IN 47907.

Edwin Bocardo-Delgado is a principal professor in the Department of Biological Sciences and a graduate Environmental Science professor at the Universidad Nacional de San Agustín de Arequipa. He also works as an environmental consultant for several companies and a natural resource management specialist. He can be contacted at ebocardo@unsa.edu.pe or Av. Sánchez Carreón s/n , Cercado Arequipa.

Laura Bowling is a Professor of hydrology in the Department of Agronomy at Purdue University. Her research investigates the water resources impact of environmental change across multiple scales, climate regimes, and ecosystems and communicates these findings to stakeholders. She can be contacted at bowling@purdue.edu or 915 W. State St., West Lafayette, IN 47907.

Fariborz Daneshvar is a Postdoctoral Research Associate in the Department of Agricultural and Biological Engineering at Purdue University. He conducts watershed hydrology research with respect to environmental and socioeconomic impacts. He can be contacted at fdaneshv@purdue.edu or 225 S. University St., West Lafayette IN 47907.

José Pinto is a professor in the Department of Agronomy at the Universidad Nacional de San Agustín de Arequipa. He conducts agricultural research and connects with interested associations to improve natural resource management. He can be contacted at jpinto2@unsa.edu.pe or Urb. Aurora s/n (costado Estadio UNSA) Arequipa - Perú.

Alec Watkins is a graduate student of Agricultural and Biological Engineering at Purdue University. His work is focused on the mapping of agriculture in the Arequipa department of Peru using remote sensing and pattern recognition, although he has helped with other studies in this region. He can be contacted at watkin46@purdue.edu.

Keith Aric Cherkauer is a Professor of Agricultural and Biological Engineering at Purdue University. He works to facilitate the integration of field-based observations, remote sensing products, and hydrology models to address questions and concerns related to environmental change and to further understanding of land-atmosphere interactions and the hydrologic cycle. He can be contacted at cherkaue@purdue.edu or 225 S. university St., West Lafayette, IN 47907.

References

Alarcón, J. 2019. Impactos "negativos" de mejores sistemas de tratamiento de aguas residuales en el Perú. *Ingeniería Sanitaria y Ambiental: Revista de Investigación Científica para el Desarrollo Sustentable* 1(1). Available at: https://revistas.uancv.edu.pe/index.php/ISA/article/view/762/660. Accessed November 10, 2020.

Arsenault, R. and F. Brissette. 2014. Determining the optimal spatial distribution of weather station networks for hydrological modeling purposes using RCM datasets: An experimental approach. *Journal of Hydrometeorology* 15(1): 517-526. Available at: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1175%2FJHM-D-13-088.1. Accessed November 10, 2020.

AUTODEMA. 2018. Autoridad Autónoma de Majes. Available at: https://www.autodema.gob.pe/. Accessed March 20, 2020.

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. Available at: https://hdl.handle.net/20.500.12543/2070. Accessed November 10, 2020.

Autoridad Nacional de Agua (ANA). 2019. Ley de los Recursos Hídricos: Ley Nº 29338. Available at: https://hdl.handle.net/20.500.12543/228. Accessed November 22, 2020.

Autoridad Nacional del Agua (ANA). 2020. Nosotros. Available at: https://www.ana.gob.pe/nosotros/la-autoridad/nosotros. Accessed March 20, 2020.

Bartsotas, N.S., E.N. Anagnostou, E.I. Nikolopoulos, and G. Kallos. 2018. Investigating satellite precipitation uncertainty over complex terrain. *Journal of Geophysical Research: Atmospheres* 123(10): 5346-5359. Available at: https://doi.org/10.1029/2017JD027559. Accessed November 25, 2020.

Biancamaria, S., D.P. Lettenmaier, and T.M. Pavelsky. 2016. The SWOT mission and its capabilities for land hydrology. *Surveys in Geophysics* 37: 307-337. Available at: https://doi.org/10.1007/s10712-015-9346-y. Accessed November 25, 2020.

Bnamericas. 2019. Autoridad Autónoma de Majes (Autodema). Available at: https://www.bnamericas.com/en/company-profile/autoridad-autonoma-de-majes. Accessed March 20, 2020.

Bottaro, L. and M. Sola Álvarez. 2018. Agua y megaproyectos mineros en América Latina. *Los Polvorines: Universidad Nacional de General Sarmiento-WATERLAT/GOBACIT*. Available at: https://www.ungs.edu.ar/wp-content/uploads/2019/08/9789876302869-resumen-1.pdf. Accessed November 10, 2020.

Bradford, R.B. and T.M. Marsh. 2003. Defining a network of benchmark catchments for the UK. *Proceedings of the Institution of Civil Engineers- Water and Maritime Engineering* 156(2): 109-116. Available at: https://doi.org/10.1680/wame.2003.156.2.109. Accessed November 10, 2020.

Bronstert, A. and A. Bárdossy. 2003. Uncertainty of runoff modelling at the hillslope scale due to temporal variations of rainfall intensity. *Physics and Chemistry of the Earth*, *Parts A/B/C* 28(6-7): 283-288. Available at: https://doi.org/10.1016/S1474-7065(03)00039-1. Accessed November 10, 2020.

Brown, L.C. and G.R. Foster. 1987. Storm erosivity using idealized intensity distributions. *Transactions of the ASAE* 30(2): 379-386. Available at: https://elibrary.asabe.org/abstract.asp?aid=31957. Accessed November 10, 2020.

Cacya, L., P. Meza, V. Carlotto, and L. Mamani. 2013. Aluvión del 8 de febrero del 2013 en la ciudad de Arequipa. En: *Foro Internacional Peligros Geológicos*, Arequipa, Peru, 14-16 Octubre 2013, pp. 195-200. Available at: https://hdl.handle.net/20.500.12544/1132. Accessed November 25, 2020.

Carreño-Meléndez, F., A.Y. Vásquez-González, and G.V. González. 2019. Problemas sociales y ambientales por el uso de agroquímicos en Tenancingo, México. *Tlatemoani* 10(31). Available at: https://dialnet.unirioja.es/servlet/articulo?codigo=7295545. Accessed November 10, 2020.

Chevallier, P., B. Pouyaud, W. Suarez, and T. Condom. 2011. Climate change threats to environment in the tropical Andes: Glaciers and water resources. *Regional Environmental Change* 11: 179-187. DOI: 10.1007/s10113-010-0177-6.

Cobb, E.D. and J.E. Biesecker. 1971. *The National Hydrologic Bench-mark Network*. U.S. Department of the Interior, Geological Survey Circular 460-D. Available at: https://doi.org/10.3133/cir460D. Accessed December 7, 2020.

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22: 99-113. Available at: https://www.int-res.com/articles/cr2002/22/c022p099.pdf. Accessed November 11, 2020.

Daly, C. 2006. Guidelines for assessing the suitability of spatial climate data sets. *International Journal of Climatology* 26(6): 707-721. Available at: https://doi.org/10.1002/joc.1322. Accessed November 11, 2020.

Delgado, J., M. Rodríguez-Rodríguez, and M. Díaz-Azpiroz. 2019. Niveles de contaminación por metales pesados en el acuífero aluvial del Agrio en el entorno minero de Aznalcóllar (Sevilla) durante el periodo 2012-2018. *Geogaceta* 66: 47-50. Available at: http://hdl.handle.net/10272/17704. Accessed November 11, 2020.

Department of Commerce/National Oceanic and Atmospheric Administration/The National Environmental Satellite, Data, and Information Service/National Climatic Data Center (DOC/NOAA/NESDIS/NCDC). 2020. Global Surface Summary of the Day. Available at: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00516#. Accessed March 11, 2020.

Diamond, H.J., T.R. Karl, M.A. Palecki, C.B. Baker, J.E. Bell, R.D. Leeper, et al. 2013. U.S. climate reference network after one decade of operations: Status and assessment. *Bulletin of the American Meteorological Society* 94(4): 485-498. Available at: https://doi.org/10.1175/BAMS-D-12-00170.1. Accessed November 25, 2020.

Dore, M.H. 2005. Climate change and changes in global precipitation patterns: What do we know? *Environment international* 31(8): 1167-1181. Available at: https://doi.org/10.1016/j.envint.2005.03.004. Accessed November 11, 2020.

Fiebrich, C.A. and K.C. Crawford. 2009. Automation: A step toward improving the quality of daily temperature data produced by climate observing networks. *Journal of Atmospheric and Oceanic Technology* 26(7): 1246-1260. Available at: https://doi.org/10.1175/2009JTECHA1241.1. Accessed March 11, 2020.

Garcia Quijano, J.F. 2018. Estudio hidrológico de las cuencas Camaná, Majes, Sihuas, Quilca-Vittor-Chili con informacion satelital. Tesis, Universidad Nacional Agraria La Molina, Lima, Perú. Available at: http://repositorio.lamolina.edu.pe/handle/UNALM/3530. Accessed March 11, 2020.

Garreaud, R.D. 2009. The Andes climate and weather. *Advances in Geosciences* 22: 3-11. Available at: www.adv-geosci.net/22/3/2009/. Accessed November 11, 2020.

Garreaud, R., M. Vuille, and A. Clement. 2003. The climate of the Altiplano: Observed current conditions and mechanism of past changes. *Paleogeography, Palaeoclimatology, Palaeoecology* 194(1-3): 5-22. Available at: https://doi.org/10.1016/S0031-0182(03)00269-4. Accessed November 11, 2020.

Goody, R., J. Anderson, T. Karl, R.B. Miller, G. North, J. Simpson, G. Stephens, and W. Washington. 2002. Why monitor the climate? *Bulletin of the American Meteorological Society* 83(6): 873-878. Available at: https://doi.org/10.1175/1520-0477(2002)083<0873:WWSMTC>2.3.CO;2. Accessed November 11, 2020.

Hunziker, S., S. Gubler, J. Calle, I. Moreno, M. Andrade, F. Velarde, L. Ticona, G. Carrasco, Y. Castellón, C. Oria, M. Croci-Maspoli, et al. 2017. Identifying, attributing, and overcoming common data quality issues of manned station observations. *International Journal of Climatology* 37(11): 4131-4145. Available at: https://doi.org/10.1002/joc.5037. Accessed November 11, 2020.

Instituto Nacional de Estadística e Informática (INEI). 2017. Arequipa. Compendio Estadístico 2017. Lima, Peru. Available at: https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1490/libro.pdf. Accessed November 11, 2020.

Jennings, M.E., W.O. Thomas Jr., and H.C. Riggs. 1994. *Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites, 1993*. U.S. Geological Survey Water-Resources Investigations Report 94-4002. Available at: https://doi.org/10.3133/wri944002. Accessed December 7, 2020.

Karl, T.R., V.E. Derr, D.R. Easterling, C.K. Folland, D.J. Hofmann, S. Levitus, N. Nicholls, D.E. Parker, and G.W. Withee. 1995. Critical issues for long-term climate monitoring. *Climatic Change* 31: 185-221. Available at: https://doi.org/10.1007/BF01095146. Accessed November 25, 2020.

Kochtitzky, W.H., B.R. Edwards, E.M. Enderlin, J. Marino, and N. Marinque. 2018. Improved estimates of glacier change rates at Nevado Coropuna Ice Cap, Peru. *Journal of Glaciology* 64(244): 175-184. Available at: https://doi.org/10.1017/jog.2018.2. Accessed November 11, 2020.

Kueppers, L.M. and M.A. Snyder. 2012. Influence of irrigated agriculture on diurnal surface energy and water fluxes, surface climate, and atmospheric circulation in California. *Climate Dynamics* 38(5): 1017-1029. DOI: 10.1007/s00382-011-1123-0.

Kueppers, L.M., M.A. Snyder, and L.C. Sloan. 2007. Irrigation cooling effect: Regional climate forcing by land-use change. *Geophysical Research Letters* 34(3). Available at: https://doi.org/10.1029/2006GL028679. Accessed November 11, 2020.

Lettenmaier, D. 1978. Design considerations for ambient stream quality monitoring. *Water Resources Bulletin* 14(4): 884-902.

Lettenmaier, D.P. 1975. *Design of Monitoring Systems for Detection of Trends in Stream Quality*. Water Resources Series Technical Report No. 39. Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington. Available at: https://www.ce.washington.edu/sites/cee/files/pdfs/research/hydrology/water-resources/WRS039.pdf. Accessed December 7, 2020.

Lobell, D.B. and C. Bonfils. 2008. The effect of irrigation on regional temperatures: A spatial and temporal analysis of trends in California, 1934–2002. *Journal of Climate* 21(10): 2063-2071. Available at: https://doi.org/10.1175/2007JCLI1755.1. Accessed November 11, 2020.

Lopez Arisaca, S.R. 2018. Evaluación de la Calidad de Agua respecto a Metales Pesados presentes en el río Tambo provincia de Islay 2016-2018. Tesis, Universidad Nacional de San Agustín Arequipa, Perú. Available at: http://repositorio.unsa.edu.pe/handle/UNSA/8894. Accessed November 11, 2020.

López-Moreno, J.I., S. Fontaneda, J. Bazo, J. Revuelto, C. Azorin-Molina, B. Valero-Garcés, E. Morán-

Tejeda, S.M. Vicente-Serrano, R. Zubieta, and J. Alejo-Cochachín. 2014. Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. *Global and Planetary Change* 112: 1-11. Available at: https://doi.org/10.1016/j.gloplacha.2013.10.010. Accessed November 11, 2020.

MADIS. 2020. Meteorological Surface Dataset. Available at: https://madis-data.ncep.noaa.gov/MadisSurface/. Accessed March 11, 2020.

Magaña, L.I.G. and C. García. 2016. Contaminación por residuos sólidos en la bahía de Chetumal, Quintana Roo. *9º Encuentro de Expertos en Residuos Sólidos*. pp. 282-289. Available at: http://www.somers-ac.org/paginas/encuentros/noveno.php. Accessed November 11, 2020.

Mazer, K.E., A.A. Tomasek, F. Daneshvar, E.F. Bocardo Delgado, L.C. Bowling, J.R. Frankenberger, S.K. McMillan, H. Novoa, and C.R. Zeballos-Velarde. Integrated hydrologic and hydraulic analysis of torrential flood hazard in Arequipa, Peru. (In review) *Journal of Contemporary Water Research and Education*.

Meehl, G.A., J.M. Arblaster, and C. Tebaldi. 2005. Understanding future patterns of increased precipitation intensity in climate model simulations. *Geophysical Research Letters* 32(18): L18719. Available at: https://doi.org/10.1029/2005GL023680. Accessed November 11, 2020.

Moraes, A.G., L.C. Bowling, C.R. Zeballos Velarde, and K.A. Cherkauer. 2019. Arequipa Climate Maps – Normals. Purdue University Research Repository. DOI:10.4231/490D-HC66.

Moreno Tovar, A.A., M. Toro Botero, and L.F. Carvaja. 2008. Revisión de criterios y metodologías de diseño de redes para el monitoreo de la calidad del agua en ríos. *Avances en Recursos Hidráulicos* 18. Available at: https://revistas.unal.edu.co/index.php/arh/article/view/9283. Accessed November 11, 2020.

National Research Council (NRC). 1999. *Adequacy of Climate Observing Systems*. National Academy Press, Washington, D.C.

Ouyang, Y., P. Nkedi-Kizza, Q.T. Wu, D. Shinde, and C.H. Huang. 2006. Assessment of seasonal variations in surface water quality. *Water Research* 40(20): 3800-3810. Available at: https://doi.org/10.1016/j.watres.2006.08.030. Accessed November 11, 2020.

Pinto Paredes, M.A. 2018. Calidad de agua superficial en el rio chili–en los sectores de Sachaca, Jacobo Hunter, Tiabaya y Uchumayo para uso de riego de vegetales y bebida de animales en la Provincia de Arequipa. Tesis, Universidad Nacional de San Agustín Arequipa, Perú. Availabe at: http://bibliotecas.unsa.edu.pe/handle/UNSA/6160. Accessed November 11, 2020.

Ramos-Herrera, S., L.F. Broca-Martínez, J.R. Laines-Canepa, and J.M. Carrera-Velueta. 2012. Tendencia de la calidad del agua en ríos de Tabasco, México. *Ingeniería* 16(3): 207-217. Available at: https://www.redalyc.org/pdf/467/46725267005.pdf. Accessed November 11, 2020.

Rodrigues, V., J. Estrany, M. Ranzini, V. de Cicco, J.M.T. Martín-Benito, J. Hedo, and M.E. Lucas-Borja. 2018. Effects of land use and seasonality on stream water quality in a small tropical catchment: The headwater of Córrego Água Limpa, São Paulo (Brazil). *Science of The Total Environment* 622-623: 1553-1561. Available at: https://doi.org/10.1016/j.scitotenv.2017.10.028. Accessed November 11, 2020.

Salmoral, G., E. Zegarra, I. Vázquez-Rowe, F. González, L. Del Castillo, G.R. Saravia, A. Graves, D. Rey, and J.W. Knox. 2020. Water-related challenges in nexus governance for sustainable development: Insights from the city of Arequipa, Peru. *Science of The Total Environment* 747: 141114. Available at: https://doi.org/10.1016/j.scitotenv.2020.141114. Accessed November 23, 2020.

Salzmann, N., C. Huggel, M. Rohrer, W. Silverio, B.G. Mark, P. Burns, and C. Portocarrero. 2013. Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. *The Cryosphere* 7(1): 103-118. Available at: https://doi.org/10.5194/tc-7-103-2013. Accessed November 11, 2020.

Schauwecker, S., M. Rohrer, D. Acuña, A. Cochachin, L. Dávila, H. Frey, C. Giráldez, J. Gómez, C. Huggel, M. Jacques-Coper, E. Loarte, N. Salzmann, and M. Vuille. 2014. Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited. *Global and Planetary Change* 119: 85-97. Available at: https://doi.org/10.1016/j.gloplacha.2014.05.005. Accessed November 11, 2020.

SENAMHI. 2020a. Descarga de Datos Meteorológicos a Nivel Nacional. Available at: https://www.senamhi.gob.pe/?&p=descarga-datos-hidrometeorologicos. Accessed March 20, 2020.

SENAMHI. 2020b. Datos Hidrometeorológicos a Nivel Nacional. Available at: https://www.senamhi.gob.pe/?&p=estaciones. Accessed March 20, 2020.

Silverman, B.W. 1986. Density estimation for statistics and data analysis. In: *Monographs on Statistics and Applied Probability*, Chapman and Hall, London.

Singh S., G. Krishan, N.C. Ghosh, R.K. Jaiswal, T. Thomas, and T.R. Nayak. 2018. Identification and planning of water quality monitoring network in context of integrated water resource management (IWRM). In: *Environmental Pollution*. Water Science and Technology Library, vol 77, V. Singh, S. Yadav, and R. Yadava (Eds.). Springer, Singapore. Available at: https://doi.org/10.1007/978-981-10-5792-2_41. Accessed November 11, 2020.

Sistema Nacional de Información de Recursos Hídricos (SNIRH). 2020. Sistema Nacional de Información de Recursos Hídricos. Available at: https://www.ana.gob.pe/portalsnirh/portada. Accessed March 20, 2020.

Slack, J.R. and J.M. Landwehr. 1992. *Hydro-climatic Data Network (HCDN): A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climatic Variations, 1874-1988*. U.S. Geological Survey Open-File Report 92-129. Available at: https://doi.org/10.3133/ofr92129. Accessed November 11, 2020.

Stensrud, A.B. 2016. Dreams of growth and fear of water crisis: The ambivalence of "progress" in the Majes-Siguas irrigation project, Peru. *History and Anthropology* 27(5): 569-584. Available at: https://doi.org/10.1080/02757206.2016.1222526. Accessed November 11, 2020.

Strobl, R.O., P.D. Robillard, R.D. Shannon, R.L. Day, and A.J. McDonnell. 2006. A water quality monitoring network design methodology for the selection of critical sampling points: Part I. *Environmental Monitoring and Assessment* 112: 137-158. Available at: https://doi.org/10.1007/s10661-006-0774-5. Accessed November 11, 2020.

Tan, J., K.A. Cherkauer, and I. Chaubey. 2016. Developing a comprehensive spectral-biogeochemical database of Midwestern rivers for water quality retrieval using remote sensing data: A case study of the Wabash River and its tributary, Indiana. *Remote Sensing* 8(6): 517. Available at: https://doi.org/10.3390/rs8060517. Accessed December 1, 2020.

Tapia, J., J. Murray, M. Ormachea, N. Tirado, and D.K. Nordstrom. 2019. Origin, distribution, and geochemistry of arsenic in the Altiplano-Puna plateau of Argentina, Bolivia, Chile, and Perú. *Science of The Total Environment* 678: 309-325. Available at: https://doi.org/10.1016/j.scitotenv.2019.04.084. Accessed November 11, 2020.

Telci, I.T., K. Nam, J. Guan, and M. Aral. 2009. Optimal water quality monitoring network design for river systems. *Journal of Environmental Management* 90(10): 2987-2998. Available at: https://doi.org/10.1016/j.jenvman.2009.04.011. Accessed November 11, 2020.

Thouret, J.C., G. Enjolras, K. Martelli, O. Santoni, A. Luque, M. Nagata, A. Arguedas, and L. Macedo. 2013. Combining criteria for delineating lahar- and flash-flood-prone hazard and risk zones for the city of Arequipa, Peru. *Natural Hazards and Earth System Science* 13(2): 339-360. DOI: 10.5194/nhess-13-339-2013.

Urrutia, R. and M. Vuille. 2009. Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century. *Journal of Geophysical Research* 114: D02108. Available at: https://doi.org/10.1029/2008JD011021. Accessed November 11, 2020.

Vergara, W., A. Deeb, A. Valencia, R. Bradley, B. Francou, A. Zarzar, A. Grünwaldt, and S. Haeussling. 2007. Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union* 88(25): 261-264. Available at: https://doi.org/10.1029/2007EO250001. Accessed November 11, 2020.

Whitfield, P.H., D.H. Burn, J. Hannaford, H. Higgins, G.A. Hodgkins, T. Marsh, and U. Looser. 2012. Reference hydrologic networks I. The status and potential future directions of national reference hydrologic networks for detecting trends. *Hydrological Sciences Journal* 57(8): 1562-1579. Available at: https://doi.org/10.1080/02626667.2012.728706. Accessed November 11, 2020.

World Meteorological Organization (WMO). 2015. Status of the Global Observing System for Climate. Global Climate Observing System- No. 195. Geneva, Switzerland. Available at: https://library.wmo.int/index.php?lvl=notice_display&id=18962#.X76dV1Bbrct. Accessed November 25, 2020.

World Meteorological Organization (WMO). 2018. Guide to Instruments and Methods of Observation. WMO- No. 8. Geneva, Switzerland. Available at: https://library.wmo.int/index.php?id=12407&lvl=notice_display#.X6wO1lBbo2w. Accessed November 11, 2020.

World Meteorological Organization (WMO). 2019. GCOS Surface Reference Network (GSRN): Justification, Requirements, Siting and Instrumentation Options. Global Climate Observing System- No. 226. Geneva, Switzerland. Available at: https://library.wmo.int/doc_num.php?explnum_id=6261. Accessed November 25, 2020.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 49-62, December 2020

Development of a Pilot Smart Irrigation System for Peruvian Highlands

Santiago Guevara[1], Yogang Singh[1,2], Austin Shores[1], Juan Mercado[3], Mauricio Postigo[3], Jose Garcia[1], and *Brittany Newell[1]

*[1]Purdue Polytechnic School of Engineering Technology, Purdue University, West Lafayette, IN, USA; [2]KU Leuven Department of Mechanical Engineering, Belgium; [3]School of Electronics Engineering Universidad Nacional San Agustin Arequipa, Peru; *Corresponding Author*

Abstract: With growing developments in the technology of cloud storage and the Internet of Things, smart systems have become the latest trend in major agricultural regions of the world. The Arequipa and Caylloma provinces of Peru are highly productive agricultural areas that could benefit from these technologies. This region has low precipitation, generally less than 100 mm per year. Electricity is not available in most of the agricultural fields, limiting the types of irrigation methods and technologies that can be supported. Currently, 20 ponds supplied by water runoff from the Andean glaciers are used for irrigating approximately 545 hectares of land in the Majes district (Caylloma province). In order to develop optimal techniques for water irrigation in Arequipa and improve the infrastructure, there is a need for development of a smart water irrigation system applicable to the existing conditions in the region. The current study proposes a pilot smart water irrigation framework comprised of a drip irrigation module, wireless communication module, and a sensor network for intelligently regulating water flow from the cloud. In this study, a TEROS 12 soil moisture sensor is connected to a Digi XBee wireless module for collecting measurements of volumetric water content, temperature, and electrical conductivity, which are sent through a secure IP gateway to the cloud. A user-friendly web interface is available for end-users to access and analyze real-time data. The proposed framework is easily implementable, low-cost, and is predicted to conserve water through optimization of irrigation cycles based on a set moisture threshold.

Keywords: *volumetric water content, Internet of Things, soil moisture sensor, microcontroller, irrigation efficiency*

Irrigation is crucial for the economy, poverty reduction, and food security in the Peruvian highlands, leading to a need for sustainable use of water (Davis et al. 2009; McCready et al. 2009). The recession of the Peruvian glaciers is estimated to have a significant impact on the downstream ecosystem and communities (Vuille et al. 2008). Glacier meltwater runoff buffers the water shortage caused by low precipitation during the dry season in the Peruvian highlands (Kaser et al. 2003). Water used for irrigation accounts for 80% of water usage for this region (Maos 1985). The Arequipa district of Peru benefits from high land fertility and favorable temperatures for agriculture, leading to cultivation of crops such as grapes, avocados, quinoa, onion, garlic, corn, and wheat (Gelles 2000). Until the late 1980s, a lack of effective irrigation in the Arequipa district of Peru led to poor vegetation growth (Stensrud 2016). Local farmers in the Arequipa region most commonly use flood irrigation which leads to waste of agricultural water and ineffective use of natural resources (Gurovich and Riveros 2019). The irrigation infrastructure in Peru is defined by the agricultural land and water resources, with 5.5 million hectares in use, of which 3.75 million hectares utilize rainfed agriculture and 1.75 million hectares use water reserves like lakes, ponds, and reservoirs (Huamanchumo et al. 2008). The irrigation infrastructure in Arequipa suffers from limited measurement of the actual performance, improper scheduling, low precipitation of 100 mm per year, lack of power sources, and proper logistic management (Netherly 1984; Ertsen 2010). This creates an immediate requirement for a low-cost, intelligent irrigation schedule coupled with an optimized irrigation system to manage the available water for irrigation, improve crop yield, and optimize the quality of the yield. Therefore, the goal of this work is to develop an integral solution using a microcontroller and wireless communication modules for an autonomous, low-cost smart irrigation system. Purdue University students and faculty, in collaboration with faculty from Universidad Nacional San Agustin (UNSA), Peru, under the Purdue Center for the Environment, C4E, and the Arequipa Nexus Institute, developed the testing of the pilot smart irrigation system presented in this article in order to drive forward the development of low-cost, high-tech agricultural systems for the local Arequipa region.

This paper is organized as follows: In Section 2, literature regarding the use of intelligent techniques and Internet of Things (IoT) framework in irrigation systems in the last decade is discussed. Section 3 provides details of the design and development of the proposed smart irrigation system and the collaboration between Purdue University and UNSA. Section 4 contains the details of the experiments conducted in the laboratory and Peruvian highlands for the designed smart irrigation system. As a part of this experimental validation, Section 5 contains a discussion about the outcomes from the experimental study. Section 6 summarizes the work and presents the conclusions.

Literature Review

Advancements in IoT during the last decade have led to a boom in the agricultural sector in which a combination of IoT devices, control approaches, and cloud computing has improved the effectiveness of agriculture and irrigation. Abdullah et al. (2016) conducted a study on a Smart Agriculture System (AgriSys) that could analyze an agricultural environment and intervene to maintain optimized productivity. The system dealt with general agricultural challenges such as temperature, humidity, pH, and nutrient support. Additionally, the system dealt with the desert specific challenges of dust, infertile sandy soil, constant wind, very low humidity, and extreme variations in diurnal and seasonal temperatures, using a fuzzy-logic based smart agriculture system. Nesa Sudha et al. (2011) proposed two different energy conservation mechanisms that have been analyzed based on the Time Division Multiple Accesses scheduling plan for automatic irrigation systems. Both methods provided a better performance in simulation scenarios compared to other conventional methods used in smart irrigation systems. In the last decade, ZigBee has gained a lot of popularity as a communication protocol to transfer important information, such as flow and pressure readings for use in smart irrigation decision making. This protocol may use the digicloud as a possible interface to transfer important data to and from edge to the cloud (Foster et al. 2008). Prathibha et al. (2017) proposed an IoT based smart irrigation system based on the ZigBee communication protocol to monitor and control a set of sensors and actuators assessing the water needs of crops. A similar study conducted by Usha Rani and Kamalesh (2014) used an Arduino microcontroller to monitor a smart irrigation setup. The studies proved that ZigBee has been an effective tool in optimizing labor and water costs on agricultural land. A review of the use of ZigBee communications has been conducted by Zhou et al. (2009) by investigating large scale data assimilation using a ZigBee protocol across a large field area. Valente et al. (2007) investigated multi-hop networking across a larger agricultural land using a ZigBee protocol and Multifunctional Probes (MFPz). To make the agricultural systems smarter there is a need to acquire accurate data, in addition to having an effective communication protocol. Towards this effort, a few studies (Kim et al. 2008; Gutiérrez et al. 2013; Veeramanikandasamy et al. 2014) have presented site-specific data transmission approaches for smart irrigation systems, to ensure that water use efficiency is increased through the use of intelligent approaches and automation of drip irrigation systems. The proposed approach in this study combines the communication protocol approach of ZigBee as seen in Prathibha et al. (2017) and the data transmission approach of Kim et al. (2008) to develop an IoT based smart irrigation system for the Peruvian highlands to improve productivity and conserve water in water-deprived agricultural lands.

Design and Methodology

The initial design of the smart irrigation system was prototyped in a laboratory with the intent that it would be replicated and expanded at Peruvian field sites, as demonstrated in this work. The proposed system incorporated three major design factors: 1) low-cost, 2) autonomy, and 3) replicability. The goal of the project was to provide a low-cost IoT architecture for irrigation leading to improved water use efficiency and improved crop yields. The proposed schematic for the IoT based smart irrigation system is shown in Figure 1. It must be noted that a filter was not required for the laboratory setup but was used for the on-site application due to low water quality in the region. The available pressure at the field sites in Arequipa (generated by gravity) was emulated at the laboratory by using an electrical pump and a pressure regulator to reduce the pressure to 6 PSI, enough pressure for the emitters (pressure compensating) to work as expected.

In order to make the proposed system shown in Figure 1 low-cost and easy to replicate, off the shelf components were specified, along with common sensors and popular microcontrollers which have open source technical support available online. The authors took into account the availability of components in the local Arequipa region to design the current setup at a cost affordable for local farmers, compared to the current off the shelf, solar powered irrigation systems (Wazed et al. 2017). Such systems are not only expensive, compared to the proposed setup, but also need better technical management of the resources required to maintain the system, primarily the communication methods. The proposed system in Figure 1 is easy to maintain, cheaper, and replicable using local resources available in Arequipa. The bill of materials of the components, microcontrollers, and sensors used in the development of the setup is presented in Table 1.

The proposed IoT system consists of three nodes: a sensor, a receiver, and a transmitter node. Node 1 was the sensing node where a TEROS 12 sensor measured 1) volumetric water content (VWC) or the ratio of the volume of water to the total volume,

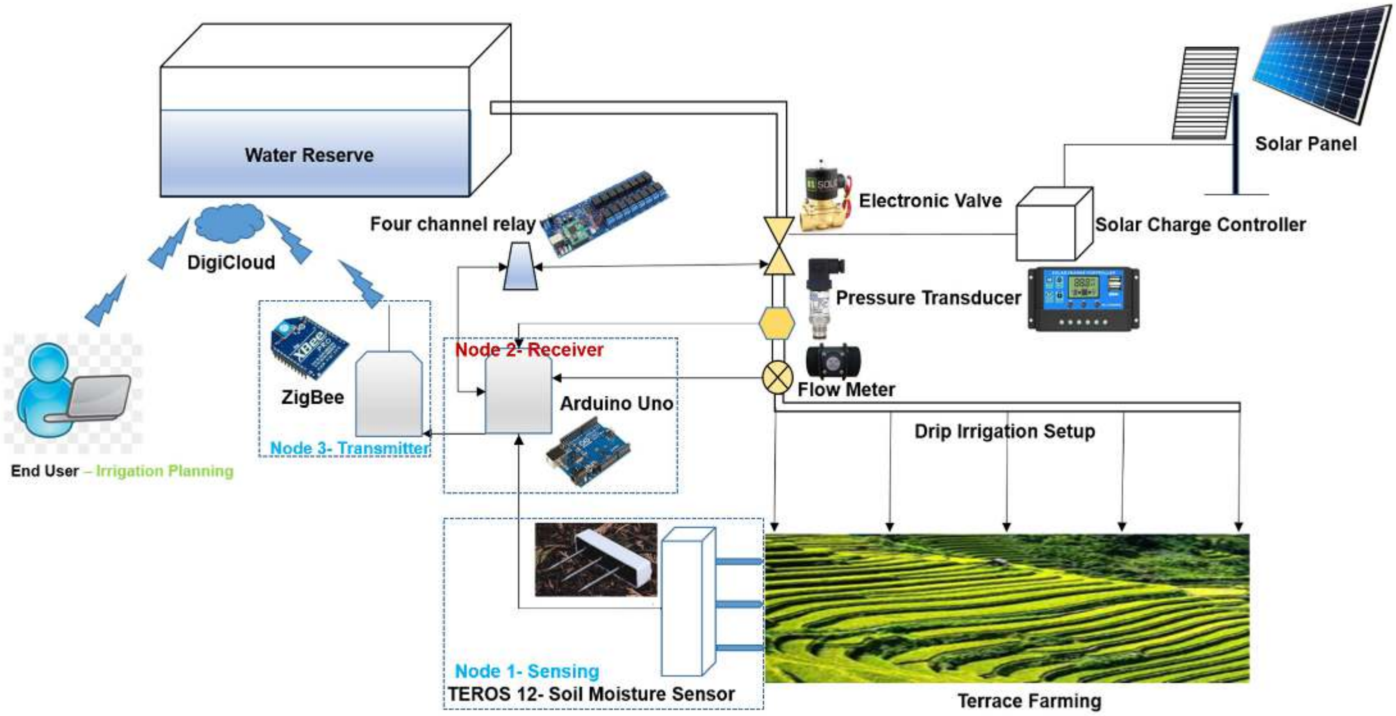


Figure 1. Schematic of the proposed IoT based smart irrigation system. The details and specifications of the sensor and microcontrollers used in this setup are described in Table 1.

Table 1. Bill of materials.

Name	Type	Cost (in US$)
PVC Fittings	Hydraulic	70
Drip Tubes and Fittings	Hydraulic	90
Digi XBee Development Kit	Electronics	90
Digi Gateway	Electronics	250
Teros12 Soil Moisture Sensor	Electronics	225
Arduino Uno	Electronics	25
12 VDC Relay Module	Electronics	16
½” NPS Flow Meter – Hall Effect Sensor Switch	Electronics	13
Wika A-10 Pressure Transmitter 0-15 PSI, ¼” NPT	Electronics	175
100W Solar Panel and 10 Amp Charger Controller 12 VDC	Electronics	100
12 VDC Electric Solenoid Viton Valve – Normally Closed	Electronics and Hydraulic	30
Battery (12 VDC - 18 Ah) and Electric Accessories	Electrical	150
Total Cost		1234

2) temperature, and 3) electrical conductivity (EC). The sensed data were sent to an Arduino Uno receiver. The Arduino also took pressure and flow data from a pressure transducer and flow meter. All these data were then transferred to a Digi gateway using the ZigBee communication standard with an XBee module. The Digi gateway then transmitted the data to the cloud for analysis. The irrigation cycle time and moisture threshold were set in the Arduino controller to regulate when irrigation was needed. The Arduino produced a control signal to turn on a relay connected to an electronic solenoid valve. When a value below the moisture threshold was reached, the valve was turned on via the relay to start the irrigation cycle. The control system implemented in this design only used the minimum and maximum moisture levels to activate or de-activate the irrigation cycle. Cycle data and timing were recorded and stored on the digicloud allowing users to view the data from a remote location. The use of real-time measurements in combination with the microcontroller allows for the implementation of closed-loop control locally, and the remote collection and manipulation of data in the cloud. The system was constructed to run on local power, but because in certain locations in Arequipa there is no electrical grid, the system was also set up with a set of solar panels to charge a battery for powering the system.

Experimental Setup

Laboratory Setup

Figure 2 shows the flowchart and block diagram of the smart drip irrigation system design using IoT components. In order to benchmark the proposed schematic, a laboratory based experimental prototype was initially developed. The complete assembled experimental setup of the smart drip irrigation system is shown in Figure 3, including the electronic and hydraulic components.

Using a controlled temperature chamber with artificial light, the prototype was tested under different conditions to evaluate its performance and effectiveness with spider plants, grown in pots containing approximately three kilograms of soil. The soil used in the laboratory test was a mix of sand and silt mixed at a 76/24% ratio for all experiments. This mixture was representative of the soil conditions found in Majes and was acceptable for growing this type of plant. Cruz Chavez (2018) conducted a study to evaluate the impact of three different tillage techniques in soil structure, water retention capacity, and the presence of compacted layers at the Centro de Investigación, Enseñanza y Producción Agrícola (CIEPA), an agricultural research center in Majes. Before applying the various treatments on the different plots, a representative soil sample was

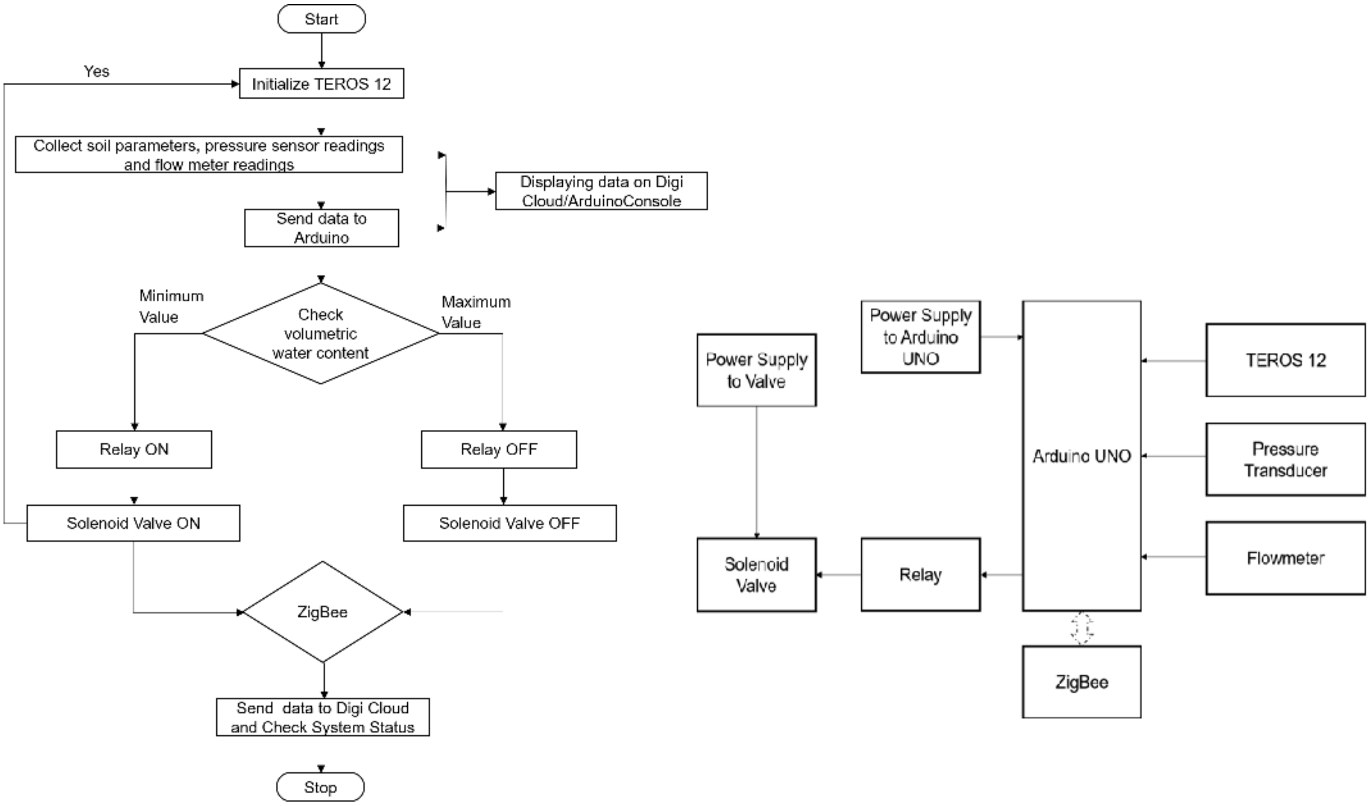


Figure 2. Flowchart and block diagram of the developed smart drip irrigation system using IoT.

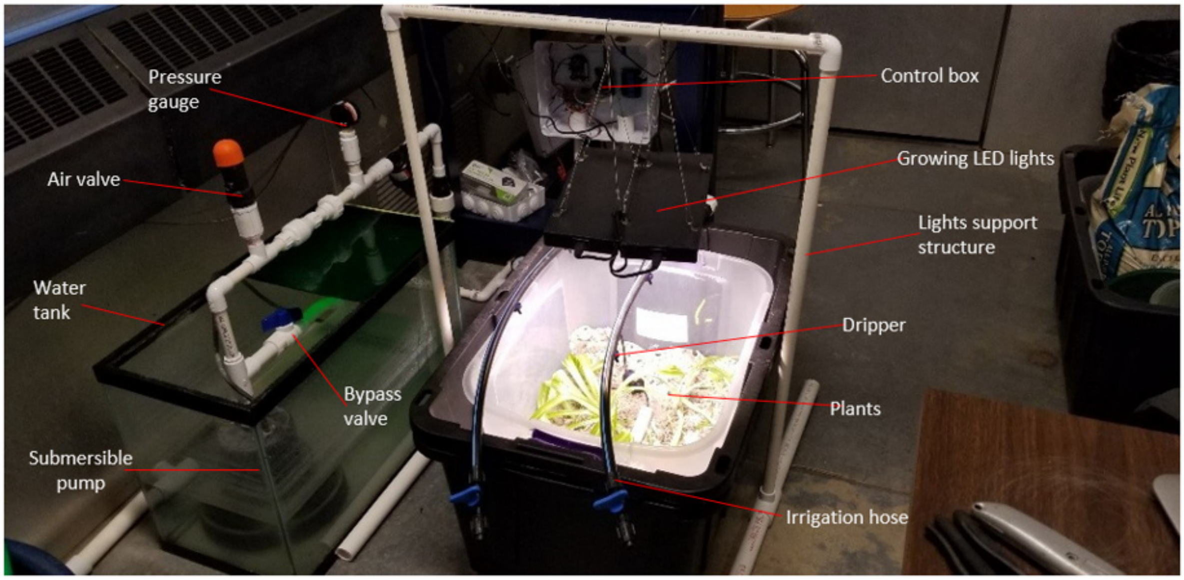


Figure 3. Assembled experimental setup of the smart irrigation system in laboratory.

analyzed. The laboratory results showed a sandy loam soil texture, with 76% of sand, 19.2 % of silt, and 4.9% of clay.

The spider plant (*Chlorophytum comosum*), native to South Africa, has been proven to thrive well in a wide range of soils, and to be drought and heavy-metal tolerant (Wang et al. 2011; Sanchez-Lizarraga et al. 2018). Due to its easy cultivation, spider plants are readily available (Sanchez-Lizarraga et al. 2018). Sandy soils such as the one proposed for the laboratory tests offer a well-drained substrate for growing spider plants, which is key for their development (Lattoo et al. 2006).

The setpoints were defined by taking soil samples to the saturation point and then after releasing excess water, field capacity was achieved. It was found that the field capacity corresponds to a VWC close to 30% (m^3/m^3). The field capacity was chosen as the upper setpoint, to avoid water waste. On the other hand, the lower setpoint was determined based on the soil texture. Sandy soils have a small water holding capacity of around 10% (Sharma 2019) and considering how well the water is drained and that the spider plant root zone is just four inches from the surface, a VWC of 27.5% was chosen as the irrigation triggering condition.

Once the VWC is below 27.5%, the controller will start irrigating for a pre-set amount of time (1.5 or 3 minutes, see Table 2). After finishing the irrigation cycle, the controller will take a new measurement, if the VWC is equal to or larger than 27.5%, the controller will not irrigate and will wait until water is consumed by the plant or it evaporates.

Six soil samples were used to test the accuracy of the chosen soil moisture sensor. Each soil sample was watered until saturation was attained, and the weight was measured and compared with the dry weight. The TEROS 12 sensor was installed in the soil sample before the watering process. Once the sample released the excess water, the sensor reading was captured. The calibration equation provided by the sensor's manufacturer for mineral soils (any soil different than artificial substrates) was employed to convert the raw data into VWC values. A 5% error was found when comparing the VWC calculated based on dry and saturated weights and the VWC provided by the sensor, proving its effectiveness and easy setup.

Field Testing in CIEPA-Majes

The prototype developed at Purdue University was taken to two different field test sites in Peru. The first tests took place in a plot planted with grass inside the CIEPA agricultural research center. The test was adapted to the hydraulic connections of the system. The plot used received water by gravity from a nearby water pond which was filled daily from a main channel.

The solar array was replicated with local components because there was no electric grid on the plot, simulating the conditions of a traditional farm. Hose laterals were installed over the area to be irrigated and emitters were inserted using a punch tool every 20 cm, producing flows of two liters per hour each. Finally, the gateway was placed in the research center's main building at the highest accessible point, powered by a battery and sending data to the cloud using a 3G-SIM card from a local provider. The main objective of performing this test was to prove the effectiveness of the prototype in the real environment by letting the system work during the irrigation time window (when water is provided from the water pond), running the closed-loop program, and sending information to the cloud.

Field Test in Moquegua

A farm growing avocados and other fruit trees, located in the Moquegua State next to Arequipa, was used to test the prototype in a different agricultural setup. The farm had a hilly topology and the lines of trees were aligned with topographic curves, conditions challenging for common flood irrigation practice. A similar approach to the Majes test took place. Hoses with emitters were connected to a tank which was filled using an electrical pump installed in a nearby channel and powered by a solar energy array. In this case, taking advantage of Wi-Fi availability over the weak 3G signal in the area, the microcontroller sent the data to the Ubidots platform.

Results and Discussion

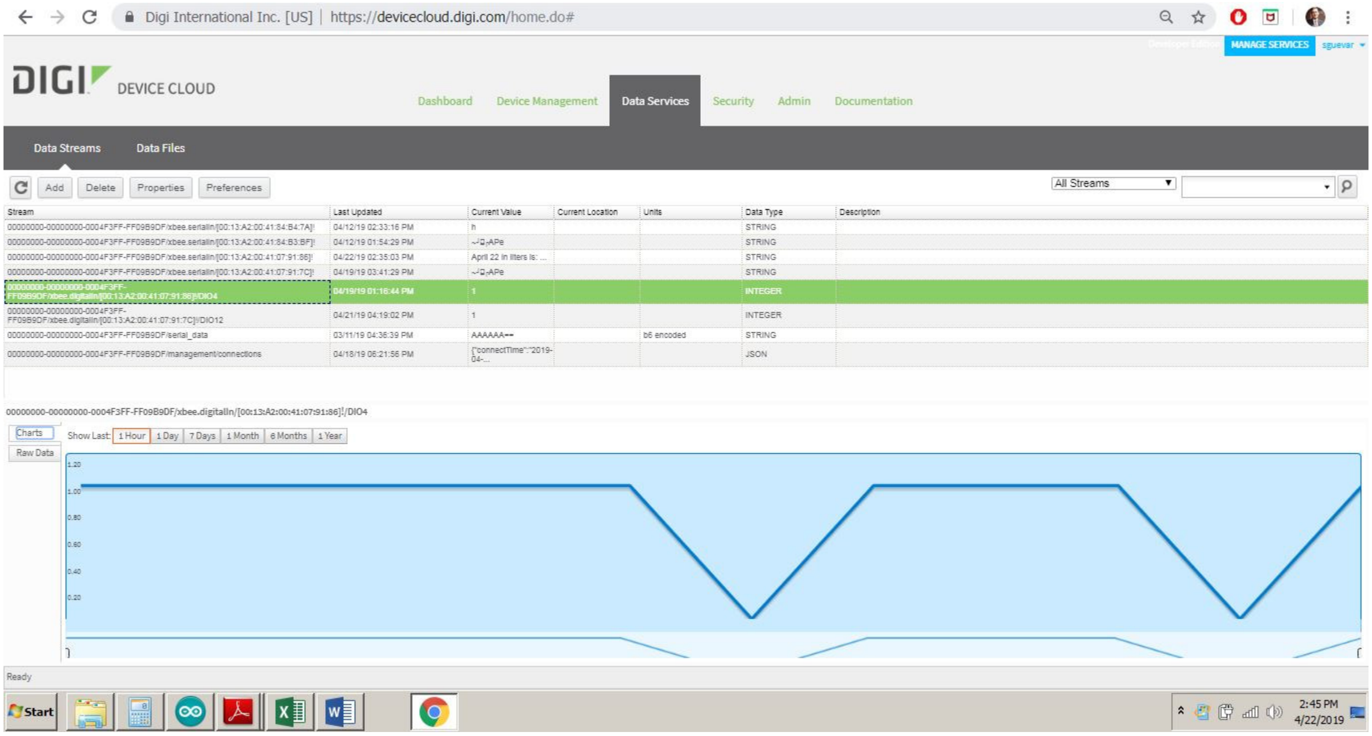
The laboratory prototype of the experimental setup was able to communicate data to the cloud effectively. This is evident from the relay data recorded in binary format on the cloud shown in

Figure 4. The data from the soil moisture sensor, pressure transducer, and flow meter were also recorded on the cloud and retrieved from the digicloud web interface.

The irrigation time, system pressure, and time between measurements were changed as described in Table 2, to test variations in irrigation cycles. The prototype was tested under steady environmental conditions of 22°C and relative humidity of 60%, which represent the maximum monthly average temperature and average humidity (Cruz Chavez 2018) in the Majes region. The experimental parameters for producing the various experimental cases were changed in the software. The initial soil moisture was also specified for each case. The flexibility of the system becomes a strength when installing the setup in different regions. Different soil types and plants will require a short calibration process to then determine the irrigation setpoints.

The results demonstrate the closed loop effectiveness of keeping the VWC of the soil within a small threshold, providing the plants with favorable growing conditions. The VWC was recorded over 19 hours for cases one to four. Figure 5 presents these results. System pressure was adjusted beforehand using a manual bypass valve installed on the system to prevent over pressurization. A pressure of 6 PSI was set to emulate the water head pressure created by the height difference between the water pond and the field.

Cases number one and two exhibit similar behavior. Once irrigation is triggered, the VWC increases over the setpoint due to the lag caused while the water infiltrates. Then evapotranspiration takes away part of the available water. Once the water content goes below the setpoint, the system turns on the irrigation mechanism. Case number three involves an irrigation time two times larger than cases one and two, creating higher peak values for the soil moisture level after each irrigation cycle, therefore, reducing the system's start times. Case number four uses the same irrigation time as in cases one and two, but the system pressure is increased up to 10 PSI compared to the 6 PSI of the other experiments. This increase in pressure has a similar effect when compared to the increase of irrigation time, higher peak values, and lower start times.



Stream	Last Updated	Current Value	Current Location	Units	Data Type	Description
00000000-00000000-0004F3FF-FF09B9DF/xbee.serialIn/[00:13:A2:00:41:84:B4:7A]!	04/12/19 02:33:16 PM	h			STRING	
00000000-00000000-0004F3FF-FF09B9DF/xbee.serialIn/[00:13:A2:00:41:84:B3:BF]!	04/12/19 01:54:29 PM	~┘ū┐APe			STRING	
00000000-00000000-0004F3FF-FF09B9DF/xbee.serialIn/[00:13:A2:00:41:07:91:86]!	04/22/19 02:35:03 PM	April 22 in liters is: ...			STRING	
00000000-00000000-0004F3FF-FF09B9DF/xbee.serialIn/[00:13:A2:00:41:07:91:7C]!	04/19/19 03:41:29 PM	~┘ū┐APe			STRING	
00000000-00000000-0004F3FF-FF09B9DF/xbee.digitalIn/[00:13:A2:00:41:07:91:86]!/DIO4	04/19/19 01:16:44 PM	1			INTEGER	
00000000-00000000-0004F3FF-FF09B9DF/xbee.digitalIn/[00:13:A2:00:41:07:91:7C]!/DIO12	04/21/19 04:19:02 PM	1			INTEGER	
00000000-00000000-0004F3FF-FF09B9DF/serial_data	03/11/19 04:36:39 PM	AAAAAA==		b6 encoded	STRING	
00000000-00000000-0004F3FF-FF09B9DF/management/connections	04/18/19 06:21:56 PM	{"connectTime":"2019-04-...			JSON	

00000000-00000000-0004F3FF-FF09B9DF/xbee.digitalIn/[00:13:A2:00:41:07:91:86]!/DIO4

Figure 4. Data on the cloud from the laboratory test of the experimental setup showing ON/OFF switching of relays in binary format. Sensor data from different on-board sensors are recorded on the cloud.

Table 2. Laboratory tests.

Case number	Time between measurements (min)	Irrigation time (min)	System pressure (PSI)	Soil initial moisture level
1	3	1.5	6	Dry
2	3	1.5	6	Slightly dry
3	3	3	6	Dry
4	3	1.5	10	Dry
5	30	1.5	6	Dry

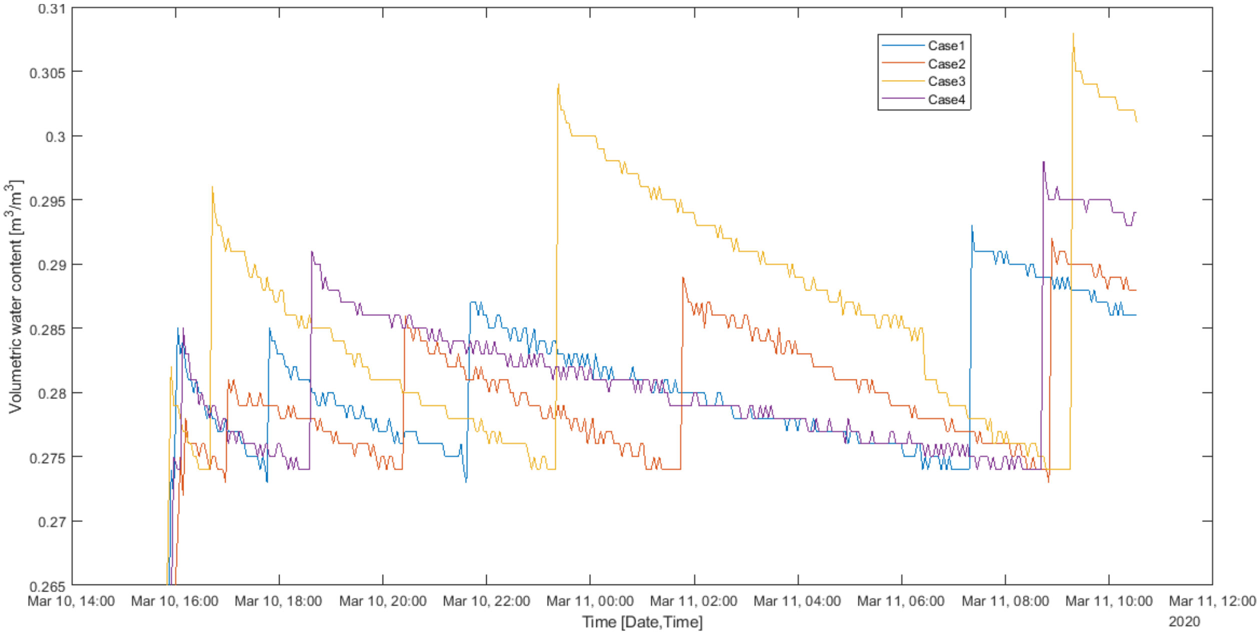


Figure 5. Volumetric water content through time for cases one to four.

Test case five was carried out for 73 hours; the VWC, soil temperature, and soil EC were recorded. A plot containing the three variables was generated along with the irrigation trigger (black line) to visualize its effect as seen in Figure 6.

Figure 6 presents the behavior of the VWC initially increasing after the first irrigation event. From that point, a consistent pattern between water consumption from the plant and irrigation triggering is displayed for the 73-hour irrigation cycle. Soil temperature (Temp.) tends to remain around a steady value, affected by the cooling effect of irrigation as seen in Figure 6.

The soil EC shown in Figure 6 decreases through time as the plant consumes the available minerals of the soil. When the irrigation cycle takes place, a peak on the EC is generated as a result of the momentary increased ability of the soil to conduct electricity due to the water. To display the values on the plot, a multiplier of ten was applied to increase the scale of the axis.

The effectiveness of the system was demonstrated under laboratory conditions. The prototype was able to respond to different VWC levels assuring the plants' wellbeing while conserving water through drip irrigation at optimized times. Since the laboratory setup was designed to be replicated in the Peruvian environment, after the experimental lab testing was completed, the experimental prototype was installed in an agricultural farm,

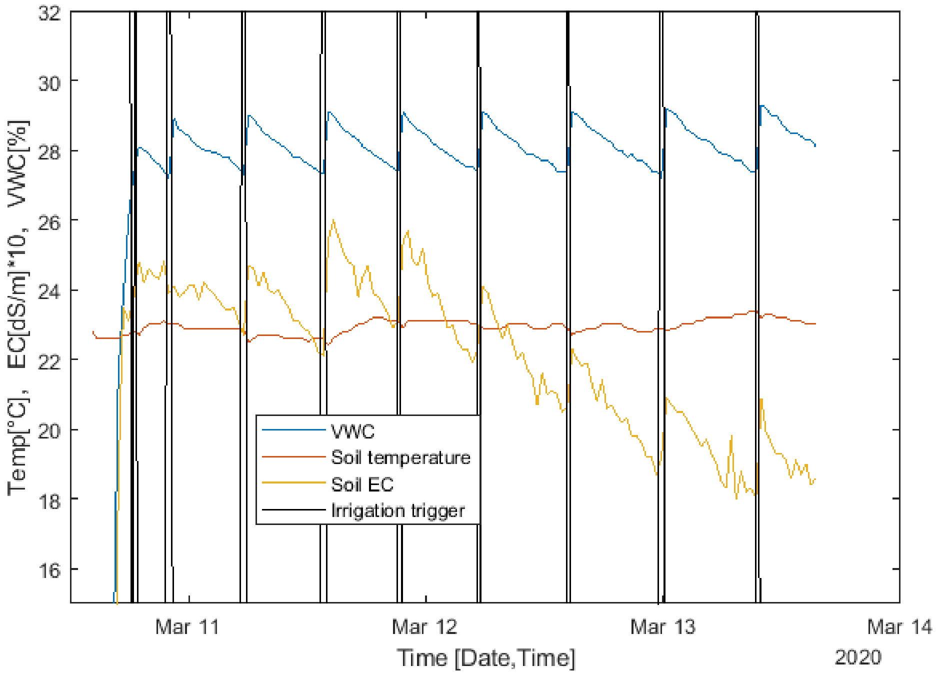


Figure 6. Volumetric water content through time for case five.

CIEPA-Majes at UNSA and a field site in the neighboring state, Moquegua. The major objective of the replication experiment was to determine the effectiveness of the developed laboratory setup in a real environment. Figure 7 (top) shows the implementation of the experimental prototype at CIEPA-Majes.

Six cases were measured in Moquegua, for three zones with 15 trees planted in rows in each zone. The approximated full irrigation area was 330 m^2. The soil moisture sensor was installed at approximately 20 cm below the surface at the end of each row of trees, and the system was set so that the irrigation control valve would turn on when the soil moisture value was below 40%. The picture in Figure 8 (left) shows the hardware used in the field. Since the test area was located on land previously inaccessible for agriculture, due to its hilly topology and non-optimal topographical features for flood irrigation, growing these trees is a remarkable improvement. Moreover, water saved by implementing the smart irrigation setup is an important step towards the region's sustainability. If the trees had been placed next to the water ditch, 5,000 liters of water would have been used to flood a zone of similar size (15 trees in a row) by letting a pump work for five minutes with a flow rate of 1,000 liters per minute. Flood irrigation has a reported efficiency of 40% in the region (The World Bank 2013), meaning that from those 5,000 liters, just 2,000 liters would have been delivered to the trees. On the other hand, the smart irrigation setup used 362.3 liters to bring the soil to field capacity in zone 1, employing drip irrigation with an efficiency in the range of 75% to 95% (Howell 2003). Assuming an efficiency of 85% for the smart irrigation setup, 308 liters were estimated to be delivered to the trees in one and a half hours compared to the application of 2,000 liters in five minutes offered by flood irrigation. Considering the soil in the Arequipa region is well known for its high drainage capabilities, the use of the proposed smart irrigation system allows farmers to effectively provide water to the root zone in a constant manner, saving water and as demonstrated in past work, maintaining yield (Miller et al. 2018).

The plots shown in Figure 8 (right) portray the results captured by the smart irrigation system implemented at the field site in Moquegua. This setup measured six cases, where cases 1 and 2 refer to node 1 row of trees. Similarly, cases 3 and 4, refer to node 2 for the second row of trees on the same days, and cases 5 and 6 refer to the third row of trees. In all cases the solenoid-controlled

Control box installed. TEROS 12 located at a soil depth of 20 cm. Assembled smart drip irrigation setup.

DIGI Gateway installed on building roof. Waterhead for the assembled smart drip irrigation setup. Installed drip lines with drippers.

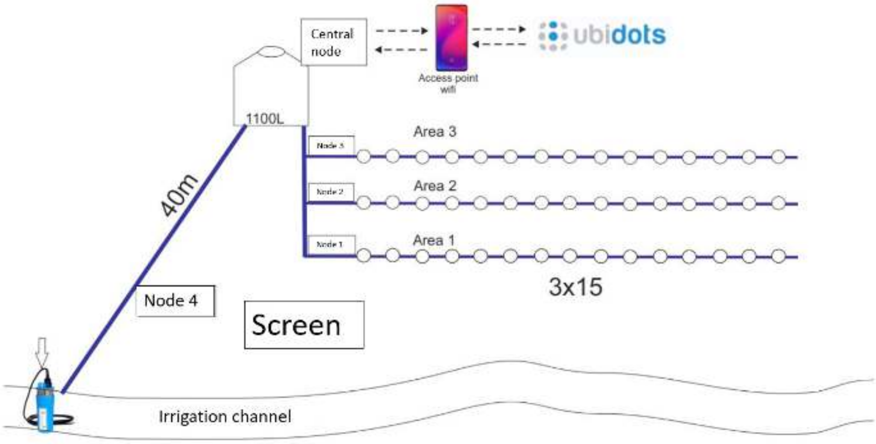


Figure 7. Replication of the smart irrigation setup at CIEPA-Majes (top) and Schematic representation of the measurement setup used in Moquegua (bottom).

irrigation valve was turned on until the humidity threshold (40%) was reached. Due to the larger area of the field, it was observed that attaining the desired humidity at the sensor took an approximate time of 1 hour and 30 minutes for node 1, 2 hours and 30 minutes for node 2, and 3 hours and 45 minutes for node 3. While the reason for the discrepancies between the nodes is unknown, it is believed that the differences in measurement may be due to the sensors' locations and the unevenness of the terrain. As drip irrigation does not wet the entire soil surface, irrigation uniformity is both hard to estimate and usually low (Howell 2003). In cases 1 and 2, the soil moisture sensor was installed close to the emitter, which exposed it to a higher moisture content than surrounding areas. Soil topography and infiltration variations within the same farm negatively affect the generalization of the sensors' measurements (Howell 2003). It is also noted that adding more sensors in each irrigation node would improve the performance of the irrigation control system.

Conclusion

The current study developed a closed-loop, autonomous smart drip irrigation system based on

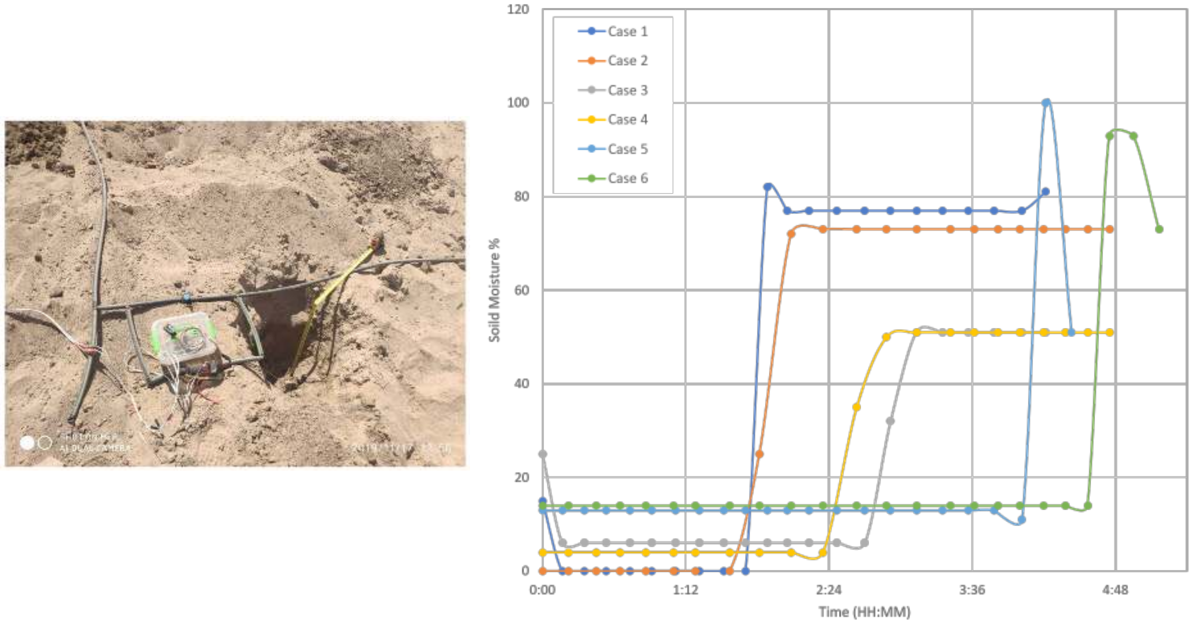


Figure 8. Hardware setup at the Moquegua test site.

concepts of IoT. A low-cost, autonomous smart drip irrigation system was initially designed and tested in a laboratory setting with replicability in mind and later tested in agricultural farms in Peru. This system was found to be effective in providing reliable measurements of soil moisture, temperature, and conductivity along with optimization of the irrigation cycles based on a set moisture threshold. This design provides a simple, low-cost, autonomous solution for the irrigation needs in Peru and addresses issues like lack of electrical power by using solar panels, and the Digi module for communication. The working prototype was designed and built at around U.S. $1,000 using readily available components, and was demonstrated to operate consistently overnight and in varying temperature, moisture, and soil conditions.

The field tests proved that the cellular network availability and poor signal quality impose a challenge in remote areas for the prototype to effectively send the information to the cloud. Similarly, in remote areas, additional attention must be paid to securing the components from theft. Another drawback of the system is the lack of synchronization between the water supply from the irrigation district and the operating hours of the prototype. Irrigation might be triggered when there is no water supply from the water pond or the determined reservoir, wasting energy on operating the electro valve and depressurizing the system.

Acknowledgements

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustin.

Author Bio and Contact Information

Santiago Guevara-Ocana received a B.S. in Agricultural Engineering from Universidad Nacional de Colombia – Bogota Campus in 2017. From 2016 to 2018, he worked for an irrigation consulting firm as a design engineer specialized in automation and alternative energy. In 2019, he was a Visiting Scholar at Purdue University, USA, developing a smart irrigation system for the "Robotics Water Quality and Monitoring Distribution System" project, as a pilot study for the Arequipa Nexus Institute in Peru. He is a Graduate Research Assistant since Fall 2019, enrolled in a Ph.D. program in Technology at Purdue University. He may be contacted at sguevar@purdue.edu.

Yogang Singh is currently working as a post-doctoral research associate in the Department of Mechanical Engineering at KU Leuven, Belgium. Prior to this, Dr Singh held a postdoctoral researcher position at Purdue University, USA, from December 2018 to December 2019. He has completed his Ph.D. in Mechanical

Engineering from University of Plymouth, UK as a Commonwealth Scholar in 2018. He has completed his M.S from IIT Madras, India, in 2015 with specialization in underwater gliders. He obtained his B.Tech. in Mechanical Engineering in 2010 from SRM University, Chennai. His areas of interest are marine robotics, autonomous systems and multi-robot systems. He may be contacted at yogang.singh@kuleuven.be.

Austin Shores is an undergraduate student and senior at Purdue University studying Mechanical Engineering Technology through the Purdue Polytechnic Institute School of Engineering Technology. Austin performed research under Dr. William Hutzel in the Applied Energy Laboratory (AEL) on the Purdue BioWall and worked in the AEL as a Lab Technician. His research and curriculum focus has been mechanical systems and design, electrical systems and design, system controls, data acquisition, and power/utility systems. He may be contacted at shores@purdue.edu.

Juan C. Mercado received a bachelor in Electronic Engineering from San Agustin University, Arequipa - Perú, in 2012. He worked for maintenance of biomedical equipment contract in EsSalud - Arequipa from 2013 to 2014. He also worked for a construction and operation contract wastewater treatment plant from 2015 to 2016. He returned to work as a maintenance manager for different mines in southern Peru as an instrumentalist from 2017 to the present. His research interests are Internet of Things, industrial automation, sensor network, and solar and wind energy sources. He may be contacted at jc4rlosmg@gmail.com.

Mauricio Postigo-Malaga received a B.S. in Electronic Engineering from Universidad Nacional de Ingenieria-Lima, Peru, in 1989, and M.Sc. in Telecommunication Engineering and candidate Ph.D. degrees from Universidad Nacional de San Agustin de Arequipa, Peru, in 2010 and 2018, respectively. From 1989 to actually, he has been Senior Professor with the Schools of Electronic and Telecommunication engineering at Universidad Nacional de San Agustin de Arequipa. From 2012 to 2015, he was head of the Engineering Electronic Department. He has been Project Manager and External Consultant in research and development in telecommunications. His research interests include wireless sensor networks, and wireless and fiber optic communications systems. He may be contacted at mpostigom@unsa.edu.pe.

Jose M. Garcia-Bravo received a B.S. in Mechanical Engineering from Universidad de Los Andes in Bogota, Colombia, in 2002 and M.Sc. in Engineering and Ph.D. degrees from Purdue University, USA, in 2006 and 2011, respectively. From 2011 to 2012, he was a Research Assistant Professor at the Illinois Institute of Technology. Since 2015, he has been an Assistant Professor with the School of Engineering Technology at Purdue University. His research interests include electric and hydraulic hybrid drive trains, additive manufacturing of hydraulic and pneumatic components, and energy efficiency and duty cycles of hydraulic systems. He may be contacted at jmgarcia@purdue.edu.

Brittany A. Newell (corresponding author) received a B.S. degree in Biomedical Engineering, a M.Sc. and Ph.D. in Agricultural and Biological Engineering from Purdue University in 2009, 2010, and 2012, respectively. From 2013 to 2015, she worked for a contract manufacturing company in quality and regulatory engineering and as a Quality Manager. In 2015, she returned to Purdue as an Assistant Professor with the school of Engineering Technology. Her research interests are intelligent sensors and actuators, adaptive structures, additive manufacturing, and energy efficiency. Dr. Newell is interested in implementation of these technologies into industrial applications. She may be contacted at bnewell1@purdue.edu.

References

Abdullah, A., S. Al Enazi, and I. Damaj. 2016. AgriSys: A smart and ubiquitous controlled-environment agriculture system. In: Proceedings *3rd MEC International Conference on Big Data and Smart City (ICBDSC)*, Muscat, Oman, 15-16 March 2016, pp. 306-311. Available at: https://doi.org/10.1109/ICBDSC.2016.7460386. Accessed October 2, 2020.

Cruz Chavez, J.F. 2018. Evaluación del efecto de tres sistemas de labranza sobre la capacidad de almacenamiento de agua del suelo, en la irrigación majes. Thesis, Universidad Nacional de San Agustin de Arequipa. Available at: http://repositorio.unsa.edu.pe/bitstream/handle/UNSA/7693/AGcrchfj.pdf?sequence=1&isAllowed=y. Accessed October 2, 2020.

Davis, S.L., M.D. Dukes, and G.L. Miller. 2009. Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in southwest Florida. *Agricultural Water Management* 96(12): 1828-1836.

Ertsen, M.W. 2010. Structuring properties of irrigation systems: Understanding relations between humans and hydraulics through modeling. *Water History* 2: 165-183. Available at: https://doi.org/10.1007/s12685-010-0023-2. Accessed October 2, 2020.

Foster, I., Y. Zhao, I. Raicu, and S. Lu. 2008. Cloud computing and grid computing 360-degree compared. In: *2008 Grid Computing Environments Workshop,* Austin, TX, 12-16 November 2008. Available at: https://doi.org/10.1109/GCE.2008.4738445. Accessed October 2, 2020.

Gelles, P.H. 2000. *Water and Power in Highland Peru: The Cultural Politics of Irrigation and Development*. Rutgers University Press, New Brunswick, NJ.

Gurovich, L.A. and L.F. Riveros. 2019. Agronomic operation and maintenance of field irrigation systems. In: *Irrigation - Water Productivity and Operation, Sustainability and Climate Change*, S. Ricart (Ed.). Intech Open, London, UK. Available at: https://doi.org/10.5772/intechopen.84997. Accessed October 2, 2020.

Gutiérrez, J., J.F. Villa-Medina, A. Nieto-Garibay, and M.Á. Porta-Gándara. 2013. Automated irrigation system using a wireless sensor network and GPRS module. *IEEE Transactions on Instrumentation and Measurement* 63(1): 166-176.

Howell, T. 2003. Irrigation efficiency. *Encyclopedia of Water Science* 467-472. DOI: 10.1081/E-EWS 120010252.

Huamanchumo, J., Y. Peña, L. Silva, and J. Hendriks. 2008. Developing capacity in water users organizations: The case of Peru. *Irrigation and Drainage* 57(3): 300-310.

Kaser, G., I. Juen, C. Georges, J. Gómez-Lopez, and W. Tamayo. 2003. The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Perú. *Journal of Hydro*logy 282(1): 130-144.

Kim, Y., R.G. Evans, and W.M. Iversen. 2008. Remote sensing and control of an irrigation system using a distributed wireless sensor network. *IEEE Transactions on Instrumentation and Measurement* 57(7): 1379-1387. Available at: https://doi.org/10.1109/TIM.2008.917198. Accessed October 2, 2020.

Lattoo, S.K., S. Khan, S. Bamotra, and A.K. Dhar. 2006. Cytomixis impairs meiosis and influences reproductive success in *Chlorophytum comosum* (Thunb) Jacq. - An additional strategy and possible implications. *Journal of Biosciences* 31(5): 629-637. Available at: https://doi.org/10.1007/BF02708415. Accessed October 2, 2020.

Maos, J.O. 1985. Water resource development and land settlement in southern Peru: The Majes Project. *GeoJournal* 11: 69-78. Available at: https://doi.org/10.1007/BF00572940. Accessed October 2, 2020.

McCready, M.S., M.D. Dukes, and G.L. Miller. 2009. Water conservation potential of smart irrigation controllers on St. Augustinegrass. *Agricultural Water Management* 96(11): 1623-1632.

Miller, L., G. Vellidis, and T. Coolong. 2018. Comparing a smartphone irrigation scheduling application with water balance and soil moisture-based irrigation methods: Part II—Plasticulture-grown watermelon. *HortTechnology* 28(3): 362-369. Available at: https://doi.org/10.21273/horttech04014-18. Accessed October 2, 2020.

Nesa Sudha, M., M.L. Valarmathi, and A.S. Babu. 2011. Energy efficient data transmission in automatic irrigation system using wireless sensor networks. *Computers and Electronics in Agriculture* 78(2): 215-221. Available at: https://doi.org/10.1016/j.compag.2011.07.009. Accessed October 2, 2020.

Netherly, P.J. 1984. The management of late Andean irrigation systems on the North Coast of Peru. *American Antiquity* 49(2): 227-254. Available at: https://doi.org/10.2307/280017. Accessed October 2, 2020.

Prathibha, S.R., A. Hongal, and M.P. Jyothi. 2017. IOT based monitoring system in smart agriculture. In: Proceedings *International Conference on Recent Advances in Electronics and Communication Technology (ICRAECT)*, Bangalore, India, 16-17 March 2017, pp. 81-84. Available at: https://doi.org/10.1109/ICRAECT.2017.52. Accessed October 2, 2020.

Sanchez-Lizarraga, A.L., V. Arenas-Montaño, E.N. Marino-Marmolejo, L. Dendooven, J.B. Velazquez-Fernandez, G. Davila-Vazquez, J. Rodriguez-Campos, L. Hernández-Cuevas, and S.M. Contreras-Ramos. 2018. Vinasse irrigation: Effects on soil fertility and arbuscular mycorrhizal fungi population. *Journal of Soils and Sediments* 18(11): 3256-3270. Available at: https://doi.org/10.1007/s11368-018-1996-1. Accessed October 2, 2020.

Sharma, V. 2019. Basics of Irrigation Scheduling. University of Minnesota Extension. Available at: https://extension.umn.edu/irrigation/basics-irrigation-scheduling. Accessed October 2, 2020.

Stensrud, A.B. 2016. Dreams of growth and fear of water crisis: The ambivalence of 'progress' in the Majes-Siguas Irrigation Project, Peru. *History and Anthropology* 27(5): 569-584. Available at: https://doi.org/10.1080/02757206.2016.1222526. Accessed October 2, 2020.

Usha Rani, M. and S. Kamalesh. 2014. Web based service to monitor automatic irrigation system for the agriculture field using sensors. In: Proceedings

International Conference on Advances in Electrical Engineering (ICAEE), Vellore, India, 9-11 January 2014, pp.1-5. Available at: https://doi.org/10.1109/ICAEE.2014.6838569. Accessed October 2, 2020.

Valente, A., R. Morais, C. Serodio, P. Mestre, S. Pinto, and M. Cabral. 2007. A ZigBee sensor element for distributed monitoring of soil parameters in environmental monitoring. In: Proceedings *IEEE Sensors*, Atlanta, GA, 28-31 October 2007, pp. 135-138. Available at: https://doi.org/10.1109/ICSENS.2007.4388354. Accessed October 2, 2020.

Veeramanikandasamy, T., K. Rajendran, K. Sambath, and D. Sangeetha. 2014. Remote monitoring and closed loop control system for social modernization in agricultural system using GSM and Zigbee technology. In: Proceedings *International Conference on Advances in Electrical Engineering (ICAEE)*, Vellore, India, 9-11 January 2014. Available at: https://doi.org/10.1109/ICAEE.2014.6838438. Accessed October 2, 2020.

Vuille, M., G. Kaser, and I. Juen. 2008. Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. *Global and Planetary Change* 62(1): 14-28.

Wang, Y., J. Tao, and J. Dai. 2011. Lead tolerance and detoxification mechanism of *Chlorophytum Comosum*. *African Journal of Biotechnology* 10(65): 14516-14521. Available at: https://doi.org/10.5897/ajb11.1496. Accessed October 2, 2020.

Wazed, S.M., B.R. Hughes, D. O'Connor, and J.K.S. Calautit. 2017. Solar driven irrigation systems for remote rural farms. *Energy Procedia* 142: 184-191.

The World Bank. 2013. Instalacion de Un Sistema de Riego Tecnificado Por Aspersion Para El GGE La Ponderosa, Distrito Huambo, Provincia Caylloma, Region Arequipa. Programa Subsectoral de Irrigaciones. Contrato De Prestamo Nº7878 – PE BIRF PSI SIERRA. Tecnificacion Del Riego Parcelario.

Zhou, Y., X. Yang, L. Wang, and Y. Ying. 2009. A wireless design of low-cost irrigation system using ZigBee technology. In: Proceedings *International Conference on Networks Security, Wireless Communications and Trusted Computing*, Wuhan, Hubei, China, 25-26 April 2009, pp. 572-575. Available at: https://doi.org/10.1109/NSWCTC.2009.231. Accessed October 2, 2020.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 63-73, December 2020

3D Interactive Modeling of Pipe Failure in Water Supply Systems

*Thikra Dawood[1], Emad Elwakil[1], Hector Mayol Novoa[2], and José Fernando Gárate Delgado[2]

*[1]School of Construction Management, Purdue University, West Lafayette, IN, USA; [2]School of Civil Engineering, National University of St Augustin of Arequipa, Arequipa, Peru; *Corresponding Author*

Abstract: The increased incidences of pipe breaks worldwide are posing a serious threat to potable water security in urban communities. The consequences may involve water loss and service interruptions, compromised water quality, infrastructure disruptions, and loss of revenue. Thus, creating failure assessment models is quite crucial to sustain water distribution networks (WDNs) and to optimize maintenance spending. This research paper aims at developing an assessment framework for water systems, as well as modeling the failure phenomena toward sustainable management of underground infrastructure. The city of El Pedregal in Peru was chosen to exemplify the methodology of the research due to the rapid pace of urbanization and growing economic activities in the region, which make water infrastructure even more critical. The framework is based on the application of modeling techniques stemming from statistical regression analysis (RA) and 3D schematic representation. First, the influential factors that lead to the deterioration of the WDNs are determined. Second, the RA technique is leveraged to evaluate and model the failure rate through consecutive simulation operations and a 3D surface plot. Finally, the efficacy of the model is investigated using different performance metrics, in conjunction with a residual analysis scheme. The validation results revealed the robustness of the model with R-squared (R^2) and the sum of squares error (SSE) of 0.9767 and 0.0008, respectively. The developed model is a predictive tool that can be used by municipal engineers as a preemptive measure against future pipeline bursts or leaks.

Keywords: *deterioration, water infrastructure, regression analysis, sustainability, condition assessment*

Water supply systems are integral elements of underground infrastructure and indispensable constituents for urban communities (Folkman 2018; Dawood et al. 2019a). Recurrent incidents of water main breaks are long-standing problems all over the world, causing water loss and floods, interrupted access to safe drinking water, compromised water quality, damage to the surrounding civil structures, disruptions to businesses, and loss of revenue (Harvey et al. 2014). The American Society of Civil Engineers (ASCE) 2017 report card estimated a daily water loss of six billion gallons due to pipe leakages, with yearly water main breaks totaling 240,000 in the United States. This water loss could support 15 million households per day, which equates to approximately 14% to 18% of treated potable water. Moreover, the report recorded that pipe break rates escalated by 40% between 2012 and 2018 in North America (ASCE 2017). Consequently, the American Water Works Association estimated one trillion dollars is required for U.S. water infrastructure over the next 25 years (AWWA 2012).

The image is not different in Latin America, where it enjoys an abundance of water resources. The region includes some of the largest lakes in the world, such as Titicaca in Peru, as well as four of the world's 25 largest rivers. Additionally, the Amazon Basin supplies 20% of the total runoff of the world's fresh water. However, in most of Latin America's big cities, more than 50% of the treated water is lost due to leaky pipes. This rate might escalate up to 90% in some congested cities (Barlow and Clarke

2007). Faced with this litany of growing risk of pipe failure in Latin America, the burden has increased on water utilities to ensure safe and reliable water services (Dawood et al. 2019a). This research work is relevant to water resources management in Latin America because of the significance of prioritizing infrastructure investments as an engine for growth, as well as saving money and water resources in this developing world. This emphasizes the need for condition assessment models capable of assisting the decision-makers in the prioritization of replacement and/or rehabilitation procedures of underground water systems (Kleiner and Rajani 2001a; Dridi et al. 2009), especially during the economic recession that minimized the funding policies.

Substantial efforts have been found in the literature to evaluate the water pipe deterioration and model its risk of failure. Many of these efforts adopted statistical-based approaches, while others focused on artificial intelligence and soft computing methods to develop failure prediction models. Statistical models are created from historical data that link pipe attributes, operational factors, environmental factors, and frequencies of pipe breaks (Kleiner and Rajani 2001b). Such models are based on collecting long-range data pertaining to past pipe bursts and applying the regression analysis (RA) techniques to process the data (St. Clair and Sinha 2012). Generally, statistically-derived models are classified into two categories: deterministic and probabilistic. Statistical deterministic models are known as time-dependent models. Examples of these models can be found in (Shamir and Howard 1979; McMullen 1982; Walski and Pelliccia 1982; Jacobs and Karney 1994). Whereas, probabilistic statistical models utilize the probability theory and uncertainty to estimate the likelihood of pipe failures. Examples of such models may be found in (Jeffrey 1985; Constantine et al. 1996; Mavin 1996; Deb et al. 1998).

The objective of this paper is to develop a methodology for the deterioration evaluation of water distribution networks (WDNs), in addition to modeling their failure rates. The proposed methodology is grounded in the RA technique by utilizing the embedded statistical package of *MATLAB © R2019b*.

Background

Regression Analysis

RA is a set of statistical procedures for analyzing and modeling the relationships between two or more variables. Hence, predicting the response variables from predictor variables. The most common form of this relationship is linear regression, which is expressed in Equation (1) (Chatterjee and Hadi 2012):

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{1}$$

where, Y_i is the response variable in the ith trial, β_0 and β_1 are the model regression coefficients, X_i is the predictor variable in the ith trial, and ε_i is the random error.

The generic form of this relation is attained when there is more than one predictor variable, and the generated model is called a multiple regression. This relationship is presented in Equation (2) (Kutner et al. 2005).

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{p\text{-}1} X_{i,p\text{-}1} + \varepsilon_i \tag{2}$$

Generally, the regression coefficient values β_0, β_1, β_2, etc., in Equation (2) are unknown and must be calculated from the available data. Because no previous information exists about the form of regression relationship (e.g., linear or curvilinear) and the appropriate predictor variables, it is quite essential to analyze the data in order to develop a proper regression model.

There exist several methods to check the forms of linearity by observing the curvatures in different plots, such as looking at the scatterplot of residuals as opposed to the fitted values. Moreover, checking the scatterplot of residuals against each predictor. If the scatterplot proposes a curvilinear relationship, it means this is a polynomial regression model. The mathematical definition of this model is postulated in Equation (3) (Kutner et al. 2003):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2}^{\ 2} + \ldots + \beta_h X_{i1}^{\ h} + \varepsilon_i \tag{3}$$

where, h is the degree of the polynomial equation, and the relationship is called quadratic when $h = 2$, cubic when $h = 3$, quartic when $h = 4$, and so forth. Although the polynomial regression fits a non-linear relationship between the response variable and the predictor variable, it is recognized as a linear regression model.

Literature Review

Several endeavors have emerged recently as a step toward the evaluation and modeling of water pipe failure rates using different statistical and machine learning techniques. For example, in the statistical modeling of water infrastructure, Wang et al. (2009) proposed five multiple regression models for the evaluation of break rates in the water supply system, after considering a multitude of factors (i.e., pipe diameter, length, material, year of installation, and cover depth). Asnaashari et al. (2009) applied multiple regression, together with Poisson regression, to develop two failure prediction models based on ten years of historical data. They then compared the performances of the two models and found that the Poisson model revealed superior prediction results. In the artificial neural networks (ANNs) domain, Sattar et al. (2019) constructed an extreme learning machine (ELM) model to forecast water pipes' failure and to optimize maintenance and/or rehabilitation operations. Notwithstanding the high accuracy of the ELM model, its practicality was limited due to missing pipe break records. Dawood et al. (2019b) leveraged the ANNs and pattern recognition techniques to predict the risk of water quality failure in Peru. Christodoulou et al. (2010) trained an ANNs model, then analyzed the risk associated with buried pipes via a survival analysis approach. In the fuzzy logic modeling, Fayaz et al. (2018) introduced a hybrid approach through the fusion of the Kalman filter and the Hierarchical Fuzzy Logic. Their approach aimed at improving the risk assessment in the water piping system. Malinowska (2017) integrated the geographic information system (GIS) and a fuzzy inference system (FIS) to predict the pipeline failure hazards in a mining field. The model validation showed a good correlation between the predicted and observed results. Li and Yao (2016) used the Analytic Hierarchy Process (AHP), in conjunction with fuzzy logic to estimate the risk of failure of long water mains. In the boosting algorithms applications, Winkler et al. (2018) designed a boosted decision tree model that is based on machine learning algorithms to address the deterioration and failure mechanisms in WDNs. Later, the model performance was evaluated through confusion matrices and receiver operating characteristic curves. Some researchers combined the statistical and machine learning techniques to develop their methodologies. For instance, Fahmy and Moselhi (2009) presented a framework that involved the multiple regression technique, multilayer perceptron ANNs, and general regression neural network to predict the remaining useful life of water pipes in North America. Their model was designed on the basis of several factors, including physical, mechanical, operational, and environmental factors. Tabesh et al. (2009) incorporated three data-driven modeling techniques, i.e., ANN, neuro-fuzzy systems (NFS), and multivariate regression (MVR), to assess the risk of failure of water mains and mechanical reliability. The ANN model outperformed the NFS and MVR models in assessment capability and performance. Najjaran et al. (2004) developed a fuzzy expert system capable of modeling the deterioration of metallic pipes based on surrounding soil properties. Their system was built using expert knowledge and field information and through the fusion of linear regression and FIS. Aydogdu and Firat (2015) combined three machine learning techniques (least squares support vector machine, feed-forward neural network, and generalized regression neural network) to develop a methodology for estimating the failure frequency in water infrastructure. These studies mainly focused on the computational modeling of breaks and risk of failure. Nevertheless, a 3D interactive representation that reveals the severity of failure in WDNs was never performed. Therefore, the intellectual contribution of this study is to bridge the gap by addressing the aforementioned limitation using simulation and RA.

Study Area

In order to recognize the failure patterns and develop the water mains failure model, seven years of historical data related to pipe characteristics and breakage rates were obtained from the WDNs of the city of El Pedregal, Peru. Figure 1 shows the geographical location of this city on Google Earth. El Pedregal is a city in the Arequipa Region in southwestern Peru with elevation 1,410 m above sea level. It is located 70 km west of the city of Arequipa in the arid coastal plain of Peru. The land in that district is partially for irrigated agriculture and the rest for desert vegetation. According to the 2017 census, the city had 44,264 inhabitants, showing an increase in population by more than double since 2007. The city of El Pedregal makes a unique case study because of the following reasons: 1) rapid increase of urbanization as a result of rural-urban migration; 2) growing economic activities in the region that promote social welfare; and 3) criticality of water infrastructure in this developing region, where the majority of population live in an extremely water scarce environment. The growing population and the rapid pace of urban sprawl has hindered the municipalities to provide infrastructure and services to the growing number of residents. Hence, the investment in water infrastructure is quite crucial as it is the engine for growth in the region (The World Bank 2018).

The economic prosperity in the Arequipa Region is the driving force behind the population growth, especially after implementing the Majes Irrigation Project, which has transformed 15,000 hectares of the desert to fertile land. The area is projected to receive new developments, such as the new dam that will be constructed in the second phase of the project in order to expand the area of irrigated land and boost the region's profit through the export-oriented agribusiness (Stensrud 2016).

The water supply system of El Pedregal was constructed in August 2012. Figure 2 illustrates laying the Polyvinyl Chloride (PVC) pipes as part of the construction process in El Pedregal. The main network consists of 6,482 m of PVC pipes with diameters ranging from 110 mm to 500 mm. In contrast, the secondary network has 11,129 m of PVC pipes with diameters ranging from 63 mm to 90 mm. The pipe characteristics of both networks (i.e., primary and secondary) were collected, classified, and analyzed. A sample of the obtained data is depicted in Table 1.

Objectives and Methodology

This paper addresses two substantial issues pertaining to the management of urban water networks, namely, the deterioration modeling and failure frequency assessment. To highlight these issues, it is imperative to study and determine the factors that contribute to pipe deterioration,

Figure 1. Study area location on Google Maps.

as well as designing a system capable of assessing and modeling the pipe failure rate. The proposed methodology encompasses several steps commencing from the data collection until achieving the study objective of estimating the failure rate. The overall flow diagram of the research methodology is displayed in Figure 3. It includes four major phases: variables selection, model building, data analytics, and model application.


Figure 2. Water networks construction in El Pedregal.

In the first phase, data on both the main and secondary networks over a period of seven years are collected. Data are divided into two sets; the first set is for building the model and setting its various parameters, and the second set is for model validation and testing its robustness to estimate the output variables. This is followed by identifying the factors (variables) that mostly contribute to the networks' deterioration, as well as selecting the predictor and response variables from El Pedregal's archived data. The predictor variables are specified to be the pipe diameter and thickness, while the response variable is identified as the failure rate.

The second phase involves building and designing the model architecture. Numerous forms of the RA models are defined in this phase. These exemplify the simple linear regression, multiple regression, and polynomial regression. After simulating and analyzing the data, a scatter plot is generated automatically to check the forms

Table 1. Sample of the collected data.

Diameter (inch)	**Thickness (inch) Serie 6.6 (Class15)**	**Thickness (inch) Serie 10 (Class10)**	**Thickness (inch) Serie 13.3 (Class7.5)**	**Thickness (inch) Serie 20 (Class5)**
2.48	0.17	0.12	0.09	0.06
2.95	0.21	0.14	0.11	0.07
3.54	0.25	0.17	0.13	0.09
4.33	0.30	0.21	0.16	0.11
5.51	0.39	0.26	0.20	0.14
6.30	0.44	0.30	0.23	0.16
7.87	0.55	0.38	0.29	0.19
9.84	0.69	0.47	0.36	0.24
12.40	0.87	0.59	0.45	0.30
13.98	0.98	0.67	0.51	0.34
15.75	1.10	0.75	0.57	0.39
17.72	1.24	0.85	0.64	0.43
19.69	1.37	0.94	0.71	0.48

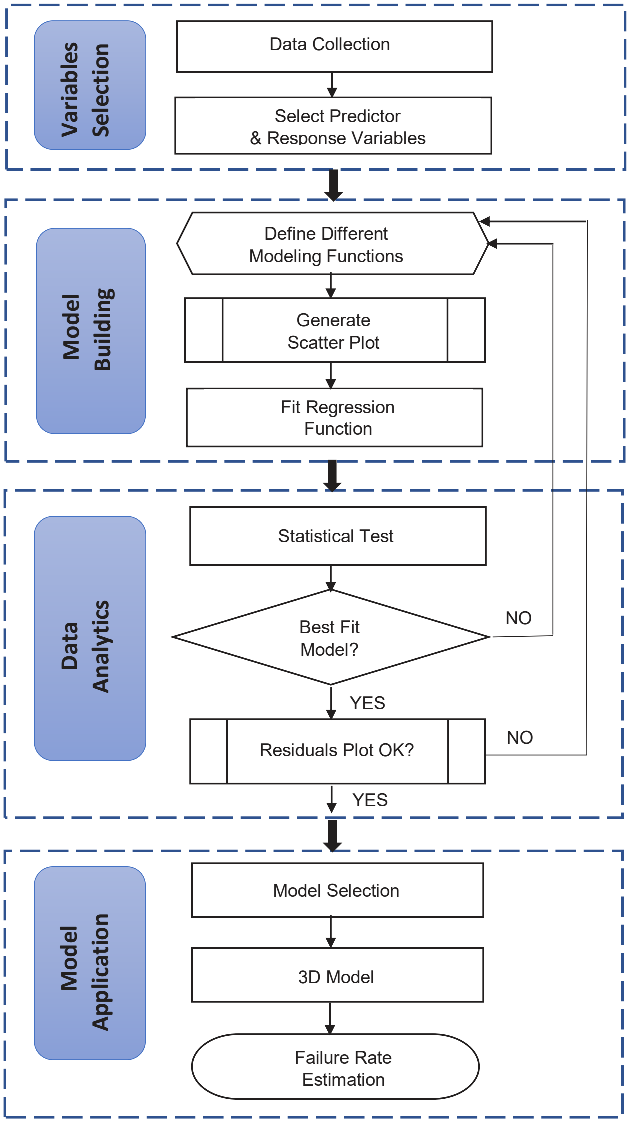


Figure 3. Overall flowchart for pipe failure estimation.

of linearity. This graph also determines the best fit model and provides a prediction of the pipe failure rate. Figure 4 displays the regression model building.

In the data analytics phase, different diagnostic checks are implemented to investigate multiple RA scenarios and interrelated functions of the proposed model. In this concern, the statistical significance of the assessed relationships is computed, which signifies the degree of confidence that the actual relationship is close to the assessed relationship (Elwakil 2017). Hence, the model is tested against four statistical metrics to underscore the goodness of fit and to ensure its robustness. These metrics comprise R-square (R^2), adjusted R-square (Adj R^2), the sum of squares due to error (SSE), and root mean squared error (RMSE). The goodness of fit of the model is determined according to the highest R^2 and Adj R^2, and the least SSE and RMSE. Additional residual graphs are conducted to corroborate the efficacy of the proposed model. In the fourth phase, the model that satisfies the statistical test conditions and the residual analysis is chosen as the best model, which will be applied later for the assessment and modeling of water system failure. Next, a 3D schematic representation was created for the selected model.

Model Development and Results

The previously described phases of the regression model (shown in Figure 3) were implemented in *MATLAB © R2019b* by utilizing

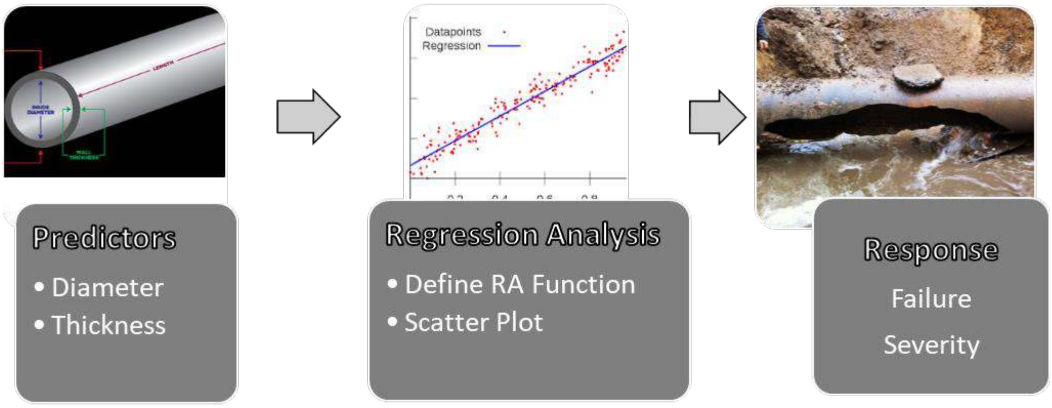


Figure 4. Data fitting using regression analysis.

the regression fitting Toolbox. First, the predictor variables (pipe diameter, thickness) and the response variable (pipe failure) were fed to the RA machine. Subsequent to processing and simulating the introduced data, a scatter plot was produced, then tested for the form of relationship, which indicated a positive linear relationship between the two predictors (diameter, thickness) as shown in Figure 5. However, the statistical analysis results revealed a negative linear relationship between the response variable (failure rate) and each of the predictors.

Since there exist two predictor variables, and after checking the function's pattern, the multiple regression function was employed to fit the data. Different multiple regression models were generated and statistically tested. These tests are conducive to assess the goodness of fit and opting for the best fit model. Several diagnostic criteria were computed and compared, as well as the interactions between a proliferation of parameters, which culminate in choosing the best model. Consequently, the best possible data fitting scenarios were determined in accordance with the highest R^2 and Adj R^2 and the lowest SSE and RMSE. The statistical analysis results reflect that R^2 is 0.9767, Adj R^2 is 0.9745, SSE is 0.0008, and RMSE is 0.0113. Since all four criteria delivered satisfactory results, the best regression model was selected. The mathematical definition of this model is presented in Equation (4):

$$y = -0.069x_1 - 0.048x_2 + 0.032 \tag{4}$$

where, x_1 is the pipe diameter, x_2 is the thickness, and y is the corresponding water pipe failure. In addition, a 3D visualization scheme was extracted for the optimal model, as showcased in Figure 6.

Furthermore, a residual analysis was carried out on the developed model to validate numerous hypotheses related to the model building; such hypotheses encompass homoscedasticity, normality of the error distribution, and lack of correlation. The first hypothesis states that the deviation from the regression line should be the same for all X values, which could be validated by generating the residuals plot of the failure model, as represented in Figure 7. Analyzing this figure demonstrates that approximately all the residuals have tendencies to be constant. Therefore, the outcomes of this hypothesis are deemed reasonable. The normality of the error distribution that specifies departures from normality was conducted. Examining the probability of normal distribution reveals no significant errors or notable outliers. Thus, the proposed model looks sound under this hypothesis. Finally, the lack of correlation measures the independency of error around the regression line. Figure 7 shows that the positive residuals and the negative residuals are symmetrically distributed around zero, which is confirming once again the coherency of the pipe failure model. In cases where the residual analysis does not indicate that the model hypotheses are satisfied, it often proposes solutions in which the model can be modified and rebuilt in order to attain better outcomes.

Conclusions and Future Studies

This paper developed a regression-based model to estimate the level of failure in water supply systems. Following the data collection from the city of El Pedregal in Peru, numerous diagnostic checks were conducted to test the interactions between manifold variables and algorithms. After fitting the

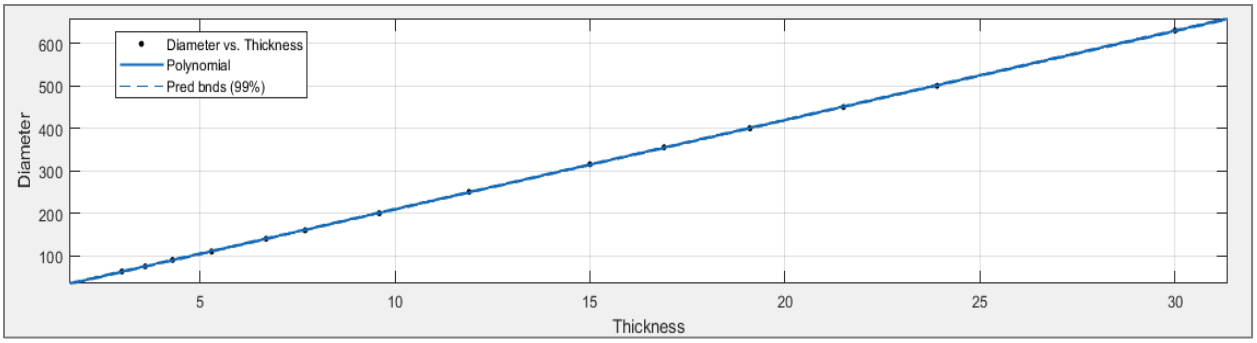


Figure 5. Relationship between diameter and thickness.

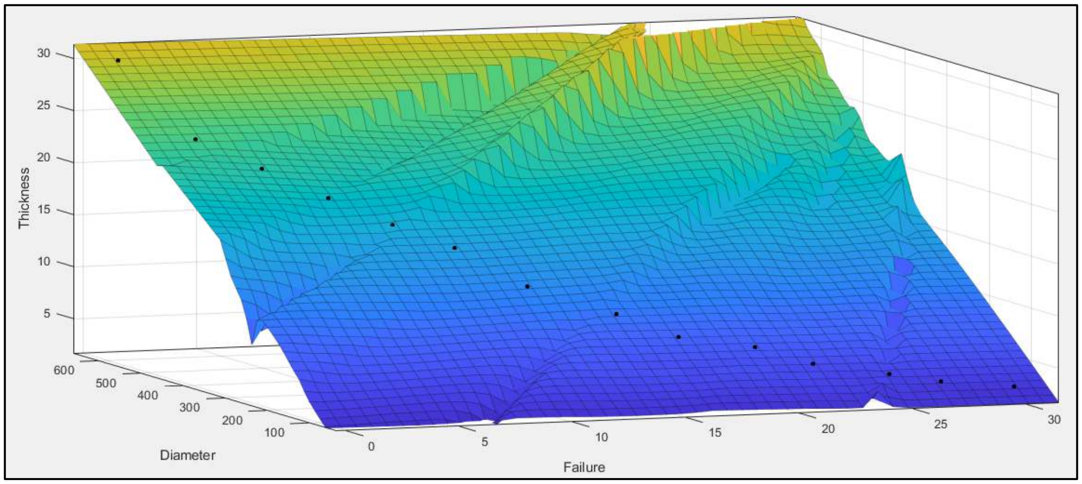


Figure 6. 3D surface presentation. This Figure indicates that the likelihood of water pipe failure increases as the pipe diameter and/or thickness decreases.

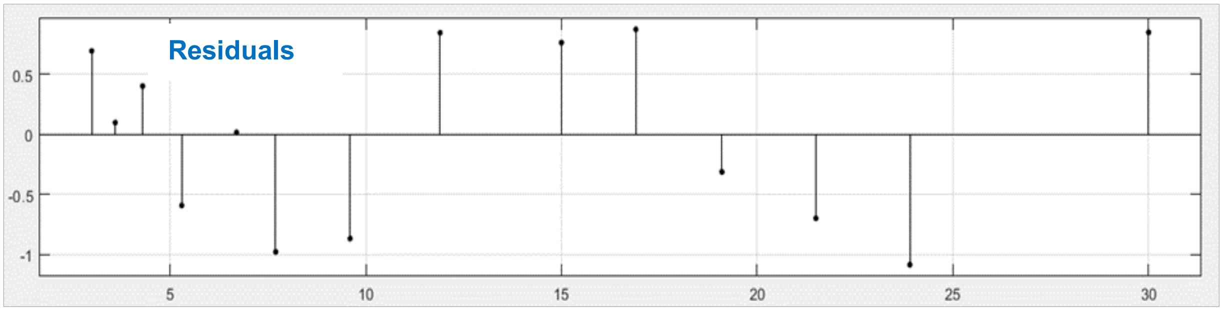


Figure 7. Model's residuals plot.

regression functions and generating a scatter plot, various multiple regression models were produced and statistically tested. The models' performance was compared against several evaluation criteria, which revealed promising results. The optimum model was selected since it achieved the highest R^2 and Adj R^2 of 0.9767 and 0.9745, respectively, and the least SSE and RMSE of 0.0008 and 0.0113, respectively. A 3D visualization plot was created automatically and the model was validated via a residual analysis scheme in which the outcome proved to be satisfactory and sound. Despite the high performance of the proposed method, there exist some limitations, as the model is designed only for PVC pipes; consequently, it cannot model the deterioration or assess the failure rates of other water pipes. This research contributed to the body of knowledge by mathematically modeling the water pipe failure with respect to the pipe diameter and thickness, in addition to creating a 3D visualization representation that can be easily perceived. The 3D surface plot reveals that pipe failure rates in El Pedregal will increase as the diameter and/or thickness decrease. In other words, a water pipe with larger diameter and/or thickness is less prone to failure and more likely to resist breakages.

Some of the suggested future topics may cover the limitations of this research by investigating the deterioration phenomena of other pipe materials, such as cast iron, ductile iron, and asbestos cement. Thus, creating new models that evaluate the level of failure in these pipes. Others may explore the automated monitoring systems using Smart Pipes, Intelligent Pigs, and Robotics for a more coherent condition assessment of the water system. Other research can investigate the Augmented Reality approach that offers a human-computer interface for real-time visualization of anomalies and defects in water pipelines. Moreover, an integrated predictive model could be accomplished by fusing and linking data streams from multiple remote sensing technologies and sensors, such as the Ground Penetrating Radar (GPR), radiographic methods, and infrared sensors that can detect the pipe deterioration and locate its leakage in a nondestructive way. This predictive model can be merged with GIS to generate highly accurate maps, hence allowing a de facto visualization of the network risk of failure. These applications could reasonably minimize the disruptions to roads and businesses, as well as, reduce the cost and time incurred.

Acknowledgments

This work is supported by the collaboration of the Universidad Nacional de San Agustín (UNSA) in Arequipa, Peru, and Purdue University in Indiana, USA, through Discovery Park's Center for the Environment (C4E).

Author Bio and Contact Information

Thikra Dawood (corresponding author) is a Postdoctoral researcher in the School of Construction Management, Purdue University. Her research efforts have focused on the creation and application of computer-aided decision support tools. Focus of this effort is on: infrastructure management, simulation and artificial intelligence applications in construction, multi-sensory data fusion, asset performance, and risk assessment for construction and rehabilitation of water systems, bridges, highways, and pavements. Dr. Dawood can be reached at dawoodt@purdue.edu.

Emad Elwakil is an Associate Professor of Construction Management, Purdue University. His primary research interests include infrastructure management systems, water systems sustainability management, modeling, simulation, risk management, and disaster management. Dr. Elwakil can be reached at eelwakil@purdue.edu.

Hector M. Novoa studied civil engineering at the National University of Engineering in Lima, Perú. He has been working intensively for more than 25 years on issues related to the environment, including: water supply systems, sewer systems, GIS applications in water resources engineering with emphasis on river channels (HEC-GeoRAS), surface water hydrology (SWAT), and design of hydraulic structures. He carried out studies on groundwater and traveled to Brazil to complete a master's degree in Water Resources. He finished his doctorate studies and is doing his thesis. He is currently a professor of fluid mechanics, hydraulics, and hydrology at the National University of San Agustin in Arequipa, Peru. Recently, he was at Purdue University, United States, conducting a research internship on Sustainable Watershed Management. He is a member of IAHR and ABRH associations. Professor Novoa can be reached at hnovoa@unsa.edu.pe.

José Fernando Gárate Delgado has his M. Sc in Business Management and is a Food Industries Engineer and Agronomist Engineer. He completed a Doctorate in Project Engineering and a Masters in Food Science and Technology, with a second specialty in Integrated Management of Water Resources, with 20 years of Agroindustrial experience. He is a University professor of Food Engineering at the National University of San Agustín de Arequipa. He is also program and project worker of the Ministry of Agriculture and Irrigation of Peru in planning, management, control, implementation, execution, monitoring, evaluation, and research aimed at strengthening productive chains in the agro-industrial sector. Professor Delgado can be reached at josegarate@gmail.com.

References

American Society of Civil Engineers (ASCE). 2017. *Infrastructure Report Card*. Available at: https://www.infrastructurereportcard.org/cat-item/drinking_water/. Accessed August 28, 2020.

American Water Works Association (AWWA). 2012. *Buried No Longer: Confronting Americas Water Infrastructure Challenge*. Available at: http://www.climateneeds.umd.edu/reports/American-Water-Works.pdf. Accessed August 28, 2020.

Asnaashari, A., E.A. McBean, I. Shahrour, and B. Gharabaghi. 2009. Prediction of watermain failure frequencies using multiple and Poisson regression. *Water Supply* 9(1): 9-19. Available at: https://doi.org/10.2166/ws.2009.020. Accessed August 28, 2020.

Aydogdu, M. and M. Firat. 2015. Estimation of failure rate in water distribution network using fuzzy clustering and LS-SVM methods. *Water Resources Management* 29: 1575-1590. Available at: https://doi.org/10.1007/s11269-014-0895-5. Accessed August 28, 2020.

Barlow, M. and T. Clarke. 2007. *The Struggle for Latin America's Water*. Nacla Reporting on the America's Since 1967. Available at: https://nacla.org/article/struggle-latin-america%27s-water. Accessed August 28, 2020.

Chatterjee, S. and A.S. Hadi. 2012. *Regression Analysis by Example*. 5th Edition. John Wiley & Sons, Inc., New Jersey, USA.

Christodoulou, S., A. Agathokleous, B. Charalambous, and A. Adamou. 2010. Proactive risk-based integrity assessment of water distribution networks. *Water Resources Management* 24: 3715-3730. DOI: 10.1007/s11269-010-9629-5.

Constantine, A., J. Darroch, and R. Miller. 1996. Predicting underground pipe failure. *Water* 23(2): 9-10. Available at: http://hdl.handle.net/102.100.100/229501?index=1. Accessed August 28, 2020.

Dawood, T., E. Elwakil, H.M. Novoa, and J.F.G. Delgado. 2019a. Water pipe failure prediction and risk models: State-of-the-art review. *Canadian Journal of Civil Engineering*. In press. Available at: http://dx.doi.org/10.1139/cjce-2019-0481. Accessed August 28, 2020.

Dawood, T., E. Elwakil, H.M. Novoa, and J.F.G. Delgado. 2019b. A contamination risk model for water distribution networks. In: *Proceedings of the International Conference on Engineering, Science and Technology*. October 7-10, 2019, Denver, CO, USA. Available at: https://www.2019.iconest.net/fulltext/pdf/IConEST037.pdf. Accessed August 28, 2020.

Deb, A.K., Y. Hasit, J.F.M. Grablutz, and R.K. Herz. 1998. Quantifying future rehabilitation and replacement needs of water mains. *AWWA Research Foundation*. Denver, CO, USA.

Dridi, L., A. Mailhot, M. Parizeau, and J.P. Villeneuve. 2009. Multiobjective approach for pipe replacement based on Bayesian inference of break model parameters. *Journal of Water Resources Planning and Management* 135(5): 344-354. Available at: https://doi.org/10.1061/(ASCE)0733-9496(2009)135:5(344). Accessed August 28, 2020.

Elwakil, E. 2017. Integrating analytical hierarchy process and regression for assessing construction organizations' performance. *International Journal of Construction Management* 17(1): 76-88. Available at: https://doi.org/10.1080/15623599.2016.1187247. Accessed August 28, 2020.

Fahmy, M. and O. Moselhi. 2009. Forecasting the remaining useful life of cast iron water mains. *Journal of Performance Constructed Facilities* 23(4): 269-275. Available at: https://doi.org/10.1061/(ASCE)0887-3828(2009)23:4(269). Accessed August 28, 2020.

Fayaz, M., I. Ullah, and D.-H. Kim. 2018. Underground risk index assessment and prediction using a simplified hierarchical fuzzy logic model and Kalman filter. *Processes* 6(8): 103. DOI: 10.3390/pr6080103.

Folkman, S. 2018. *Water Main Break Rates in the USA and Canada: A Comprehensive Study. Mechanical and Aerospace Engineering Faculty Publications.* Paper 174. Available at: https://digitalcommons.usu.edu/mae_facpub/174/. Accessed August 28, 2020.

Harvey, R., E.A. McBean, and B. Gharabaghi. 2014. Predicting the timing of water main failure using artificial neural networks. *Journal of Water Resources Planning and Management* 140(4): 425-434. Available at: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000354. Accessed August 28, 2020.

Jacobs, P. and B. Karney. 1994. GIS development with application to cast iron water main breakage rate. *2nd International Conference on Water Pipeline Systems.* Edinburgh, Scotland.

Jeffrey, L.A. 1985. Predicting urban water distribution maintenance strategies: A case study of New Haven. M.Sc. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.

Kleiner, Y. and B. Rajani. 2001a. Comprehensive review of structural deterioration of water mains: Statistical models. *Urban Water* 3(3): 131-150. DOI: 10.1016/S1462-0758(01)00033-4.

Kleiner, Y. and B. Rajani. 2001b. Comprehensive review of structural deterioration of water mains: Physically based models. *Urban Water* 3(3): 151-164. DOI: 10.1016/S1462-0758(01)00032-2.

Kutner, M., C. Nachtsheim, and J. Neter. 2003. *Applied Linear Regression Models*. 4th Edition. McGraw-Hill Company Inc., New York, USA.

Kutner, M., C. Nachtsheim, J. Neter, and W. Li. 2005. *Applied Linear Statistical Models*. 5th Edition. McGraw-Hill Company Inc., New York, USA.

Li, D., and W. Yao. 2016. Risk assessment of long-distance water transmission pipeline based on fuzzy similarity evaluation approach. *12th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD)*. Changsha, China. Available at: https://ieeexplore.ieee.org/abstract/document/7603331. Accessed August 28, 2020.

Malinowska, A.A. 2017. Fuzzy inference-based approach to the mining-induced pipeline failure estimation. *Natural Hazards* 85: 621-636. DOI: 10.1007/s11069-016-2594-4.

Mavin, K. 1996. *Predicting the Failure Performance of Individual Water Mains*. Urban Water Research Association of Australia, Research Report No. 114, Melbourne, Australia.

McMullen, L.D. 1982. Advanced concepts in soil evaluation for exterior pipeline corrosion. *Proceeding of the AWWA Annual Conference*. Miami, FL, USA.

Najjaran, H., B. Rajani, and R. Sadiq. 2004. A fuzzy expert system for deterioration modeling of buried metallic pipes. *IEEE Annual Meeting of the Fuzzy Information*. Banff, Alberta, Canada, June 27-30, 2004, pp. 1-6.

Sattar, A.M.A., Ö.F. Ertuğrul, B. Gharabaghi, E.A. McBean, and J. Cao. 2019. Extreme learning machine model for water network management. *Neural Computing and Applications* 31(1): 157-169. DOI: 10.1007/s00521-017-2987-7.

Shamir, U. and C. Howard. 1979. An analytic approach to scheduling pipe replacement. *Journal of American Water Works Association* 71(5): 248-258. Available at: https://doi.org/10.1002/j.1551-8833.1979.tb04345.x. Accessed August 28, 2020.

St. Clair, A.M. and S. Sinha. 2012. State-of-the-technology review on water pipe condition, deterioration and failure rate prediction models! *Urban Water Journal* 9(2): 85-112. Available at: https://doi.org/10.1080/1573062X.2011.644566. Accessed August 28, 2020.

Stensrud, A.B. 2016. Dreams of growth and fear of water crisis: The ambivalence of "progress" in the Majes-Siguas Irrigation Project, Peru. *History and Anthropology* 27(5): 569-584. Available at: https://doi.org/10.1080/02757206.2016.1222526. Accessed August 28, 2020.

Tabesh, M., J. Soltani, R. Farmani, and D. Savic. 2009. Assessing pipe failure rate and mechanical reliability of water distribution networks using data-driven modeling. *Journal of Hydroinformatics* 11(1): 1-17. Available at: https://doi.org/10.2166/hydro.2009.008. Accessed August 28, 2020.

Walski, T. and A. Pelliccia. 1982. Economic analysis of water main breaks. *Journal of American Water Works Association* 74(3): 140-147. Available at: https://doi.org/10.1002/j.1551-8833.1982.tb04874.x. Accessed August 28, 2020.

Wang, Y., T. Zayed, and O. Moselhi. 2009. Prediction models for annual break rates of water mains. *Journal of Performance of Constructed Facilities* 23(1): 47-54. Available at: https://doi.org/10.1061/(ASCE)0887-3828(2009)23:1(47). Accessed August 28, 2020.

Winkler, D., M. Haltmeier, M. Kleidorfer, W. Rauch, and F. Tscheikner-Gratl. 2018. Pipe failure modelling for water distribution networks using boosted decision trees. *Structure and Infrastructure Engineering* 14(10): 1402-1411. DOI: 10.1080/15732479.2018.1443145.

The World Bank. 2018. National Urban Cadaster and Municipal Support Project (P162278). Available at: http://documents1.worldbank.org/curated/en/115551541449971634/pdf/Concept-Project-Information-Document-Integrated-Safeguards-Data-Sheet-National-Urban-Cadaster-and-Municipal-Support-Project-P162278.pdf. Accessed August 28, 2020.

UNIVERSITIES COUNCIL ON WATER RESOURCES
JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION
ISSUE 171, PAGES 74-92, DECEMBER 2020

Using Remote Sensing to Discover Historic Context of Human-Environmental Water Resource Dynamics

*Zachary Brecheisen[1], Nicholas Hamp-Adams[1], Abigail Tomasek[1], Erika J. Foster[1], Timothy Filley[1], Martín Villalta Soto[2], Lucia Zuniga Reynoso[1], Andre de Lima Moraes[1], and Darrell G. Schulze[1]

[1]Purdue University, West Lafayette, IN, USA; [2]National University of St Augustin of Arequipa, Arequipa, Peru;
**Corresponding Author*

Abstract: Analysis of historic and contemporary high-resolution imagery can help to fill knowledge gaps in land cover and management history in locations where documentation is non-existent or records are difficult to access. Historic imagery dating back to the 1960s can be used to structure quantitative investigation and mapping of land use and land cover change across space and time to enhance earth science, policy, and social science research. Imagery can further inform municipal planning and implementation in areas of natural resource allocation, infrastructure, and hazard mitigation. For management and public education, historic imagery can help people to understand environmental processes and the impacts of human activity in the local environment. Here we emphasize the value of high-resolution historic satellite imagery from the Corona and Keyhole satellite programs to inform environmental research, public education, and environmental management. Within the Region of Arequipa in southern Peru we highlight examples of urban development, agricultural expansion, river channelization, and glacial retreat via comparison of historic and modern satellite imagery. By incorporating these types of historic imagery data in formats accessible to non-professionals, public engagement as well as research into human-environmental investigations will be greatly enhanced.

Keywords: *historic imagery, declassified, Corona, Keyhole, glacier melt, agricultural development, Arequipa Peru*

In a world with increasingly complex human-mediated environmental changes, water accessibility is one of the leading causes of environmental social conflicts globally and particularly in Peru (Stark, Guillén, and Brady 2012). Anthropogenic activities are a dominant driver concerning water quality, abundance, and distribution. For instance, urban expansion leads to increased population density and a greater demand for water resources, while increased impervious surfaces and industrial practices lead to increased flows and contaminant transport to downstream areas (Carpio and Fath 2011; Wang et al. 2018). Additionally, agricultural modernization and expansion impacts water quality due to increased erosion, application of pesticides and fertilizers, (Canfield, Glazer, and Falkowski 2010; Lu and Tian 2017; Li et al. 2020) and changing water availability (Stark, Guillén, and Brady 2012). Globally, land use change has caused drastic alterations of soil fertility (Khaledian et al. 2017) and stability (Diringer et al. 2020; Lacroix, Dehecq, and Taipe 2020), hydrology (Ochoa-Tocachi et al. 2016), loss of ecosystem services (Castello and Macedo 2016; Peng et al. 2017), and susceptibility to natural disasters such as flooding (Rogger et al. 2017) and drought (Bagley et al. 2014). While these issues are occurring at a global scale, research has shown that they disproportionally affect developing countries (Givens, Huang, and Jorgenson 2019), exacerbated by data scarcity in these regions (Hilbert 2016). This paper describes how satellite imagery can be used as a resource to document and visualize anthropogenic changes in the context of the Arequipa Region of Peru, which has undergone extraordinary human-mediated environmental change over the last 60 years.

The Arequipa Region of southern Peru is approximately 63,000 km^2 and has tremendous variation in climate and topography, ranging from sea level along the Pacific coast to more than 6,000 m elevation in the Andes. Correspondingly, temperature varies across the Region from continually frozen glacial flows in the mountains to 30° C on the desert plateau (Moraes et al. In preparation for submission). Annual precipitation has similarly high variability from ~5 mm in the alluvial desert plateau of the Majes agricultural project (EcoUrbe Consultores 2013), a mid-elevation Andes rain shadow, to 800 mm at higher elevations. The Region is home to the city of Arequipa, Peru's second largest city with a population of 1,382,730 (INEI 2017). Within these topographic and climatic extremes exists a great diversity of human and natural environments including historic and modern agricultural areas, mountain top glacial ice and snow cover, sprawling cities, and large rivers inside huge canyons. Across the Region, there is a long history of human-environmental interaction dating back into Inca history and evolving into the present day (Sandor and Homburg 2017). Despite this richness in anthropogenic activity across the landscape, challenges arise when trying to locate precise records and documentation of where and when humans have shaped the landscape.

For this study, declassified, high-resolution satellite imagery from 1966 was compared to current imagery to determine the anthropogenic impacts on environmental systems in the Region of Arequipa. The Corona satellites, which flew from the 1960s to early 1970s, produced the 1966 imagery and Keyhole satellites, which flew from the later 1970s to 1980s, produced the 1978 and 1980 imagery used in this study. The Corona program was the first United States reconnaissance spy satellite program and took over 800,000 images of the Earth's surface from 1959 to 1972 (Perry 1973). The first successful mission took place on August 18, 1960. It was a highly classified program under the management of the Central Intelligence Agency and the United States Air Force, which together would go on to form the National Reconnaissance Office (McDonald 1995). Since declassification in 1995, Corona imagery has played an instrumental role in archeological investigations (Ur 2003; Fowler 2004; Goossens et al. 2006; Alizadeh and Ur 2007; Casana and Cothren 2008; Fowler 2013; Sevara et al. 2018). Corona imagery is available for public purchase from the United States Geological Survey (USGS) Earth Explorer (USGS 2016). Keyhole is the satellite reconnaissance program that followed Corona and it ended in the 1980s (Perry 1973). Despite its potential value for enhancing research, environmental scientists have not yet fully utilized the historic imagery of Corona or Keyhole (Schlesinger and Gramenopoulos 1996; Shroder, Bishop, and Overton 2005; Boyle et al. 2014; Pope et al. 2014; Guan et al. 2017; Lacroix, Dehecq, and Taipe 2020).

In this article, we explore several case studies from the Arequipa Region showing the utility of remote sensing for large scale multidisciplinary research like that done by the Arequipa Nexus Institute (Filley and Polanco Cornejo 2018). Such collaborative research endeavors can assess sustainability challenges via delineation of human-environment interactions in historic and modern satellite imagery. The case studies presented in this investigation include urbanization, agricultural development, river channelization, and loss of snowpack and glaciers. These examples provide an introduction to the capacity of satellite imagery, particularly historic imagery, to capture environmental history pertaining to water resource risks. We will conclude with an example of how high-resolution imagery can be shared with and used by the public via the Soil Explorer application (Isee Network 2015-2020; Schulze 2018). Soil Explorer allows non-specialist stakeholders to interact dynamically with remotely-hosted geospatial data across landscapes. Raster and vector spatial data can be explored at different scales and users are geolocated if they are within the map display boundary. Technologies like this could be incorporated in strategies to enhance public adoption of water management policies addressing challenges like climate change.

Methods

This study used historic images from two satellites, KH-40 (Corona J-1) and KH9-14, to investigate examples of human-environmental change in water resource contexts across the 63,000 km^2 Region of Arequipa, Peru (Figure 1). Both satellites captured imagery onto photographic film. KH-40 flew from August 1963 to October 1969, collecting imagery with an approximate pixel resolution of 2.75 m, and KH9-14 flew from March 1978 to September 1978, collecting imagery with an approximate pixel resolution of 6 m (Goossens et al. 2006; Hamandawana, Eckardt, and Ringrose 2007). It would not be until 1999, with the launch of the IKONOS satellite which collected ~1 m resolution panchromatic imagery in addition to ~4 m multispectral imagery, that imagery with such high-resolution would be available again, due to technological advances in the intervening 20-30 years (Pope et al. 2014). The historic imagery was compared with multispectral Sentinel satellite imagery obtained via Google Earth Engine (Gorelick et al. 2017) or 3 m PlanetScope satellite multispectral imagery via Planet Labs, Inc. (2020). This was done in order to update and edit existing land cover vector polygons from the Ecological and Economic Zoning (ZEE) project (Gobierno Regional Arequipa 2016) to conduct analyses of changes in land cover through time. PlanetScope data were employed when image resolution finer than 10 m (as in Sentinel imagery) was required, such as for detailed polygon delineation around small urban areas.

The 1966 Corona images and 1978 Keyhole images were purchased for 30 United States Dollars (USD) per image strip via USGS Earth Explorer (USGS 2016), within the declassified dataset listings. Both Corona and Keyhole image strips were exported as 7 micron digital scans of the film. Each 1966 Corona image strip was provided in four split components (a, b, c, and d) (~220 MB each), whereas the Keyhole image strips were supplied in two image components (a and b) each ~1.1 GB in size. The five-fold difference in file sizes between the two historic image types is due to the fact that the later Keyhole images individually cover a much larger spatial area than do the Corona images.

Prior to georectification in GIS software, all of the historic satellite images were processed in Adobe Photoshop to crop out the film edges of the photographs. The next pre-georectification task was to mosaic the components of each image together. The image components were lined up, from right (a) to left (d) for Corona or top (a) to bottom (b) for Keyhole imagery, and mosaicked into image strips.

Following the completion of this process for all of the historic imagery, the image strips were then georeferenced to the high-resolution ArcGIS aerial basemap and to other image strips. The accuracy of the ArcGIS basemap was checked frequently against 10 m resolution Sentinel satellite data across the Region of Arequipa, to ensure that the basemap accurately accounted for dynamic topography. Because the image strips cover extensive areas, the Corona images required at least 200 ground control points to be precisely georectified to the contemporary surface. Due to optical lens distortion, the angle at which the images were taken, and very extreme elevation relief between valley bottoms and mountain or hilltops, distortion of these historic images was challenging to address, especially in montane parts of the Region (Goossens et al. 2006). Pincushion optical distortion also led the georectified Corona image strips to have a distinct horizontal hourglass shape. Approximately 200 control points were placed equidistant from each other around the border and within each of the Corona strips, especially in areas with complex topography and in areas of research interest for the topics discussed in this paper. Visible features used for georectification included town centers, roadway intersections, mountain peaks, river confluences, stone livestock corrals, and drainage features.

The complete collection of 1966 Corona strips combined form a high-resolution image across the Region of Arequipa. The same methodology was used for a 1978 imagery strip (satellite KH9-14), which required more than 900 control points to achieve comparable accuracy because of the much larger spatial extent of that imagery. The georectified 1978 Keyhole image strip had vertical pincushion distortion due to the fact that it was oriented roughly north-south whereas the 1966 Corona images were oriented east-west. Lastly, upon discovering unique evidence of salinization in the San Camilo area we georectified a small portion of a Keyhole image from 1980 (satellite KH9-16).

In order to estimate land cover change between one to two periods in the past via Corona and Keyhole imagery (1966-06-30 and 1978-05-16) and modern times we employed a combination of vector shapefile delineation and raster image analyses. Vector shapefile analyses were based on subsetting and manually updating the delineations of the land cover polygon dataset, published in the ZEE project (Gobierno Regional Arequipa 2016), for different time periods across the Region. To estimate changes in urban and agricultural area and river channelization, the areas of multipolygon features were tabulated and summed to estimate total area coverage at different times. Basic raster image manipulation prior to shapefile generation was used to estimate change in snow and ice cover on the peak of the Coropuna Volcano. Because ice and snow cover were mapped only as barren land in the ZEE land cover dataset, area coverage was estimated via panchromatic raster pixel value thresholding on 1978-05-16 Keyhole and 2019 May median-value Sentinel imagery generated via Google Earth Engine (Gorelick et al. 2017) to isolate ice and snow.

Land cover changes in the areas around the city of Arequipa necessitated more complex analyses. Both vector delineation and raster analyses were used to estimate land cover change among barren, agricultural, and developed urban coverage between 1966, 1978, and 2019. In these analyses the ZEE (Gobierno Regional Arequipa 2016) polygon delineations for 2015 were updated to match slight changes for 2019, as well as the much larger changes needed to map these land covers for 1966 and 1978. This entailed deletion of some polygons, changes in the border delineation of others, and the delineation of new polygons via manual digitization of features visible in the historic imagery. For each year (1966, 1978, and 2019), polygons were assigned classes of either urban development ("U") or agricultural development ("A"), with the non-delineated background considered to be barren ground ("B"). This is a slight simplification of the system, but barren ground does and did cover much of the undeveloped area around the city of Arequipa. Following the completion of polygon editing and delineation for U and A classes for each year, the vector datasets were merged in R and converted to 30 m pixel resolution rasters aligned to Landsat 8, as exported via Google Earth Engine, using the sf ("simple features"), raster, and fasterize packages (Gorelick et al. 2017; Pebesma 2018; Hijmans 2020; R Core Team 2020; Ross and Sumner 2020). In cases of slight polygon overlap between U and A classes, the U class was chosen to ensure that the delineations of small town centers in the midst of large agricultural areas were preserved. This land cover change among B, U, and A classes from 1966 to 1978 to 2019 was analyzed in terms of area in km^2 and percent cover, using the SDMTools package (VanDerWal et al. 2019).

Results and Discussion

Following georectification, each of the 11 horizontal 1966 Corona image strips was ~330 km by ~22 km and covered an area of ~8,000 km^2, accounting for image warping and pincushion distortion. This comes to a cost of ~0.0037 USD km^{-2} or 270 km^2 USD^{-1} for the 1966 Corona imagery. The later 1978 Keyhole image processing resulted in an image that covers ~43,000 km^2 at 1,400 km^2 USD^{-1}, following mosaicking and georectification. In the case of the 1966 Corona imagery, there is ~2.5 km of image overlap between image strips near the center and ~7 km of image overlap near the ends of the strips, due to pincushion distortion. In areas of overlap like this, stereo imagery analysis could be used to generate historic Digital Elevation Models (DEMs) (Casana and Cothren 2008).

Relative to modern high-resolution imagery, this historic imagery at 3-6 m pixel resolution is a low-cost data source. Considered in terms of cost per unit area (km^2 USD^{-1}), early Corona or later Keyhole imagery is available at 270 km^2 USD^{-1} and 1,400 km^2 USD^{-1}, respectively. In comparison, for the 1990s to 2000s, SPOT2 (10 m pixel resolution) and IKONOS (80 cm pixel resolution) can be purchased at 2.22 km^2 USD^{-1} and 0.14 km^2 USD^{-1}, respectively (Land Info 2020). The two to four order of magnitude difference in cost per unit area does not factor in the time and effort needed to georectify the historic imagery nor the fact that more modern imagery derived from IKONOS, SPOT, and other satellites may be available in multispectral format and at sub-meter resolution, in some cases. Nonetheless, the potential value of hundreds to thousands of square kilometers of satellite imagery per USD at finer than 10 m spatial pixel resolution is high. With this data we explored four examples of human-environmental water resource issues across the Region of Arequipa, proceeding east to west: urban development near the city of Arequipa (-16.4°, -71.5°); rural agricultural development near Santa Rita de Siguas (-16.5°, -72.1°) and the Majes agricultural project (-16.3°, -72.2°); river channelization of the Rio Majes (-16.3°, -72.45°); and snowpack and glaciers on the peak of the Coropuna Volcano (-15.55°, -72.6°).

Urban Expansion and Development

Arequipa is the capital of the Arequipa Region in Peru. Back in 1966 the human-modified landscape was ~73% agricultural fields (85 km^2) and ~27% urban (32 km^2). By 1978 the human-modified landscape was ~68% agricultural fields (100 km^2) and ~32% urban (46 km^2). Finally, by 2019, the landscape had become ~63% urban (172 km^2) and only ~37% agricultural fields (103 km^2). The marginal increase in agricultural area between 1978 and 2019 is due to much of the new agricultural development to the west of the city in Cerro Colorado (Figure 2) being largely offset by the development of ~14 km^2 of agricultural fields into urban areas. Approximately 65% of the developed urban area in the landscape around Arequipa was developed in the last 42 years from barren land totaling ~113 km^2 (Table 1). Only ~18% (~32 km^2) of the 2019 urban area across the landscape dates back to 1966 or earlier, with ~10.5% of the urban area (~18 km^2) having been developed on previously agricultural lands.

Most of the agricultural area (~66% or ~68 km^2) across the landscape has been cultivated since at least 1966 (Table 2). The proportions of 2019 agricultural land linked to agricultural expansion, i.e., the conversion of barren land to agriculture, between 1966 and 1978 (~18% or ~18 km^2) and 1978 to 2019 (~16% or ~16.5 km^2) are nearly identical despite a 3.4 times longer time interval (41 years vs. 12 years) in the second case, reflecting relatively little recent net agricultural expansion.

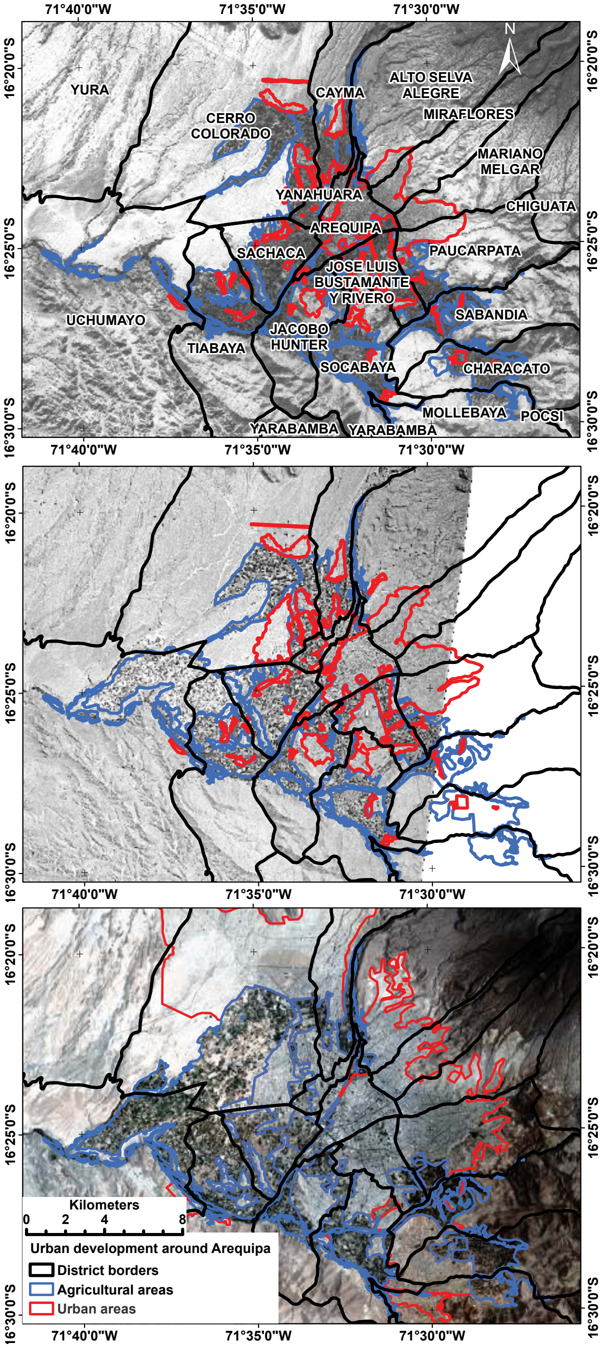


Figure 1. Urban expansion - Arequipa city located in the eastern part of the Arequipa Region in June 1966 (top, KH-40), May 1978 (center, KH9-14), and December 2019 (bottom, PlanetScope). Agricultural areas are outlined in blue and urban areas in red in each panel. Provinces are labeled by name in the top panel and outlined in black in all panels. The 1978 Keyhole panel is missing a small portion of landscape analyzed. For this area we used a Keyhole image from 1980 to complete the delineation of those agricultural and urban polygons. Urban expansion is particularly prominent in the Districts of Cayma, Cerro Colorado, and Alto Selva Alegre in the north abutting large lava flows from the Volcanoes El Misti and Chachani.

Table 1. Land cover change analyses of urban developed areas in and around the city of Arequipa. Land cover transitions are read from left to right via three letters corresponding to the cover in 1966, 1978, and 2019. "B" is barren, "U" is urban, and "A" is agricultural fields.

Land Cover Transition	Total Area (km^2)	Percent of Total 2019 Urban Landscape
BBU	112.9	65.1%
BUU	10.3	5.9%
UUU	31.9	18.4%
AUU	4.3	2.5%
BAU	1.4	0.8%
AAU	12.6	7.3%

Table 2. Land cover change analyses of agricultural developed areas in and around the city of Arequipa. Land cover transitions are read from left to right via three letters corresponding to the cover in 1966, 1978, and 2019. "B" is barren and "A" is agricultural fields.

Land Cover Transition	Total Area (km^2)	Percent of Total 2019 Agricultural Landscape
BBA	16.5	16.1%
BAA	18.1	17.6%
AAA	68.2	66.3%

In total, agricultural land under cultivation has increased by about a third over the last 53 years with an average rate of increase of +0.6% or 0.65 km^2 per year. This was matched by an average increase in urbanization from 1966 to 1978 of ~0.7% or 1.2 km^2 per year; however, between 1978 and 2019 the rate of urban expansion more than doubled averaging ~1.8% or ~3 km^2 per year. Over two thirds of the agricultural fields date back to at least 1966, and 84% date back to at least 1978. Most of the urban developed areas are far newer, with 82% of the area more recent than 1966 and 73% more recent than 1978, reflecting a large influx of people in the last forty years.

Urban expansion is a concern because it draws upon surface or subsurface water sources and potential for water pollution downstream from cities (Carpio and Fath 2011). Latin America experienced large increases in urbanization from the 1930s to the 1970s, with over 45% of urban growth attributed to internal migration from rural to urban areas (Rodriguez-Vignoli and Rowe 2018). Most of this migration was focused to a few, large urban areas (Zlotnik 1994), spurred by the lack of educational and employment options in rural areas (ECLAC 2012). This can be seen in Peru, where economic troubles and political violence in the 1980s led to increased internal rural to urban migration largely focused in the cities of Lima, Callao, Chiclayo, Trujillo, Chimbote, and Arequipa (Durand 2010). Urban centers in Peru continue to have large rates of urbanization, with the province of Arequipa experiencing a population growth from approximately 677,000 in 1993 to 1,081,000 inhabitants in 2007 (INEI 2017). These migrants tend to concentrate on the peripherals of the city, forming informal communities. Figure 1 clearly shows increased agricultural and urban areas from 1966 to 2019, with particular increases in peri-urban sprawl from 1978 to 2019.

The Region of Arequipa is made up of 29 districts, of which five contain 54% of the provincial population (MPA 2016). Four of these, Alto Selva Alegre, Cayma, Cerro Colorado, and Socabaya, were either predominantly agricultural or undeveloped land, as seen in the Corona imagery in 1966 (Figure 1). Cayma, in the northeastern portion of Figure 1, serves as an interesting case study on urbanization in Arequipa. The central part of Cayma is inhabited by traditional farmers, and their ancestral fields are being encroached on from the south by the urban expansion of Arequipa's city center, and from the north, where informal migrant communities are forming in previously unoccupied areas. This expansion has led to differential socioeconomic levels in the district. According to a governmental study, the southern portion of the district, near the city center, has the highest socioeconomic status, the middle of the district occupied by traditional farmers has a medium-low socioeconomic status, and the northern portion of Cayma, settled by migrant communities, represents the lowest socioeconomic classes (MPA 2016). Since the migrant communities are not legally established and are not recognized by the government, they do not have formal water or sewage services.

Historic imagery can aid in determining how these informal settlements have formed over time, particularly when there are no historic governmental records, and can also help in governmental planning and resource allocation. Imagery can also help in establishing more precise dates, locations, and extents of city land cover to evaluate anecdotal information provided by residents. For instance, when talking to farmers in Alto Cural (part of the district of Cerro Colorado) about when farming began on their plots, dates provided spanned many decades and were almost unanimously before 1978 when Keyhole imagery clearly shows that irrigation had not yet expanded to this area (Figure 1). Farming in Arequipa was developed over centuries, and the information provided by historic imagery can provide valuable information on how these lands have developed over the last 60 years, assisting in evaluation of spatial variation in soil properties and crop yield. Since Arequipa is a water scarce region, the historic imagery can also provide information to various stakeholders on water needs, allocation, and future projections.

Rural Agricultural Development

In addition to tracking urban development, high-resolution satellite imagery can provide information about less populous rural areas experiencing agricultural expansion and changing water use (Nellis, Lulla, and Jensen 1990; Naylor 2011). Moving west across the Arequipa Region towards Santa Rita de Siguas, we are confronted by an example of agricultural development in arid sub-optimal soils, the Majes-Siguas project. In 1966, only Santa Rita de Siguas, to the east of what would become the Majes, was under cultivation of ~11.8 km^2 (Figure 2, top). By 2018 the cultivated area of Santa Rita de Siguas would more than double to ~30 km^2, but this agricultural expansion seems minimal in comparison to the Majes agricultural development (Maos 1985). Totaling ~166 km^2 in 2018, Majes, along with the expansion of Santa Rita de Siguas, increased agricultural land cover by more than 16 times relative to 1966 (Figure 2, bottom).

Majes-Siguas is located in the hyper-arid rain shadow of the Andes Mountains (Alva et al. 1976; Stark, Guillén, and Brady 2012), receiving only 6 mm of annual precipitation and 519 $cal^{-1}cm^{-1}min^{-1}$ of solar radiation (Gobierno Regional Arequipa 2016; Moraes et al. In preparation for submission). Although the total Peruvian area in this rain shadow contains the two largest cities in the country and over one third of Peru's population, agriculture has been limited, as the area contains only 1.8% of Peru's water (Alva et al. 1976; Hendriks 2009). The Peruvian government has worked to enhance and regulate the distribution of water spatially and temporally through dams and other hydraulic infrastructure to irrigate arid uplands (Maos 1985; Hendriks 2009). This expansion and its impact can be mapped and tracked through historic, remotely sensed images. Figure 2 shows the result of irrigation expansion in the Majes-Siguas agricultural fields after the massive hydrologic engineering completion of tunnels and canals for water transport between 1971 and 1982. The

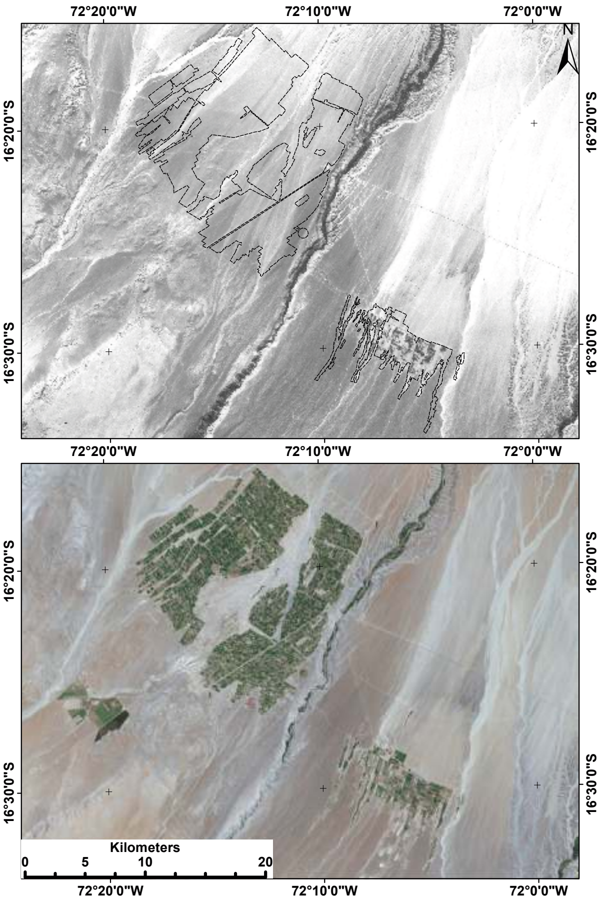


Figure 2. Rural agricultural development - Majes-Siguas agricultural development project area in May 1978 (top, KH9-14) and 2018 (bottom, Sentinel 2018 mosaic).

Majes-Siguas irrigation project now provides water to farms managed by nearly 2,700 farmers (Maos 1985; EcoUrbe Consultores 2013).

Such agricultural development necessitates massive water movement and distribution infrastructure with the possible downstream transportation of leached salts, fertilizers, and pesticides into streams and rivers (Russo 1983; Russo 1985; Arnon et al. 2006; Hu et al. 2008, 2010; Aranibar et al. 2011; Andraski et al. 2014; Jin et al. 2015; Shareef et al. 2019; van Es et al. 2020). Access to inexpensive, remotely sensed imagery can provide critical baseline data to assess agricultural development project impacts, especially for hydrologic engineering (Roy et al. 2016). Land managers and policy makers can use such imagery to observe historic and modern programs, quantify both formal and informal farmland expansion, estimate annual crop productivity levels, and plan and evaluate development programs (Osman-Elasha et al. 2006; Roy et al. 2016; Chang 2019). With the pressures of increasing global food demand (Grau and Aide 2008), climate change-induced desertification (Sivakumar 2007), and limited water availability (Stark, Guillén, and Brady 2012), agricultural production often must expand into marginal lands like those found in the Majes-Siguas project (Olesen and Bindi 2002; Smith and Olesen 2010).

Such drastic increases of water input to naturally dry soils can have detrimental environmental impacts, observed via satellite imagery. Agricultural irrigation flushes salts naturally found in these soils and transports them downstream. This can be seen visually in the area of San Camilo, ~30 km southeast from Santa Rita de Siguas (Figure 3). In 1980, salts flushed from agricultural fields then totaling ~16 km^2 had begun to leach and accumulate on soil surfaces as bright white streaks. Water chemistry analyses indicate that the lagoon, formed due to agricultural runoff and leaching over the last several decades, has over twice the dissolved salt concentration of average seawater, leaching from what is now ~22 km^2 of cultivated area. The movement of water through soils is not only a concern through the appearance of brilliant salts or lagoons in Arequipa but also as water enters into major rivers, some of which have been highly engineered to maximize cultivable floodplains.

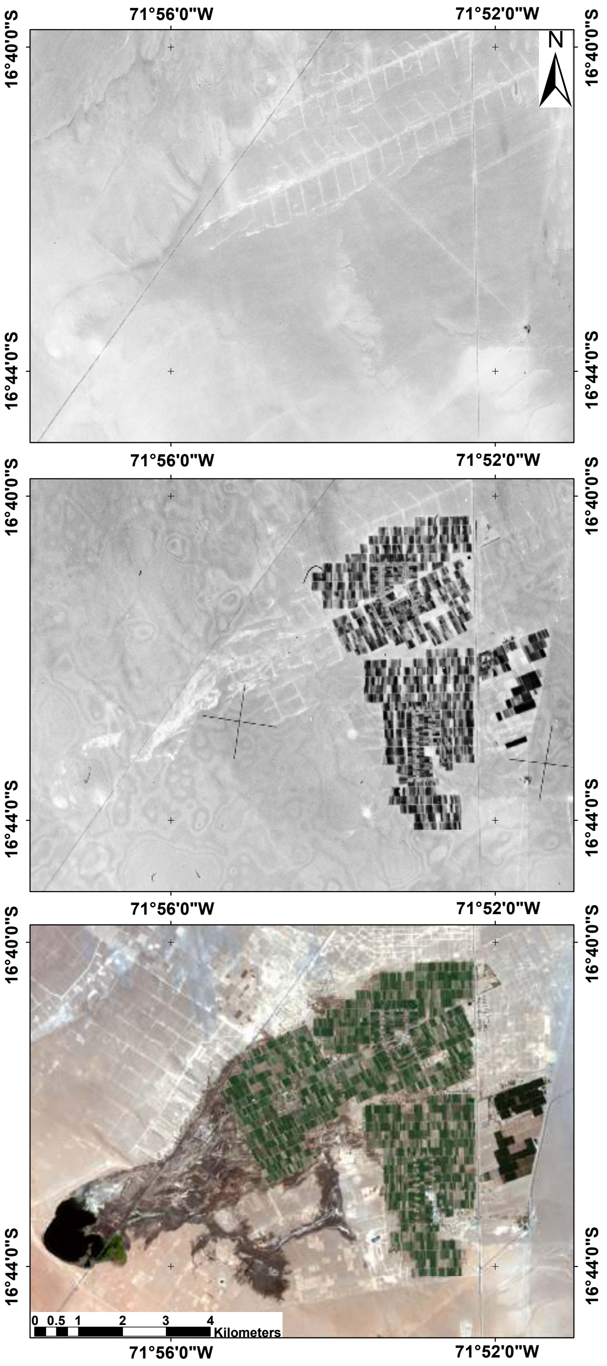


Figure 3. Rural agricultural development - Agricultural development around San Camilo prior to development in 1966 (top, KH-40) with subtle solar illumination of future lagoon topography. Mid-agricultural development in 1980 (middle, KH9-16) with white salts visible derived from agricultural soil leaching and runoff tracing flow path and future lagoon areas. The concentric patterns visible here are Newton's rings and are a result of the film scanning process. Modern 2018 satellite view (bottom, Sentinel mosaic) of agricultural fields, moist saline soils, and saline lagoon.

River Channelization

Aside from the potential leaching of salts, fertilizers, or extracted minerals into rivers and streams, river channelization of braided streams is another major global human hydrological impact (Tockner and Stanford 2002; Kennedy and Turner 2011). West of the Majes-Siguas project flows the Majes River from which the project gets its name. The Majes River lies in a valley which is, in places, up to a kilometer lower in elevation compared to the dissected sloping plateau through which it cuts. Analyses of river bed area change were conducted along ~90 km of the river between the town of Chuquibamba, where a tributary joins the Majes River, and the city of Camaná, where the river reaches the Pacific Ocean. Between 1966 and 2018 the initial meandering braided river bed became extremely channelized and reduced in area by ~62% from ~59 km^2 to just ~22 km^2 in area (Figure 4).

River channelization for floodplain conversion to fields and landscape drainage has had a dramatic impact on stream paths in the valleys of the Region. Valley bottom agriculture has existed in Arequipa since pre-Columbian times (Sandor and Homburg 2017). Fertile alluvial soils and relatively abundant access to water are ideal for crop production. As modern demand for food has increased with the rise of urbanization and population growth in the region, the need for more agricultural land has led land managers to channelize the braided stream beds at the bottom of these valleys. The channelization process has accelerated over the past 60 years in the Rio Majes Valley, shown clearly when comparing 1966 Corona imagery with modern Sentinel imagery. Figure 4 provides a clear example of this in Río Camaná, located directly west of Majes. As discussed by Rosenberg et al. (2005), linear stream channelization has a dramatic impact on channel morphology, sediment transport, and flow characteristics. Changes to flow dynamics and sediment deposition or transport, along with a simple reduction in flood plain area, have almost certainly impacted river shrimp harvests (Alvarez Ocola 2015; Campos León et al. 2017; Medina Rivera 2019; IMARPE 2020) and rice cultivation management (Amesquita et al. 2017; Salazar Ticona 2018), which are principal agricultural products in the District of Camaná. River channelization can also lead to larger flood events and increased damage to crops and communities when river levels rise above their banks or constructed levees. This includes the potential for large changes in sediment delivery to river deltas depending on the nature of channel engineering (Hey and Philippi 1995; Winer 2011). Heavy precipitation or increased flow from snow and glacial meltwater on Coropuna Volcano to the northwest of this channelized streambed may lead to increased stream velocity, channel scouring, and redistribution of material further downstream (Xu 2015). Historic imagery can aid in the quantification of these changes and provide information for future management decisions.

Snowpack and Glaciers

Along with many human-mediated physical changes to the environment we are increasingly

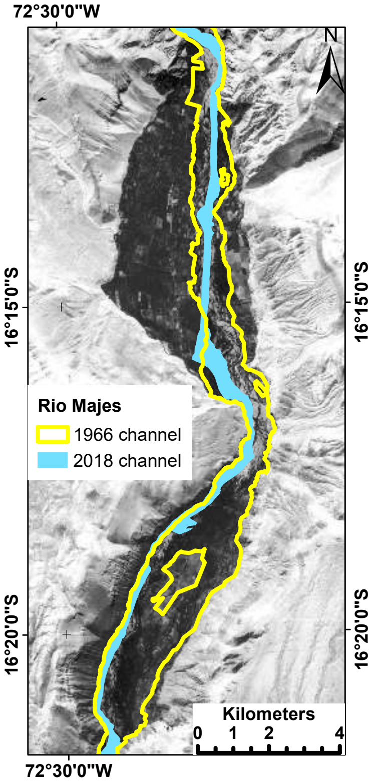


Figure 4. River channelization - A short section of the Majes River west of the Majes agricultural development project in 1966 (left, KH-40) with the historically-braided streambed manually-delineated in yellow and modern 2018 channelized streambed filled in blue. Pronounced reduction of river meanders and channel area is visible along the full length of the river in this region.

seeing and experiencing the impacts of anthropogenic climate change, including loss of snowpack and glaciers (Yao et al. 2012; Laghari 2013; Miles et al. 2013; Moon 2017). Though there is a great focus on these issues in polar regions, it is a global concern in other parts of the world including high-elevation mountainous parts of South America. In the Region of Arequipa, Coropuna is a 6,377 m high dormant stratovolcano, 150 km northwest of the city of Arequipa (Venturelli et al. 1978; Bromley et al. 2011). Based on our analyses of historic Keyhole and contemporary Sentinel satellite imagery, from May 1978 to May 2019, respectively, Coropuna total ice and snow cover decreased by ~12.7% from ~88 km^2 to ~77 km^2. It is important to highlight that this does not factor in the depth of ice and snow cover. Coropuna has the thickest and most extensive ice cap in the Earth's tropical zone (Kochtitzky et al. 2018). It has been estimated that the ice cap has been shrinking since around 1850. Figure 5 shows Keyhole imagery of Coropuna in May of 1978 compared to May of 2019, forty-one years later. Though area analyses highlight a loss of some combination of glacial ice and snow, the boxes in Figure 5 highlight areas where visible ice-shelf retreat has taken place over this period of time. While it is expected that the ice cap will remain until 2120 (Kochtitzky et al. 2018), this shrinkage will likely have significant consequences for the local environment, local water security, and the communities which rely on the glacier meltwater downstream. Coropuna lies on the watershed divide of the Ocoña and Majes River basins which supply water for agricultural production in the regions. Tropical glaciers throughout this region also supply water to alpine wetlands, i.e., bofedales, which contain the largest amount of soil carbon in the region (Maldonado-Fonkén 2015; Pérez, Lau, and Schuler 2015; Araya-López et al. 2018). The loss of meltwater could lead to a loss of these wetlands, reduce their ability to buffer and smooth out precipitation to runoff release times, release stored organic matter as CO_2, and reduce available grazing for livestock and local herds of alpaca and vicuña (Kuentz et al. 2011; Stark, Guillén, and Brady 2012; Gałaś, Panajew, and Cuber 2014). Additionally, ~80% of Peru's hydropower capacity is buffered by glacial meltwater. Thus, glacial loss may also impact renewable energy production in Peru (Stark, Guillén, and Brady 2012; Hanshaw and Bookhagen 2014).

Community Engagement

Historic and modern imagery can help with communication of critical findings, collection of social-environmental data, and co-production of knowledge across geographic scales with broad audiences, as implemented by the Arequipa Nexus Institute for Food, Energy, Water, and the Environment (Filley and Polanco Cornejo 2018). Farmers, students, and researchers working with the Arequipa Nexus Institute have responded positively to spatial mapping and satellite imagery in digital and printed formats. Digital imagery presentation and discussion with farmers and

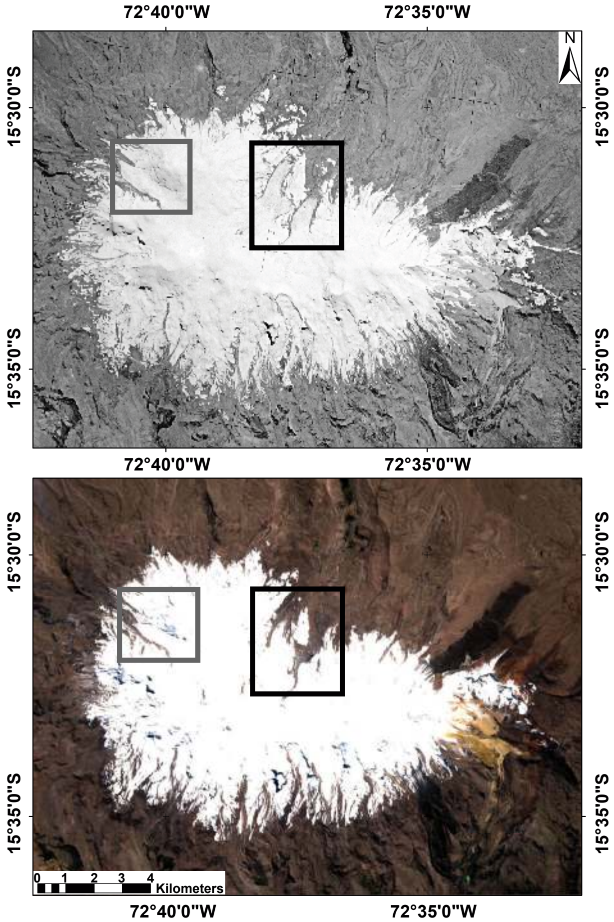


Figure 5. Snowpack and glaciers - Coropuna Volcano viewed from above in May of 1978 (top, KH9-1) and in May of 2019 (bottom, Sentinel). Grey and black boxes are used to highlight several glacial ice flows and reductions in their size through time.

collaborators within the Arequipa Nexus Institute have been implemented primarily via the free Soil Explorer application on iPad. There is also web-based interface available, which allows users to interact easily with packaged map datasets and requires no previous geospatial training (Isee Network 2015-2020; Schulze 2018). Figure 6 is an example of what a user sees in Soil Explorer at the scale of the Arequipa Region, with a user's location in the city of Arequipa indicated in blue. Users can pan and zoom to explore spatial data such as those presented in the figures of this study via tile packages hosted remotely or locally saved to users' Apple iOS and iPadOS devices. The ability to easily incorporate and interact with large satellite imagery datasets has been of great benefit to the Arequipa Nexus Institute during conversations with stakeholders in the field, research planning meetings, formal training workshops, and has greatly enhanced engagement and project-based participation in knowledge co-production and capacity building (Duncan, Kyle, and Race 2010; Sletto et al. 2010; Canevari-Luzardo et al. 2015; Kar et al. 2016; Wachowiak et al. 2017; Kim 2018; Onencan, Meesters, and Van de Walle 2018). Recent field research activities, pairing the use of historic and contemporary satellite imagery in the field with data collection applications like Epicollect (Aanensen et al. 2009) and LandPKS (Herrick et al. 2016), have been very successful. Further, it is our hope that making datasets like the Corona, Keyhole, Sentinel, Landsat, or other satellite imagery freely available in an easy to use format will increase public engagement which, with further discussion and planning, can positively affect management and policy decisions (Duncan, Kyle, and Race 2010; Koti 2010; Yates and Schoeman 2013; Kar et al. 2016).

Looking forward, accessible and affordable historic and contemporary imagery can enhance awareness and accountability for environmental impacts and disruptions which might otherwise go undiscovered. During visits to Arequipa, Peru, Soil Explorer was used to show irrigation commissions imagery regarding the history of agricultural expansion in their districts. These commissions are headed by elected volunteers, usually older members of their community, who may never have

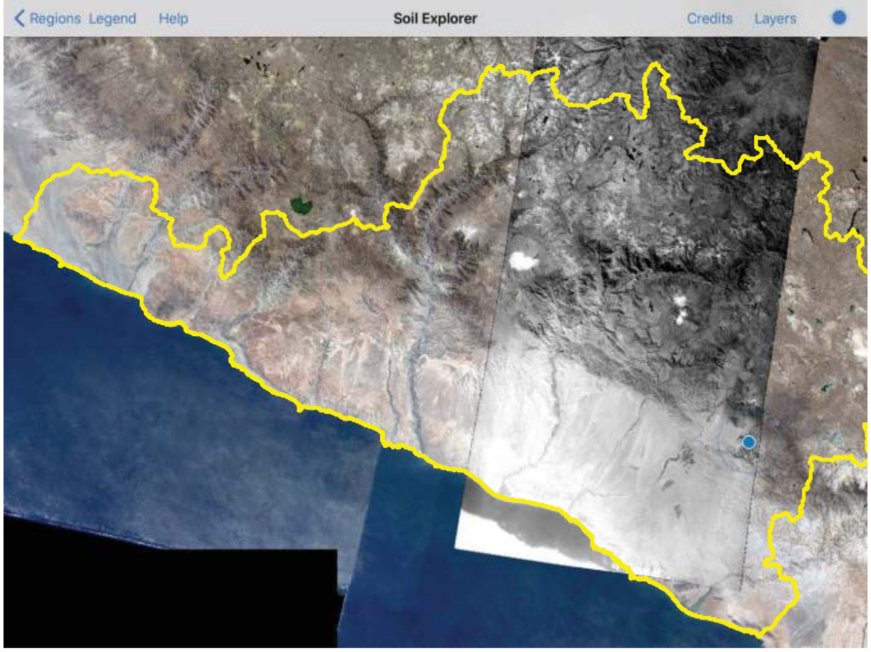


Figure 6. Community engagement - Soil Explorer application screenshot of what a user may see with a 2018 Sentinel mosaic background, Arequipa Region outlined in yellow, and 1978 Keyhole (KH9-14) georectified image strip tile packages loaded on an iPad. The blue dot near the right edge of the 1978 image indicates the GPS location of a user in the city of Arequipa.

seen spatial imagery but have experienced the history personally. These elected stakeholders offer a unique insight for validation of environmental histories, as detailed in White, Kingston, and Barker (2010). This can highlight the utility of this type of historic spatial data, both in providing information to stakeholders and building collaborative teams in applied multidisciplinary and transcontinental partnerships (Filley and Polanco Cornejo 2018).

Conclusions

Arequipa, like much of the world, faces a diversity of new and evolving human-caused environmental challenges related to water quality and availability. Processes of urbanization, migration, irrigation, and salinization following intensive agricultural development are linked by water, as are the flows of melting glaciers and snowpack into channelized rivers more prone to flooding farms and cities. Here, we have demonstrated and discussed the utility of historic satellite imagery, paired with modern Earth observation, to document and quantify environmental change through a series of small illustrative case studies in the Arequipa Region of Peru. The incredibly low cost of historic Corona and Keyhole satellite imagery makes them an excellent initial or supporting data source for environmental research. The potential value and utility of historic imagery like Corona and Keyhole is perhaps highest in areas where records are sparse or nonexistent, due to inadequate monitoring or nonpoint sourced human impacts. The use of imagery and mapping to capture spatial environmental history is not limited to academic research. Imagery like Corona and Keyhole can be used to educate and empower citizens, managers, and researchers by providing them with tangible documentation of the history of their surrounding landscape, in formats accessible to non-specialists.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín. PlanetScope imagery was provided courtesy of Planet Labs, Inc.

Author Bio and Contact Information

Zachary Brecheisen (corresponding author) is a "critical-zonist" interested in how ecosystems respond to human disturbance, especially agriculture and old-field succession. He pairs remote sensing with field observations to enhance soils and forestry investigations. His research includes land cover classification, geomorphic terrain analyses, gas chromatography, 3D printing, X-ray computed tomography, and data logging environmental sensors. His academic training from undergraduate (NMSU) through graduate (Duke University) education to postdoctoral research (Purdue University) has been inherently cross-disciplinary as he has worked with researchers from earth sciences, social sciences, and the humanities as part of the Critical Zone Observatory network and currently the Arequipa Nexus Institute. He may be reached at zbrechei@purdue.edu.

Nicholas G. Hamp-Adams is a senior in the College of Science at Purdue University. He is currently pursuing a Bachelor of Science in Environmental Geoscience expecting to graduate in December 2020. Nicholas started research with the Arequipa Nexus Institute in the summer of 2019 and has focused on mosaicking, georectifying, and analyzing Corona and Keyhole imagery. This is with the goal of understanding and quantifying how land cover has changed through time across the Region of Arequipa, Peru.

Abigail Tomasek received her Ph.D. in Civil Engineering in 2017 from the University of Minnesota. Her research has largely focused on how anthropogenic activities have affected water quality and flow. For her dissertation, she researched the driving parameters of microbial denitrification and investigated how potential management strategies could reduce nitrate loads in agricultural watersheds in Minnesota. She is currently a postdoctoral researcher in Agricultural and Biological Engineering at Purdue University and is researching the linkages between the social, environmental, and economic challenges facing urban agriculture in Arequipa, Peru.

Erika J. Foster is a Soil Agroecologist researching the response of soil biogeochemistry to management. She quantifies the accumulation and stabilization of organic matter under agricultural systems in arid environments. As an investigator within the Arequipa Nexus Institute she works within a massive irrigation project in a hyper-arid region of southern Peru to develop an agricultural chronosequence of carbon development. Dr. Foster compiled and designed a soil health field test kit for small shareholder farmers of the region to combine with rapid scans of elemental content (pXRF) and organic carbon (Vis-NIR) to contribute to digital soil maps.

Timothy Filley is a professor of stable isotope biogeochemistry in the Department of Earth, Atmospheric, and Planetary Sciences at Purdue University. He is the Director for the Purdue Center for the Environment, the U.S.-China EcoPartnership for Environmental Sustainability, and co-Director of the Arequipa Nexus Institute. Filley's research focuses on carbon and nitrogen cycling in natural and managed ecosystems and implications of emerging pollutants. His group investigates how ecosystem disturbance affects soil organic matter stability. Filley received his B.S. in chemistry from Loyola University of Chicago and his Ph.D. in isotope geochemistry from Pennsylvania State University.

Martín J.C. Villalta Soto received his bachelor's degree in Agricultural Sciences in 1988, title of Agricultural Engineer in 1989, Master in Agroecology in 2007 at the Peruvian National University San Agustín de Arequipa (UNSA), and Postgraduate Course in Edaphology in Spain (1996). He became Head of Edaphology Practices at UNSA in 1989 and is currently a professor of Edaphology, Soil Fertility, Soil Management and Conservation. He participates in Agricultural Research and Extension in the High Andean zones (1989); Collection of soil monoliths INIAA - ISRIC (1991); Agricultural Soil Analysis Service (1990-1995) School of Agronomy-UNSA; and Soil Health and Vulnerability Assessment UNSA-Purdue (2018-2020).

Lucia Zuniga is currently a master's student in the department of Earth, Atmospheric and Planetary Science at Purdue University expecting to graduate in August 2020. Lucia did her undergraduate degree in natural resources and environmental science with concentration in resource conservation and ecological restoration at University of Illinois - Urbana-Champaign. Lucia is researching the accumulation of carbon and heavy metals in the arid environment in Majes Irrigation, Arequipa, Perú.

Andre Geraldo de Lima Moraes was born in Muzambinho, Minas Gerais, Brazil, and concluded his bachelor's degree in Agronomy (2011), Masters (2013), and Ph.D. (2018) in Agronomy-Soil Science (CPGA-CS) at the Federal Rural University of Rio de Janeiro (UFRRJ). Currently, he is a postdoc at the Agriculture and Biologic Engineering (ABE) Department at Purdue University. Research interests include soil management and conservation, genesis, morphology, survey, classification, digital soil mapping, erosion and infiltration spatial modeling, climate mapping, climate trend analysis, and general applications of remote sensing and GIS.

Darrell Schulze is a Professor of Soil Science at Purdue University. His research and teaching interests include pedology, digital soil mapping, mineralogy, soil chemistry, and international agriculture. He teaches a field-based course titled, Soils and Landscapes, for which he developed an innovative teaching-with-maps approach that is used in various courses at Purdue and elsewhere. He leads the development of Soil Explorer, a soil data visualization platform that is available as an app for iOS and Android and as a website (SoilExplorer.net). His work with the Arequipa Nexus Institute is primarily focused on visualizing soil and landscape data.

References

Aanensen, D.M., D.M. Huntley, E.J. Feil, F. al-Own, and B.G. Spratt. 2009. EpiCollect: Linking smartphones to web applications for epidemiology, ecology and community data collection. *PLoS One* 4(9): e6968. Available at: https://doi.org/10.1371/journal.pone.0006968. Accessed October 26, 2020.

Alizadeh, K. and J.A. Ur. 2007. Formation and destruction of pastoral and irrigation landscapes on the Mughan Steppe, north-western Iran. *Antiquity* 81(311): 148-160.

Alva, C.A., J.G. van Alphen, A. de la Torre, and L. Manrique. 1976. Problemas de Drenaje y Salinidad en la Costa Peruana. International Institute for Land Reclamation and Improvement, Bulletin 16, Wageningen, Netherlands. Available at: https://edepot.wur.nl/59708. Accessed October 26, 2020.

Alvarez Ocola, A.Z. 2015. Estimación del rendimiento máximo sostenible de cryphyops caementarius (molina, 1782) "camarón de rio" en la cuenca del rio ocoña, Arequipa 1999 2012. Thesis, Universidad Nacional de San Agustín de Arequipa. Available at: http://repositorio.unsa.edu.pe/handle/UNSA/417. Accessed October 26, 2020.

Amesquita, B., C. John, J. Alexis, and L. Uchuchoque. 2017. Características y prácticas de las organizaciones de riego y la percepción de los usuarios respecto a las autoridades de la comisión de regantes de Pucchún Sector Norte, Camaná, Arequipa. Thesis, Universidad Nacional de San Agustín de Arequipa. Available at: http://repositorio.unsa.edu.pe/handle/UNSA/7327. Accessed October 26, 2020.

Andraski, B.J., W.A. Jackson, T.L. Welborn, J.K. Bohlke, R. Sevanthi, and D.A. Stonestrom. 2014. Soil, plant, and terrain effects on natural perchlorate distribution in a desert landscape. *Journal of Environmental Quality* 43(3): 980-994. Available at: https://www.

ncbi.nlm.nih.gov/pubmed/25602827. Accessed October 26, 2020.

Aranibar, J.N., P.E. Villagra, M.L. Gomez, E. Jobbágy, M. Quiroga, R.G. Wuilloud, R.P. Monasterio, and A. Guevara. 2011. Nitrate dynamics in the soil and unconfined aquifer in arid groundwater coupled ecosystems of the Monte Desert, Argentina. *Journal of Geophysical Research* 116(G4). Available at: https://doi.org/10.1029/2010jg001618. Accessed October 26, 2020.

Araya-López, R.A., J. Lopatin, F.E. Fassnacht, and H.J. Hernández. 2018. Monitoring Andean high altitude wetlands in central Chile with seasonal optical data: A comparison between Worldview-2 and Sentinel-2 imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* 145: 213-224. Available at: https://doi.org/10.1016/j.isprsjprs.2018.04.001. Accessed October 26, 2020.

Arnon, S., Z. Ronen, A. Yakirevich, and E. Adar. 2006. Evaluation of soil flushing potential for clean-up of desert soil contaminated by industrial wastewater. *Chemosphere* 62(1): 17-25. Available at: https://www.ncbi.nlm.nih.gov/pubmed/15949835. Accessed October 26, 2020.

Bagley, J.E., A.R. Desai, K.J. Harding, P.K. Snyder, and J.A. Foley. 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *Journal of Climate* 27(1): 345-361. Available at: https://doi.org/10.1175/jcli-d-12-00369.1. Accessed October 26, 2020.

Boyle, S.A., C.M. Kennedy, J. Torres, K. Colman, P.E. Perez-Estigarribia, and N.U. de la Sancha. 2014. High-resolution satellite imagery is an important yet underutilized resource in conservation biology. *PLoS One* 9(1): e86908. Available at: https://doi.org/10.1371/journal.pone.0086908. Accessed October 26, 2020.

Bromley, G.R.M., B.L. Hall, K.M. Rademaker, C.E. Todd, and A.E. Racovteanu. 2011. Late Pleistocene snowline fluctuations at Nevado Coropuna (15°S), southern Peruvian Andes. *Journal of Quaternary Science* 26(3): 305-317. Available at: https://doi.org/10.1002/jqs.1455. Accessed October 26, 2020.

Campos León, S., K. Pinazo, P. Gutierrez, and M. Quiroz Ruiz. 2017. Biological and population monitoring of the resource 'river shrimp' Cryphiops caementarius (Molina 1782) in the Majes-Camana and Ocona Rivers. *Instituto del Mar del Peru* 44(3): 442-448.

Canevari-Luzardo, L., J. Bastide, I. Choutet, and D. Liverman. 2015. Using partial participatory GIS in vulnerability and disaster risk reduction in Grenada. *Climate and Development* 9(2): 95-109. Available at: https://doi.org/10.1080/17565529.2015.106759. Accessed October 26, 2020.

Canfield, D.E., A.N. Glazer, and P.G. Falkowski. 2010. The evolution and future of Earth's nitrogen cycle. *Science* 330: 192-196.

Carpio, O.V. and B.D. Fath. 2011. Assessing the environmental impacts of urban growth using land use/land cover, water quality and health indicators: A case study of Arequipa, Peru. *American Journal of Environmental Sciences* 7(2): 90-101.

Casana, J. and J. Cothren. 2008. Stereo analysis, DEM extraction and orthorectification of CORONA satellite imagery: Archaeological applications from the Near East. *Antiquity* 82(317): 732-749.

Castello, L. and M.N. Macedo. 2016. Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology* 22(3): 990-1007. Available at: https://www.ncbi.nlm.nih.gov/pubmed/26700407. Accessed October 26, 2020.

Chang, N-B. (Ed.). 2019. *Environmental Remote Sensing and Systems Analysis.* CRC Press, Boca Raton, FL.

Diringer, S.E., A.J. Berky, M. Marani, E.J. Ortiz, O. Karatum, D.L. Plata, W.K. Pan, and H. Hsu-Kim. 2020. Deforestation due to artisanal and small-scale gold mining exacerbates soil and mercury mobilization in Madre de Dios, Peru. *Environmental Science & Technology* 54(1): 286-296. Available at: https://doi.org/10.1021/acs.est.9b06620. Accessed October 26, 2020.

Duncan, D.H., G. Kyle, and D. Race. 2010. Combining facilitated dialogue and spatial data analysis to compile landscape history. *Environmental Conservation* 37(4): 432-441. Available at: https://doi.org/10.1017/s0376892910000767. Accessed October 26, 2020.

Durand, J. 2010. The Peruvian Diaspora: Portrait of a migratory process. *Latin American Perspectives* 75(5): 12-28.

Economic Commission for Latin America and the Caribbean (ECLAC). 2012. Population, Territory and Sustainable Development. Santiago, Chile. Available at: https://repositorio.cepal.org/bitstream/handle/11362/22426/1/S2012013_en.pdf. Accessed October 26, 2020.

EcoUrbe Consultores. 2013. Plan de Desarrollo Urbano de Ciudad de Majes - Villa el Pedregal 2012-2021. edited by Municipalidad distrital de Majes. Lima, Peru: Ministerio de Vivienda, Construcción y Saneamiento. Available at: https://munimajes.gob.pe/urbano/. Accessed October 26, 2020.

Filley, T. and H.G. Polanco Cornejo. 2018. Arequipa Nexus Institute for Food, Energy, Water and the Environment. Purdue University. Available at: https://www.purdue.edu/discoverypark/arequipa-nexus/en/index.php. Accessed October 27, 2020.

Fowler, M.J.F. 2004. Archaeology through the keyhole: The serendipity effect of aerial reconnaissance revisited. *Interdisciplinary Science Reviews* 29(2): 118-134.

Fowler, M.J.F. 2013. Declassified intelligence satellite photographs. In: *Archaeology from Historical Aerial and Satellite Archives*, W.S. Hanson and I.A. Oltean (Eds.). Springer, New York, NY, pp. 47-66.

Gałaś, A., P. Panajew, and P. Cuber. 2014. Stratovolcanoes in the western Cordillera – Polish scientific expedition to Peru 2003–2012 reconnaissance research. *Geotourism* 37(2): 61-68. Available at: https://doi.org/10.7494/geotour.2014.37.61. Accessed October 27, 2020,

Givens, J.E., X. Huang, and A.K. Jorgenson. 2019. Ecologically unequal exchange: A theory of global environmental injustice. *Sociology Compass* 13(5): e12693. Available at: https://doi.org/10.1111/soc4.12693. Accessed October 27, 2020.

Gobierno Regional Arequipa. 2016. Proyecto Especial Zonificación Ecológica Económica: Elaboración del Estudio de Suelos y la Clasificación de Tierras por su Capicidad de use Mayor en la Región. Edited by Autoridad Regional Ambiental de Arequipa. Arequipa, Peru.

Goossens, R., A. De Wulf, J. Bourgeois, W. Gheyle, and T. Willems. 2006. Satellite imagery and archaeology: The example of CORONA in the Altai Mountains. *Journal of Archaeological Science* 33(6): 745-755. Available at: https://doi.org/10.1016/j.jas.2005.10.010. Accessed October 27, 2020.

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* 202: 18-27.

Grau, H.R. and M. Aide. 2008. Globalization and land-use transitions in Latin America. *Ecology and Society* 13(2): 16.

Guan, C., E. Hasi, P. Zhang, B. Tao, D. Liu, and Y. Zhou. 2017. Parabolic dune development modes according to shape at the southern fringes of the Hobq Desert, Inner Mongolia, China. *Geomorphology* 295: 645-655. Available at: https://doi.org/10.1016/j.geomorph.2017.08.009. Accessed October 27, 2020.

Hamandawana, H., F. Eckardt, and S. Ringrose. 2007. Proposed methodology for georeferencing and mosaicking Corona photographs. *International Journal of Remote Sensing* 28(1): 5-22. Available at: https://doi.org/10.1080/01431160500104400. Accessed October 27, 2020.

Hanshaw, M.N. and B. Bookhagen. 2014. Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. *The Cryosphere* 8(2): 359-376.

Hendriks, J. 2009. Los Grandes Sistemas de Riego y el Cambio Climático: Márgenes y Medidas de Gestión. Ponencia presentada en el Foro Nacional del Agua 2009, Lima, Peru. Available at: https://www.iproga.org.pe/descarga/riegoycambioclimatico.pdf. Accessed October 27, 2020.

Herrick, J.E., A. Beh, E. Barrios, I. Bouvier, M. Coetzee, D. Dent, E. Elias, T. Hengl, J.W. Karl, H. Liniger, J. Matuszak, J.C. Neff, L.W. Ndungu, M. Obersteiner, K.D. Shepherd, K.C. Urama, R. Bosch, and N.P. Webb. 2016. The land-potential knowledge system (landpks): Mobile apps and collaboration for optimizing climate change investments. *Ecosystem Health and Sustainability* 2(3): e01209. Available at: https://doi.org/10.1002/ehs2.1209. Accessed October 27, 2020.

Hey, D.L. and N.S. Philippi. 1995. Flood reduction through wetland restoration: The upper Mississippi River basin as a case history. *Restoration Ecology* 3(1): 4-17.

Hijmans, R.J., J. van Ettenraster, M. Sumner, et al. 2020. Raster: Geographic Data Analysis and Modeling. Version 3.3-13. Available at: https://rdrr.io/cran/raster/. Accesed October 28, 2020.

Hilbert, M. 2016. Big data for development: A review of promises and challenges. *Development Policy Review* 34(1): 135-174.

Hu, K., Y. Li, W. Chen, D. Chen, Y. Wei, R. Edis, B. Li, Y. Huang, and Y. Zhang. 2010. Modeling nitrate leaching and optimizing water and nitrogen management under irrigated maize in desert oases in northwestern China. *Journal of Environmental Quality* 39(2): 667-677. Available at: https://doi.org/10.2134/jeq2009.0204. Accessed October 27, 2020.

Hu, K., B. Li, D. Chen, Y. Zhang, and R. Edis. 2008. Simulation of nitrate leaching under irrigated maize on sandy soil in desert oasis in inner Mongolia, China. *Agricultural Water Management* 95(10): 1180-1188. Available at: https://doi.org/10.1016/j.agwat.2008.05.001. Accessed October 27, 2020.

Instituto Del Mar Del Peru (IMARPE). 2020. Camarón Del Rio. Ministerio de Produccion. Available at: http://www.imarpe.gob.pe/imarpe/index.php?id_seccion=I0131010202010000000000. Accessed October 28, 2020.

Instituto Nacional de Estadsítica e Informática (INEI). 2017. Características de la Población. Available at: https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1539/cap01.pdf. Accessed October 27, 2020.

Integrating Spatial Educational Experiences (Isee) Network. 2015 – 2020. Soil Explorer. Available at: http://SoilExplorer.net. Accessed October 27, 2020.

Jin, Z., Y. Zhu, X. Li, Y. Dong, and Z. An. 2015. Soil N retention and nitrate leaching in three types of dunes in the Mu Us desert of China. *Scientific Reports* 5: 14222. Available at: https://doi.org/10.1038/srep14222. Accessed October 27, 2020.

Kar, B., R. Sieber, M. Haklay, and R. Ghose. 2016. Public participation GIS and participatory GIS in the era of GeoWeb. *The Cartographic Journal* 53(4): 296-299. Available at: https://doi.org/10.1080/00087041.2016.1256963. Accessed October 27, 2020.

Kennedy, T.L. and T.F. Turner. 2011. River channelization reduces nutrient flow and macroinvertebrate diversity at the aquatic terrestrial transition zone. *Ecosphere* 2(3): 1-13. Available at: https://doi.org/10.1890/es11-00047.1. Accessed October 27, 2020.

Khaledian, Y., F. Kiani, S. Ebrahimi, E.C. Brevik, and J. Aitkenhead-Peterson. 2017. Assessment and monitoring of soil degradation during land use change using multivariate analysis. *Land Degradation & Development* 28(1): 128-141. Available at: https://doi.org/10.1002/ldr.2541. Accessed October 27, 2020.

Kim, M. 2018. Project-based community participatory action research using geographic information technologies. *Journal of Geography in Higher Education* 42(1): 61-79. Available at: https://doi.org/10.1080/03098265.2017.1335294. Accessed October 27, 2020.

Kochtitzky, W.H., B.R. Edwards, E.M. Enderlin, J. Marino, and N. Marinque. 2018. Improved estimates of glacier change rates at Nevado Coropuna Ice Cap, Peru. *Journal of Glaciology* 64(244): 175-184. Available at: https://scholar.dickinson.edu/cgi/viewcontent.cgi?article=1915&context=faculty_publications. Accessed October 27, 2020.

Koti, F.T. 2010. Confronting sociospatial exclusion on the fringe of Africa's cities using participatory GIS: Lessons from Athi River Town, Kenya. *Africa Today* 56(3): 62-82. Available at: https://doi.org/10.2979/aft.2010.56.3.62. Accessed October 27, 2020.

Kuentz, A., J-C. Thouret, M-P. Ledru, and M-É. Forget. 2011. Sociétés andines et changements environnementaux depuis 4 000 ans dans la région du Nevado Coropuna (sud du Pérou). *Bulletin de l'Institut Français d'Études Andines* 40(2): 235-257. Available at: https://doi.org/10.4000/bifea.1388. Accessed October 27, 2020.

Lacroix, P., A. Dehecq, and E. Taipe. 2020. Irrigation-triggered landslides in a Peruvian desert caused by modern intensive farming. *Nature Geoscience* 13(1): 56-60. Available at: https://doi.org/10.1038/s41561-019-0500-x. Accessed October 27, 2020.

Laghari, J. 2013. Climate change: Melting glaciers bring energy uncertainty. *Nature* 502(7473): 617-618. Available at: https://doi.org/10.1038/502617a. Accessed October 27, 2020.

Land Info Worldwide Mapping. 2020. LAND INFO Worldwide Mapping Products. Available at: http://landinfo.com/products.htm. Accessed October 27, 2020.

Li, M., E.J. Foster, P.V.V. Le, Q. Yan, A. Stumpf, T. Hou, A.N. Papanicolaou, K.M. Wacha, C.G. Wilson, J. Wang, P. Kumar, and T. Filley. 2020. A new dynamic wetness index (DWI) predicts soil moisture persistence and correlates with key indicators of surface soil geochemistry. *Geoderma* 368: 114239. Available at: https://doi.org/10.1016/j.geoderma.2020.114239. Accessed October 27, 2020.

Lu, C. and H. Tian. 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance. *Earth System Science Data* 9: 181-192. DOI: 10.5194/essd-9-181-2017.

Maldonado-Fonkén, M.S. 2015. An introduction to the bofedales of the Peruvian High Andes. *Mires and Peat* 15: 1-13.

Maos, J.O. 1985. Water resource development and land settlement in southern Peru: The Majes Project. *GeoJournal* 11(1): 69-78. Available at: www.jstor.org/stable/41143514. Accessed October 27, 2020.

McDonald, R.A. 1995. Corona: Success for space reconnaissance, a look into the Cold War, and a revolution for intelligence. *Photogrammetric Engineering and Remote Sensing* 61(6): 689-720.

Medina Rivera, D.E. 2019. Determinación de los aspectos ambientales que afectan a la población de camarón de rio (Cryphiops caementarius) en el Rio Ocoña - Región Arequipa. Thesis, Universidad

Nacional de San Agustín de Arequipa. Available at: http://repositorio.unsa.edu.pe/handle/UNSA/9659. Accessed October 27, 2020.

Miles, B.W., C.R. Stokes, A. Vieli, and N.J. Cox. 2013. Rapid, climate-driven changes in outlet glaciers on the Pacific coast of East Antarctica. *Nature* 500: 563-566. Available at: https://doi.org/10.1038/nature12382. Accessed October 27, 2020.

Moon, T. 2017. Saying goodbye to glaciers. *Science* 356(6338): 580-581.

Moraes, A.G.L., K.A. Cherkauer, L.C. Bowling, and C.R.Z. Velarde. In preparation for submission. Terrain sensitive mapping for Arequipa Department in Peru.

Municipalidad Provincial de Arequipampa (MPA). 2016. Plan de Desarrollo Local Concertado de Arequipa 2016-2021. Available at: https://www.muniarequipa.gob.pe/descargas/transparencia/pdlc/PDLC.pdf. Accessed October 27, 2020.

Naylor, R. 2011. Expanding the boundaries of agricultural development. *Food Security* 3(2): 233-251. Available at: https://doi.org/10.1007/s12571-011-0123-6. Accessed October 27, 2020.

Nellis, M.D., K. Lulla, and J. Jensen. 1990. Interfacing geographic information systems and remote sensing for rural land-use analysis. *Photogrammetric Engineering and Remote Sensing* 56(3): 329-331.

Ochoa-Tocachi, B.F., W. Buytaert, B. De Bièvre, R. Célleri, P. Crespo, M. Villacís, C.A. Llerena, L. Acosta, M. Villazón, M. Guallpa, J. Gil-Ríos, P. Fuentes, D. Olaya, P. Viñas, G. Rojas, and S. Arias. 2016. Impacts of land use on the hydrological response of tropical Andean catchments. *Hydrological Processes* 30(22): 4074-4089. Available at: https://doi.org/10.1002/hyp.10980. Accessed October 27, 2020.

Olesen, J.E. and M. Bindi. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy* 16(4): 239-262.

Onencan, A.M., K. Meesters, and B. Van de Walle. 2018. Methodology for participatory GIS risk mapping and citizen science for Solotvyno Salt Mines. *Remote Sensing* 10(11). Available at: https://doi.org/10.3390/rs10111828. Accessed October 27, 2020.

Osman-Elasha, B., N. Goutbi, E. Spanger-Siegfried, B. Dougherty, A. Hanafi, S. Zakieldeen, A. Sanjak, H.A. Atti, and H.M. Elhassan. 2006. Adaptation Strategies to Increase Human Resilience Against Climate Variability and Change: Lessons From the Arid Regions of Sudan. AIACC Working Paper No. 42. Available at: http://chs.ubc.ca/archives/files/Increasing%20Resilience%20to%20Climate%20Change%20in%20Sudan.pdf. Accessed October 27, 2020.

Pebesma, E. 2018. Simple features for R: Standardized support for spatial vector data. *The R Journal* 10(1): 439-446. Available at: https://doi.org/10.32614/RJ-2018-009. Accessed October 27, 2020.

Peng, D., B. Zhang, C. Wu, A.R. Huete, A. Gonsamo, L. Lei, G.E. Ponce-Campos, X. Liu, and Y. Wu. 2017. Country-level net primary production distribution and response to drought and land cover change. *Science of the Total Environment* 574: 65-77. Available at: https://doi.org/10.1016/j.scitotenv.2016.09.033. Accessed October 27, 2020.

Pérez, G.S., J.C. Hernani Lau, and M.S. Schuler. 2015. Biorestoration of Andean wetlands in Peru gas pipeline. In: *SPE Latin American and Caribbean Health, Safety, Environment and Sustainability Conference*, Bogotá, Colombia, 7-8 July.

Perry, R. 1973. A History of Satellite Reconnosance, Volume 1. Central Intelegence Agency, National Reconnaissance Office.

Planet Labs, Inc. 2020. Planet Products. Available at: https://www.planet.com/products/. Accessed October 27, 2020.

Pope, A., W. Gareth-Rees, A. Fox, and A. Fleming. 2014. Open access data in polar and cryospheric remote sensing. *Remote Sensing* 6(7): 6183-6220. Available at: https://doi.org/10.3390/rs6076183. Accessed October 27, 2020.

R Core Team. 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.r-project.org/. Accessed October 28, 2020.

Rodriguez-Vignoli, J. and F. Rowe. 2018. How is internal migration reshaping metropolitan populations in Latin America? A new method and new evidence. *Population Studies* 72(2): 253-273. Available at: https://doi.org/10.1080/00324728.2017.1416155. Accessed October 28, 2020.

Rogger, M., M. Agnoletti, A. Alaoui, J.C. Bathurst, G. Bodner, M. Borga, V. Chaplot, F. Gallart, G. Glatzel, J. Hall, J. Holden, L. Holko, R. Horn, A. Kiss, S. Kohnova, G. Leitinger, B. Lennartz, J. Parajka, R. Perdigao, S. Peth, L. Plavcova, J.N. Quinton, M. Robinson, J.L. Salinas, A. Santoro, J. Szolgay, S. Tron, J.J.H. van den Akker, A. Viglione, and G. Bloschl. 2017. Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources*

Research 53(7): 5209-5219. Available at: https://doi.org/10.1002/2017WR020723. Accessed October 28, 2020.

Rosenberg, D.M., P.A. Chambers, J.M. Culp, W.G. Franzin, P.A. Nelson, A.G. Salki, M.P. Stainton, R.A. Bodaly, and R.W. Newbury. 2005. Nelson and Churchill River basins. In: *Rivers of North America*, A.C. Benke and C.E. Cushing (Eds.). Elsevier Academic Press, pp. 852-901.

Ross, N. and M. Sumner. 2020. Fasterize: Fast Polygon to Raster Conversion. Version 1.0.3. Available at: https://rdrr.io/cran/fasterize/. Accessed October 28, 2020.

Roy, P., J. Chandramohan, K. Vinod Kumar, A. Raj, M. Shaik, V. Bothale, and P.G. Diwakar. 2016. Use of remote sensing and geospatial technique for pre-feasibility analysis of rural water pipeline grids. *Journal of the Indian Society of Remote Sensing* 45(4): 667-672. Available at: https://doi.org/10.1007/s12524-016-0631-0. Accessed October 28, 2020.

Russo, D. 1983. Leaching characteristics of a stony desert soil. *Soil Science Society of America Journal* 47(3): 431-438.

Russo, D. 1985. Leaching and water requirement studies in a gypsiferous desert soil. *Soil Science Society of America Journal* 49(2): 432-437.

Salazar Ticona, O.E. 2018. Centro de innovación tecnológica (CITE) del arroz en el Valle de Camaná. Thesis, Universidad Nacional de San Agustín de Arequipa. Available at: http://repositorio.unsa.edu.pe/handle/UNSA/7292. Accessed October 28, 2020.

Sandor, J.A. and J.A. Homburg. 2017. Anthropogenic soil change in ancient and traditional agricultural fields in arid to semiarid regions of the Americas. *Journal of Ethnobiology* 37(2): 196-217. Available at: https://doi.org/10.2993/0278-0771-37.2.196. Accessed October 28, 2020.

Schlesinger, W.H. and N. Gramenopoulos. 1996. Archival photographs show no climate-induced changes in woody vegetation in the Sudan, 1943–1994*. *Global Change Biology* 2(2): 137-141.

Schulze, D.G. 2018. Soil Explorer: Soils and Landscapes at Your Fingertips. Geological Society of America (GSA), Boulder, CO.

Sevara, C., G. Verhoeven, M. Doneus, and E. Draganits. 2018. Surfaces from the visual past: Recovering high-resolution terrain data from historic aerial imagery for multitemporal landscape analysis. *Journal of Archaeological Method and Theory* 25(2): 611-642. Available at: https://doi.org/10.1007/s10816-017-9348-9. Accessed October 28, 2020.

Shareef, M., D. Gui, F. Zeng, M. Waqas, Z. Ahmed, B. Zhang, H. Iqbal, and J. Xue. 2019. Nitrogen leaching, recovery efficiency, and cotton productivity assessments on desert-sandy soil under various application methods. *Agricultural Water Management* 223: 105716. Available at: https://doi.org/10.1016/j.agwat.2019.105716. Accessed October 28, 2020.

Shroder Jr., J.F. 2005. Glacier and landform change detection, Hindu Kush and western Himalaya, Afghanistan and Pakistan. Geological Society of America (GSA) Salt Lake City Annual Meeting, Salt Lake City, UT.

Sivakumar, M.V.K. 2007. Interactions between climate and desertification. *Agricultural and Forest Meteorology* 142(2-4): 143-155. Available at: https://doi.org/10.1016/j.agrformet.2006.03.025. Accessed October 28, 2020.

Sletto, B., S. Muñoz, S.M. Strange, R.E. Donoso, and M. Thomen. 2010. "El rincón de los olvidados": Participatory GIS, experiential learning and critical pedagogy in Santo Domingo, Dominican Republic. *Journal of Latin American Geography* 9(3): 111-135.

Smith, P. and J.E. Olesen. 2010. Synergies between the mitigation of, and adaptation to, climate change in agriculture. *The Journal of Agricultural Science* 148(5): 543-552. Available at: https://doi.org/10.1017/s0021859610000341. Accessed October 28, 2020.

Stark, J., S. Guillén, and C. Brady. 2012. Follow the Water: Emerging Issues of Climate Change and Conflict in Peru. CMM Discussion Paper No. 5, United States Agency for International Development, Washington, D.C. Available at: https://www.climatelinks.org/sites/default/files/asset/document/FollowWater-EmergingIssue_of_Climate_Change%2520_Conflic_Peru.pdf. Accessed October 28, 2020.

Tockner, K. and J.A. Stanford. 2002. Riverine flood plains: Present state and future trends. *Environmental Conservation* 29(3): 308-330. Available at: https://doi.org/10.1017/s037689290200022x. Accessed October 28, 2020.

United States Geological Survey (USGS). 2016. EarthExplorer. Available at: http://earthexplorer.usgs.gov/. Accessed October 28, 2020.

Ur, J. 2003. CORONA satellite photography and ancient road networks: A northern Mesopotamian case study. *Antiquity* 77(295): 102-115.

van Es, H., A. Ristow, M. Renato Nunes, R. Schindelbeck, S. Sela, and M. Davis. 2020. Nitrate leaching reduced with dynamic-adaptive nitrogen management under contrasting soils and tillage. *Soil Science Society of America Journal* 84(1): 220-231. Available at: https://doi.org/10.1002/saj2.20031. Accessed October 26, 2020.

VanDerWal, J., L. Falconi, S. Januchowski, L. Shoo and C. Storlie. 2019. Species Distribution Modelling Tools: Tools for Processing Data Associated with Species Distribution Modelling Exercises, Version1.1-221. Available at: https://rdrr.io/cran/SDMTools/. Accessed October 28, 2020.

Venturelli, G., M. Fragipane, M. Weibel, and D. Antiga. 1978. Trace element distribution in the cainozoic lavas of Nevado Coropuna and Andagua Valley, Central Andes of southern Peru. *Bulletin Volcanologique* 41(3): 213-228.

Wachowiak, M.P., D.F. Walters, J.M. Kovacs, R. Wachowiak-Smolíková, and A.L. James. 2017. Visual analytics and remote sensing imagery to support community-based research for precision agriculture in emerging areas. *Computers and Electronics in Agriculture* 143: 149-164. Available at: https://doi.org/10.1016/j.compag.2017.09.035. Accessed October 28, 2020.

Wang, M., D.Q. Zhang, J. Su, J.W. Dong, and S.K. Tan. 2018. Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling. *Journal of Cleaner Production* 179: 12-23. Available at: https://doi.org/10.1016/j.jclepro.2018.01.096. Accessed October 28, 2020.

White, I., R. Kingston, and A. Barker. 2010. Participatory geographic information systems and public engagement within flood risk management. *Journal of Flood Risk Management* 3(4): 337-346.

Winer, H.S. 2011. Re-engineering the Mississippi River as a sediment delivery system. *Journal of Coastal Research* 59: 229-234. Available at: https://doi.org/10.2112/si59-024.1. Accessed October 28, 2020.

Xu, J. 2015. A study of the scour-fill threshold based on Lane's equilibrium relation: The lower Yellow River. *Geomorphology* 250: 140-146. Available at: https://doi.org/10.1016/j.geomorph.2015.08.009. Accessed October 28, 2020.

Yao, T., L. Thompson, W. Yang, W. Yu, Y. Gao, X. Guo, X. Yang, K. Duan, H. Zhao, B. Xu, J. Pu, A. Lu, Y. Xiang, D.B. Kattel, and D. Joswiak. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change* 2(9): 663-667. Available at: https://doi.org/10.1038/nclimate1580. Accessed October 28, 2020.

Yates, K.L. and D.S. Schoeman. 2013. Spatial access priority mapping (SAPM) with fishers: A quantitative GIS method for participatory planning. *PLoS One* 8(7): e68424. Available at: https://doi.org/10.1371/journal.pone.0068424. Accessed October 28, 2020.

Zlotnik, H. 1994. Expert group meeting on population distribution and migration. *The International Migration Review* 28(1): 171-204. Available at: https://doi.org/10.2307/2547032. Accessed October 28, 2020.

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 171, Pages 93-110, December 2020

Integrated Hydrologic and Hydraulic Analysis of Torrential Flood Hazard in Arequipa, Peru

*Katy E. Mazer[1], Abigail A. Tomasek[2], Fariborz Daneshvar[2], Laura C. Bowling[1], Jane R. Frankenberger[2], Sara K. McMillan[2], Hector M. Novoa[3], and Carlos Zeballos-Velarde[4]

*[1]Department of Agronomy, Purdue University, West Lafayette, IN, USA; [2]Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN, USA; [3]Faculty of Civil Engineering, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; [4]Faculty of Architecture and Urbanism, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; *Corresponding Author*

Abstract: Seated at the foot of the Misti volcano in an area prone to intense seasonal rains and earthquakes, the city of Arequipa is highly vulnerable to natural disasters. During the rainy season, intense storms create large volumes of runoff that rush through the city's ephemeral streams, known locally as *torrenteras*. Episodic flows in these *torrenteras* have caused flooding, damage to bridges, homes, and other infrastructure, and caused many deaths. In recent years, while unprecedented rain events have caused extreme disasters, the city's population has continued to expand into these channels by creating informal or illegal settlements. Currently, detailed hazard maps of flood-prone areas surrounding the *torrenteras* are not available to stakeholders in Arequipa. In this study, hydrologic and hydraulic models were combined to assess flash flood hazards, including inundation, velocity hazards, and slope instability hazards. Hydrologic models were created using satellite precipitation data and terrain-sensitive, gridded climate maps to characterize flow within six *torrenteras* in Arequipa. These flows were used in conjunction with elevation data and data collected in the field using an online mobile application system to develop a hydraulic model of these flood events. Hydraulic model outputs were used to determine flood hazards related to inundation, velocity affecting human stability, and slope instability in case study areas of the *torrenteras*. We then discuss how this information can be used by disaster risk management groups, water authorities, planners and municipalities, and community groups.

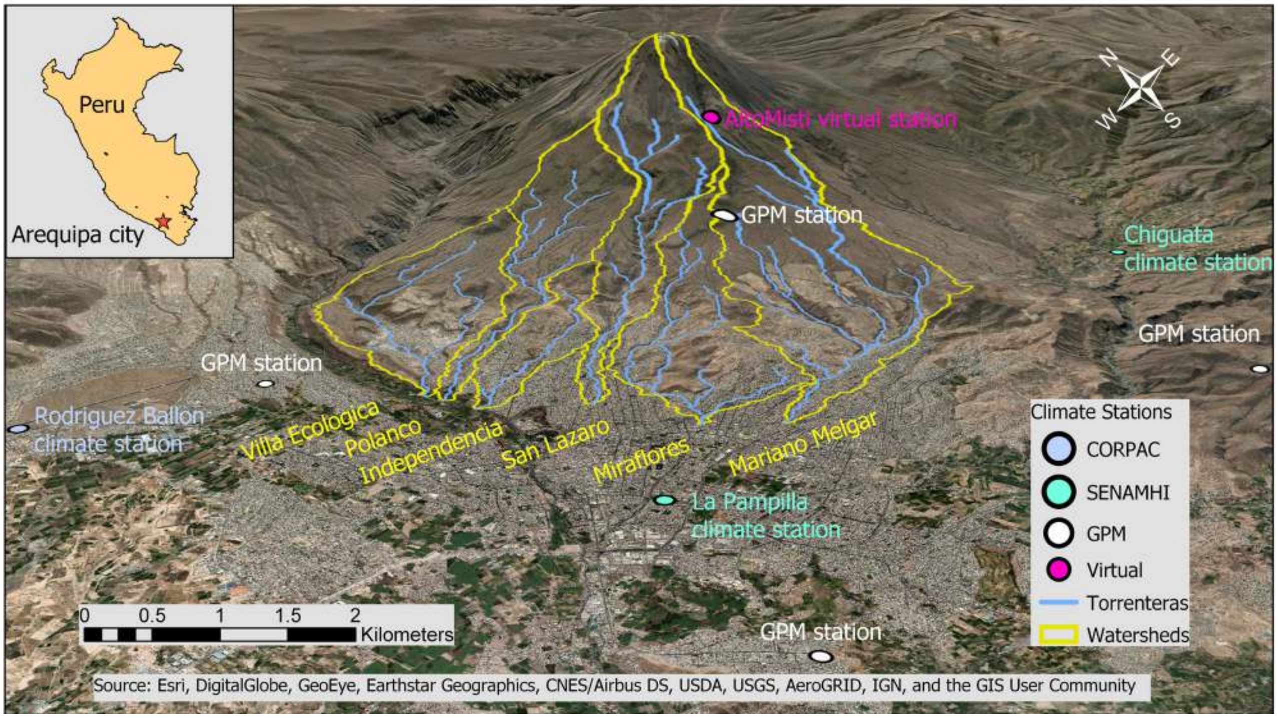
Keywords: *torrenteras, hydrologic modeling, hydraulic modeling, flash floods, inundation, velocity, slope instability, hazard maps*

Arequipa, the second largest city in Peru, is located at the foot of El Misti volcano. Rain that falls on the eastern side of the mountain drains through the city in ephemeral stream channels as destructive flash floods. Although annual precipitation within the city ranges from 100 - 150 mm on average, torrential flows occur during the rainy season through the channels that extend from their source on the mountain where rainfall is higher (Figure 1). These channels or ravines are known locally as "*torrenteras,*" signifying not only their channel shape but also the torrential flows that occur in these channels after intense rainfall. Six major *torrenteras* flow through the lower elevations of the mountainside, where residential development is increasing, and into the core of the city. Local names of each *torrentera* will be used throughout this paper (Figure 1), though common names may change further downstream.

Flash floods in the *torrenteras* of Arequipa have had devastating effects on the city's population throughout its history. Nine events that caused severe damage occurring from 1961 to 2011 were summarized by Martelli (2011) from government and other records. An exceptional flood occurred on February 8, 2013 due to a rainfall of 123 mm in three hours (Cacya et al. 2013), causing five deaths and adversely affecting thousands more people (SINPAD 2013). As the city has continued to grow, some structures have been built close to or even within the *torrenteras*, adding to the devastation that floods can cause (Thouret et al. 2013).

In this paper, we define hazards as geophysical features or processes that can cause drastic changes to a landscape. Hazards become risks when they affect people or infrastructure and are amplified when those affected are more vulnerable either due to socioeconomic, health, or simply proximity to the hazard itself. Flash floods are among the highest risk weather-related phenomena in cities around the world, resulting in more than 15,600 fatalities in China from 2000 to 2015 (He et al. 2018), and 278 deaths in the United States during an eight-year period ending in 2015 (Gourley et al. 2017), for example. In addition to the potential for inundation, floodwaters present other dangers, including water velocity hazards that can endanger humans (Jonkman and Penning-Rowsell 2008) and vehicles (Martinez-Gomariz et al. 2016), and slope instability hazards that threaten surrounding infrastructure due to bank failure (Magilligan et al. 2015). Flood hazards are projected to increase in the future in many regions from increasing precipitation intensity and changes in land cover affected by climate change and population growth, potentially leading to heavy human and economic losses in these communities (Muller 2007). It is generally not possible to eradicate these precipitation-driven flood hazards; instead, the risk management strategy usually focuses on reducing vulnerability by informing the public and enacting policies that discourage encroachment into the channels where these hazards are likely to occur. In Arequipa, current regulations limiting construction are based solely on the distance from the edge of the *torrenteras*, but do not account for the varying characteristics of flows and flood hazard (Republica de Perú 2016).

Although flood hazards from the *torrenteras* have been studied in the past, these have been based on topography and geomorphology of the landscape because no discharge monitoring data are available. Thouret et al. (2013) studied flash floods and lahars (volcanic mudflows) in the Rio Chili, the main river that runs through the city of Arequipa, and two of the *torrenteras*, which they



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. *Torrentera* flow paths from El Misti through the city of Arequipa and climate stations used for analysis.

call *quebradas* (San Lázaro and Mariano Melgar in this study, called Huarangal in their study) to create hazard maps. However, the morphology-based analysis from this study does not allow for examining changes over time, which instead requires hydrologic and hydraulic modeling based on observed and projected changes in precipitation.

Developing flood hazard maps is generally a two-step process, requiring first a hydrologic analysis to determine the magnitude of low-probability (i.e., 100-year) storm discharge, and then using a hydraulic model to estimate flow depth for the discharge of concern. In watersheds such as the *torrenteras* for which no discharge data exist, hydrologic models that compute discharge on the basis of rainfall and watershed characteristics such as land cover, soil, and slope, are used to estimate flow. Hydraulic models can use the modeled discharge together with high-resolution channel elevation data to calculate flood depth and predict hazards. However, data scarcity often limits the application of these powerful tools. For this project, high-resolution elevation data captured by an unmanned aircraft system (drone) were available for a section of the six *torrenteras*, providing a unique opportunity for hydraulic modeling.

Providing useful data to decision-makers is a primary purpose of a modeling study such as this. In Arequipa, four types of stakeholders would benefit from this type of flood modeling. The types of activities for which they are responsible are as follows:

- **Disaster risk management**: Peru's Law No. 29664 created the National Disaster Risk Management System (SINAGERD) as well as two institutions related to risk management: the National Center for Estimation, Prevention and Reduction of Disaster Risk (CENEPRED), responsible for disaster prevention and post-disaster reconstruction; and the National Civil Defense Institute (INDECI), responsible for emergency response activities.
- **Water authority**: Water courses are regulated in Peru by the National Water Authority (ANA), and its local branch the Local Water Authority (ALA), which is responsible for determining the flood boundaries and buffer zones for limited development.
- **Municipalities and planners:** The Urban Development Department, Office of Disaster Risk Management and Civil Defense, and the Office of the Environment prepare and respond to disaster events, while the Inspections Office works to limit new informal settlements in the area of the *torrenteras*. In the event of a major disaster, the municipality coordinates with the National Government and the Ministry of Housing and Construction on reconstruction.
- **Communities**: People who live in the affected communities are grouped into brigades and organized to prepare for disasters through citizen security committees. Zeballos-Velarde et al. (2019) found that community groups identify areas in Arequipa with critical environmental problems, but their perception of the spatial extents of flood impacts is often distorted.

These stakeholders are interested in acting effectively to reduce risk, but do not have access to information needed to make decisions. A detailed study would aid development planning by defining areas that are at risk and areas where complementary activities could be carried out to transform specific locations within the *torrenteras* from marginal lands into recreational spaces.

The goal of this study is to provide information on flood hazards in the six *torrenteras* of Arequipa that is useful to these stakeholders. The objectives of this study were to 1) analyze precipitation patterns and flow magnitude and how they have changed over time, 2) identify locations and extent of flood-related hazards, including inundation, velocity, and slope instability, and 3) discuss relevance for multiple stakeholder groups. Analysis of precipitation records and sub-daily estimates from satellite data provided input for the hydrologic model, resulting in long-term discharge estimates for each *torrentera*. The discharge estimates were used as inputs for hydraulic models built for each *torrentera* to estimate flood depths and velocities. Hazard classifications were developed, and examples are shown to demonstrate how stakeholders can use this information.

Methods

Precipitation

Daily precipitation data for two nearby stations were obtained from the National Meteorology and Hydrology Service of Peru (SENAMHI 2019, see Figure 1). SENAMHI climate stations, La Pampilla and Chiguata, were closest to the *torrenteras* and ranged from 2 to 4 km away. A third station, the Rodríguez Ballón airport in the city of Arequipa, is not available in the SENAMHI dataset, but is instead administered by the Peruvian Corporation of Airports and Commercial Aviation (CORPAC). A virtual weather station (hereafter called AltoMisti) was added to provide information of precipitation contributing to the *torrentera* watersheds in the study area (Location: -16.32° W, -71.42° S; Elevation: 4200 m), based on gridded, terrain-corrected climate maps developed from SENAMHI station data (Moraes et al. 2019).

This analysis required precipitation data at a time scale of hourly or less, because the time of concentration in the *torrenteras* is less than one hour. In recent years, the daily network has been supplemented with sub-daily automated gauges, but most of these gauges currently have a record length of less than five years. Therefore, we disaggregated observed daily precipitation to sub-daily in order to simulate flood response. The GPM_3IMERGHH_v06 (hereafter referred to as GPM) satellite precipitation product, available globally at 30-minute temporal resolution and 0.1 degree spatial resolution, was downloaded for grid cells corresponding to the three SENHAMI precipitation gauges and one synthetic gauge, and adjusted from Coordinated Universal Time (UTC) to Peruvian Standard Time (UTC-5) (Huffman et al. 2019). The data period of overlap with the SENHAMI stations was 6/1/2000 - 12/31/2017. Quality control screening for the GPM data included setting precipitation to zero for all 30-minute intervals in the days for which the corresponding station precipitation was zero. Additionally, if the accumulated daily intensity in the GPM data exceeded the maximum intensity observed at the corresponding daily station for the 17 years of overlap, all 30-minute values on that date were rescaled. The quality controlled GPM data were bias-corrected with respect to the station observations using linear scaling with the ratio of accumulated station precipitation to GPM precipitation (Teutschbein and Seibert 2012).

A 30-minute precipitation time series was created for the period February 1965 - March 2020 by disaggregating the station observations using a point, event-based, rectangular pulse model (Rodriguez-Iturbe et al. 1987). However, rather than simulating storm interarrivals as a Poisson process, the observed daily sequence was used, similar to Bowling et al. (2003). Each daily occurrence is associated with rainfall events of random duration and intensity. The bias-corrected GPM estimations were used to identify the empirical cumulative distribution functions (CDF) of the number of events per day, the event start time, and the event duration. Three different duration CDFs were generated for event depths of < 5 mm, 5-10 mm, and > 10 mm, since event durations tend to be shorter for lower precipitation totals. For each day with observed daily precipitation, the event CDF was sampled randomly to generate the number of events per day. The corresponding start time and duration distributions were then sampled to determine which hours of the day should receive precipitation. Within the identified hours, the observed daily precipitation depth was distributed, using a gaussian window to create a higher intensity peak in the center of the event.

Intensity-frequency diagrams were used to evaluate if the disaggregated dataset preserved characteristics important to flash flood prediction. An Extreme Value type I (EV1) distribution was fit to the maximum 30-minute intensity generated per calendar year, using the method of moments for the period 6/2000 - 12/2017. The ensemble mean frequency curve (from 100 ensemble members) was compared to the one generated from the filtered satellite data. Following verification, the single ensemble member which resulted in a 2000 - 2017 intensity-frequency curve closest to that from the GPM data was selected for further analysis.

Hydrologic Modeling Using SWAT

The Soil and Water Assessment Tool (SWAT) model (Arnold et al. 2013), used around the world for predicting streamflow in ungauged watersheds, was used to simulate flow in the *torrenteras*. SWAT is a comprehensive watershed model that evaluates impacts of land use, land management, and climate change on hydrology and water quality. Its sub-daily simulation option, critical for small watersheds like those of the *torrenteras* (Jeong et al. 2010; Boithias et al. 2017), was employed for this analysis. A radiometrically terrain corrected (RTC) elevation map with a 12.5 m resolution was obtained from the NASA Earth Data (NASA Earth Data 2019). An elevation-based watershed delineation process resulted in the creation of six watersheds (with drainage areas ranging from 5 to 36 km^2), and 79 sub-watersheds and streams (Figure 1). Watershed elevation ranged from 2258 to 5862 m along the steep side-slopes of Misti. Therefore, sub-watersheds were divided by elevation bands to consider orographic effects. Temperature data were taken from the SENAMHI and CORPAC stations and from gridded climate maps developed by Moraes et al. (2019) for the AltoMisti station. Precipitation and temperature of bands were adjusted based on the difference in elevation compared to the nearest weather station. Lapse rates (or change with altitude) of temperature (-6.2 °C/km) and precipitation (220 mm/km) were obtained from gridded climate maps developed by Moraes et al. (2019). Solar radiation, wind speed, and relative humidity simulations with 38 km resolution created by the National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) were downloaded from the Global Weather Data for SWAT (NCEP CFSR 2019).

Soil and land cover properties were estimated from regional maps and soil profiles provided by the Peruvian Ministry of the Environment (Gobierno Regional Arequipa 2016; MINAM 2017) following the methodology developed by Daneshvar et al. (2020a; 2020b). Soil classes were defined based on taxonomy and suitability maps and soil properties were estimated for associated soil profiles. Land cover properties were adapted from similar land cover classes in the SWAT database. Plant growth properties were adjusted based on remotely sensed satellite Leaf Area Index time series and annual temperature maps for the region. Dominant land covers were grassland/shrub (42%), followed by cactus (21%), and urban lands (16%) (Table 1). Overlay of these layers resulted in 610 hydrologic response units (HRUs), which are the smallest subdivision of the SWAT model based on homogeneous combinations of land cover, soil, and slope in each subbasin.

There was no streamflow monitoring station within the watershed for model calibration and validation. Therefore, the same parameters from a neighboring watershed (Daneshvar et al. 2020c) were used. Daneshvar et al. (2020c) also showed that uncertainty of simulated streamflow based on the uncertainty of developed soil and land cover datasets (Daneshvar et al. 2020a; 2020b) is constrained (-7% to 10%) and the SWAT model provides reliable prediction of streamflow. SWAT simulations were conducted from February 1965 to December 2019. The first year of simulation was considered as model warm-up and was not included in further analysis. Model predictions of the 100-year flood for each *torrentera* were evaluated with respect to a regional curve (Moraes et al. 2020). The 54-year simulations (1966–2019) were used to calculate annual water balance ratios and several

Table 1. Watershed characteristics for the six *torrenteras* modeled in this study.

Torrentera	**Watershed area (km^2)**	**Average slope (%)**	**------------- Land cover (%) -------------** **Grassland/shrub**	**Cactus**	**Urban**	**Other***
Villa Ecológica	15.5	20.8	14	58	3	25
Polanco	15.2	24.4	72	15	7	6
Independencia	5.5	18.5	24	10	42	24
San Lázaro	18.5	40.2	46	15	11	28
Miraflores	14.9	18.8	18	21	42	19
Mariano Melgar	36.0	23.3	54	13	13	20

*Includes barren, herbaceous tundra, evergreen trees, and agricultural lands hydrologic metrics including the annual maxima series, the number of peak flow events over a threshold, time of rise during events, and number of days with flow (above 0.1 m^3/s). The SWAT-simulated 100-year floods were estimated by fitting an EV1 distribution to the annual maxima series of the daily average simulated streamflow. The annual maxima series was analyzed for monotonic trends using the non-parametric Mann-Kendall test, with significance level $p = 0.05$ (Helsel et al. 2020).

Local Data Collection

Undergraduate students at the Universidad Nacional de San Agustín de Arequipa took photos in all six *torrenteras* at the 26 bridge locations and at 29 channel sections in areas with no bridges. These photos were georeferenced, described, stored, and shared using Epicollect5, the free mobile data gathering platform. Channel locations visited were selected based on sections that were accessible and representative of that portion of the channel. A Phantom 4 Pro drone collected imagery of bridge locations that were difficult to access. Photos of channel sections were used to verify model inputs such as channel roughness, general channel shapes and bed material, as well as possible areas of concern for channel stability. Bridge and culvert dimensions, culvert roughness, and estimate contraction and expansion coefficients (see Figure 7B) were extracted from bridge photos. Bridge lengths were measured and used to scale other dimensions in the photos.

HEC-RAS Modeling

The Hydrological Engineering Center - River Analysis System (HEC-RAS) is used around the world for flood depth and hazard prediction (e.g., Stoleriu et al. 2019; Munir et al. 2020). A digital elevation model (DEM) with a horizontal resolution of 0.5 m and a vertical resolution of 1 m were imported as a terrain layer into RAS Mapper, part of HEC-RAS 5.0.7. *Torrenteras* are steep, straight channels dominated by one-dimensional (1D) flow. HEC-RAS 1D, which produced the best results for a flood study in a similar landscape (Bricker et al. 2017), was used to create hydraulic models for each to identify areas of hazard potential by assessing 1D variations in depth, velocity, and flood extent. Cross sections were placed at distances to account for changes in channel shape, slope, and at bridges and culverts. Bridge and culvert cross-sections were placed per guidelines in the HEC-RAS Hydraulic Reference Manual (USACE 2016). Expansion and contraction coefficients, culvert entrance losses, and ineffective flow areas were assigned according to the HEC-RAS Hydraulic Reference Manual (USACE 2016). Steady flow simulations of 100-year peak flow events in each *torrentera* were modeled using HEC-RAS 1D. Normal depth was used for boundary conditions, and upstream and downstream slopes were used as inputs.

Model parameters were adjusted so that maximum velocities did not exceed those recorded in similar channels (Magirl et al. 2009), because there was no data available for flood extent or water levels for calibration or validation at the time of this study. Channel roughness, or Manning's n, the parameter in HEC-RAS most sensitive to changes, was adjusted to meet this criterion (Ramesh et al. 2000; Parhi 2013). The same Manning's n, 0.12, was applied throughout all *torrenteras* because they had similar bed roughness, underlying geology, soil types, and sorting of heterogeneous sediments. This value is within the range of n values found in other steep sloped streams (Aguirre-Pe et al. 1990; Reid and Hickin 2008; Zimmerman 2010). Slopes in the modeled section of these *torrenteras* range from 0.04 - 0.10.

Flood Hazard Analysis

Analysis of Inundation Hazard. Water surface elevations modeled in HEC-RAS were imported to ArcMap 10.6 using the HEC-GeoRAS 10.6.0.1 plug-in for analysis and visualization. This mapping software was used to visualize inundation boundaries and identify infrastructure within the flood zone, like bridges, roads, and housing.

Analysis of Velocity Hazard. HEC-RAS model outputs for water velocity and depth in the torrenteras were used to characterize the potential for people and objects to be swept away, defined as the velocity hazard. In this paper, toppling was considered as the mechanism for loss of human stability, when the moment force caused by the floodwaters exceeds the moment force of the human body (Jonkman and Penning-Rowsell 2008). Literature thresholds are largely reported as empirical formulas determined from flume experiments to determine the point of loss of stability for humans (Jonkman and Penning-Rowsell 2008; Pisaturo et al. 2019) and vehicles (Martinez-Gomariz et al. 2016). For this paper, the velocity hazard was calculated as the product of water velocity and depth (Pisaturo et al. 2019), and an empirical equation (Karvonen et al. 2000) was used for the threshold of movement for a typical adult and child:

$$hv_c = 0.004Lm + 0.2 \tag{1}$$

where L is the height in meters, m is the mass in kg, and hv_c is the critical depth-velocity for instability. Using this equation, the instability threshold from toppling for a child 1.4 m tall and weighing 40 kg is 0.42 m^2/s, and the threshold for an adult (assuming the adult is 1.7 m tall and 70 kg) is 0.68 m^2/s. When the product of the model's flood velocity and depth is greater than this critical value, human stability is lost. When mapping velocity hazards from model results, thresholds were set as 0.4, 0.7, 2, and 8 m^2/s. These thresholds were set using Equation 1 for human stability and empirical literature values (Jonkman and Penning-Roswell 2008; Martiniz-Gomariz et al. 2016) and represent hazards capable of destabilizing a child (0.4 m^2/s), destabilizing adults and vehicles (0.7 m^2/s), complete loss of human stability (2 m^2/s), and separation between high and extremely high velocity hazards (8 m^2/s).

Analysis of Slope Instability Hazard. Slope failure occurs when the driving forces (conditional factors such as water and slope angle) are larger than resisting forces (intrinsic soil properties such as friction angle). The infinite slope method (Skempton and DeLory 1957) has been widely used as an estimate for slope stability under conditions with limited data. For this analysis, the soil was assumed to be cohesionless and dry, simplifying the factor of safety (FS) to Equation 2, where ϕ is the characteristic soil friction for a given soil and β is the angle of the slope.

$$\mathrm{FS} = \frac{\tan(\phi)}{\tan(\beta)} \tag{2}$$

The soil was assumed to be silty sand (SM; United Soil Classification System; ASTM D2487-17el) based on classified soil data from nearby areas (MINAM 2017), and a value of 32.5 was used for ϕ (Prellwitz et al. 1994). For β, the 1 m *DEM* of the *torrenteras* was first smoothed using two-cell focal statistics, after which the percent slope was calculated. This allowed us to represent the critical slopes more accurately, particularly in areas with buildings. Factors of safety were then classified into stability classifications after Pisaturo et al. (2019). HEC-RAS outputs for stream power were also considered when determining areas with potential slope instability hazards. Stream power is used to express the flow energy of floodwaters and has been used to describe the potential for catastrophic geomorphic change (Magilligan et al. 2015).

Results

Hydrologic Analysis

Evaluation of Predictions. Thouret et al. (2014) provided a summary of 17 reported flood events that have occurred around Arequipa since 1915, with average precipitation intensities ranging from 4.5 to 73.5 mm/hr. They identified seven events with peak intensities greater than 30 mm/hr, implying a return period of about 14 years. The estimated intensity of 14-year return period events based on the disaggregated precipitation varied between 20 - 40 mm/hr. While it is not possible to directly compare these estimates, it seems that the generated frequencies are feasible based on limited recorded information of these extreme events in the area.

Figure 2 compares SWAT-predicted 100-year floods for the *torrenteras* with the regional regression developed from a Historic Reference Hydrologic Network (HRHN) (also shown) identified by Moraes et al. (2020). Estimated 100-year daily peak flows range from 213 m^3/s for Mariano Melgar to 32 m^3/s for Independencia. Given the strong association between all of these values, we conclude that the SWAT-simulated flood peak values provide a reasonable estimation of flood frequency for these ungauged basins.

Streamflow Characteristics. Analysis of 30-minute streamflow simulation over 54 years (1966 - 2019) showed that average annual flow ranged from 113 to 188 mm (37% to 46% of annual precipitation). Overall, these ephemeral streams are dry for almost

10 months per year on average and only flow 13% to 19% of the time.

As illustrated in Figure 3, streamflow events occur very rapidly in these steep channels, where peak flow is reached 30 - 60 minutes after the start of the event and total event duration is approximately 1 - 2 hours. In the 54-year SWAT simulations, maximum peak flow among all *torrenteras* occurred in Mariano Melgar, reaching 175 m^3/s, while San Lázaro peak flow exceeded 52 m^3/s. The flood of record varies among channels. The largest simulated peak in Independencia, San Lázaro, and Miraflores was in 2013, in response to the extreme 123 mm storm recorded at the La Pampilla station. This storm had very limited spatial extent, since very little precipitation was measured at the Rodríguez Ballón and Chiguata stations and did not cause substantial flooding in Villa Ecológica or Mariano Melgar. The flood of record for these two *torrenteras* occurred in 1976, while the flood of record in Polanco occurred in 1989.

Change Over Time. The daily precipitation record shows a statistically significant increase in the annual precipitation and the average daily depth of precipitation for the La Pampilla and Rodríguez Ballón stations. As a result, there has been an increase in the number of extreme precipitation events per year (Figure 4A).

This increase in extreme precipitation events translates into increasing frequency of peak flows (Figure 4B). All *torrenteras* exhibit an increasing tendency in the annual maxima series, but there is substantial spatial variability between locations. Based on the non-parametric Mann-Kendall test ($p = 0.05$), there is a statistically significant increasing trend in the simulated annual maxima series for Independencia, San Lázaro, and Mariano Melgar.

Flood frequency analysis was also performed for two time periods (1966 - 1990 and 1995 - 2020) to identify potential changes in the 100-year flood magnitude. The estimated 100-year flood magnitude has increased for the later period for the three channels for which 2013 was the flood of record, and it has decreased for the other three channels. As a result, only the 100-year floods estimated from the entire simulation period were used in the flood hazard assessment.

Hazard Mapping

In this section, we describe flood-related hazards associated with inundation, velocity, and slope

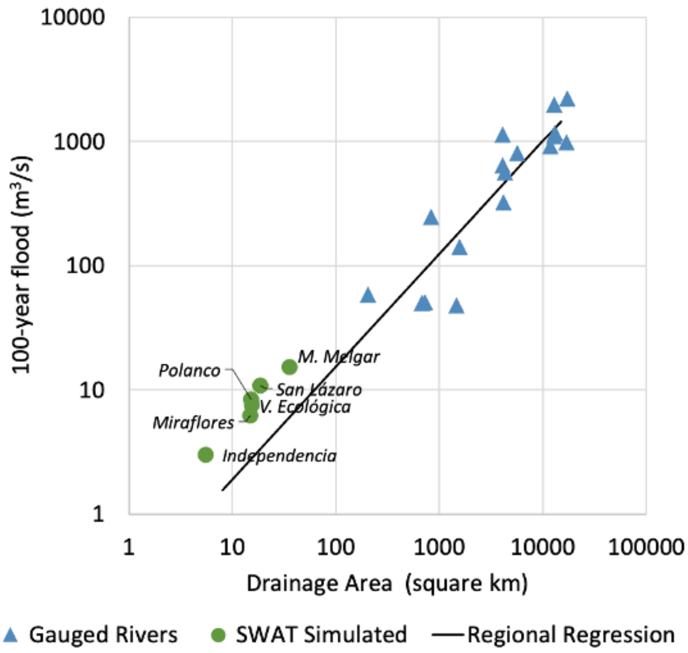


Figure 2. Log of the predicted 100-year discharge versus log drainage area for reference stream gauge locations in Arequipa (blue), estimated based on a regional regression developed from these gauges and the SWAT-simulated values for the *torrenteras*.

instability and provide case studies of problem areas for each hazard type.

Inundation Hazard. Peak flows from 100-year events showed that incidence and extent of flooding varied widely, but flood extents surpassed channel banks in at least one location in all modeled torrenteras. In all torrenteras, like the section of San Lázaro shown in Figure 5A, flooding was most likely in areas with large culvert constrictions. Overbank flow at non-bridge locations was less frequent but was often simulated in more densely urban areas where torrenteras

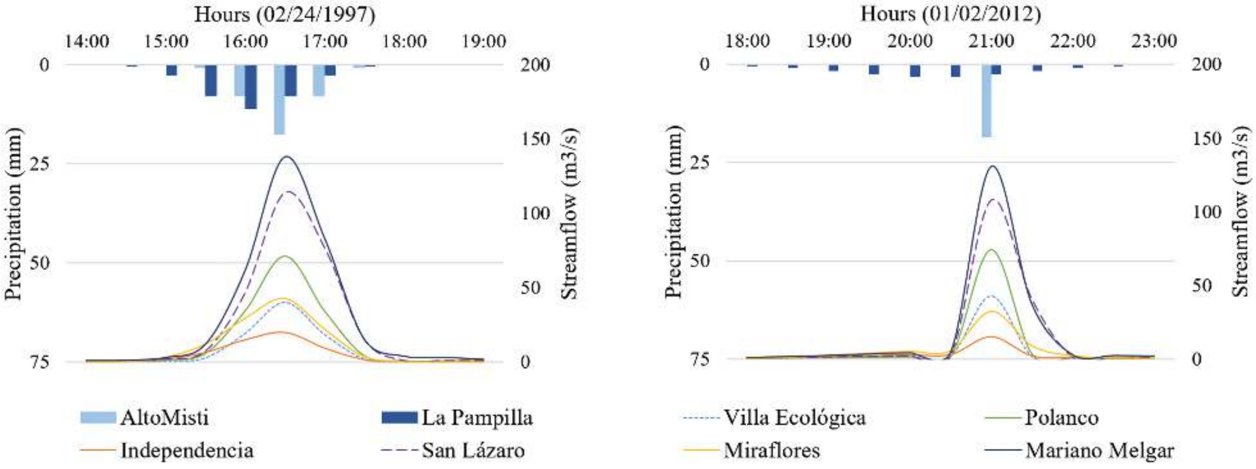


Figure 3. Simulated hydrographs for two flood events in six *torrenteras* and precipitation from the AltoMisti virtual station that was used as the precipitation station for the majority (65%) of the subbasins.

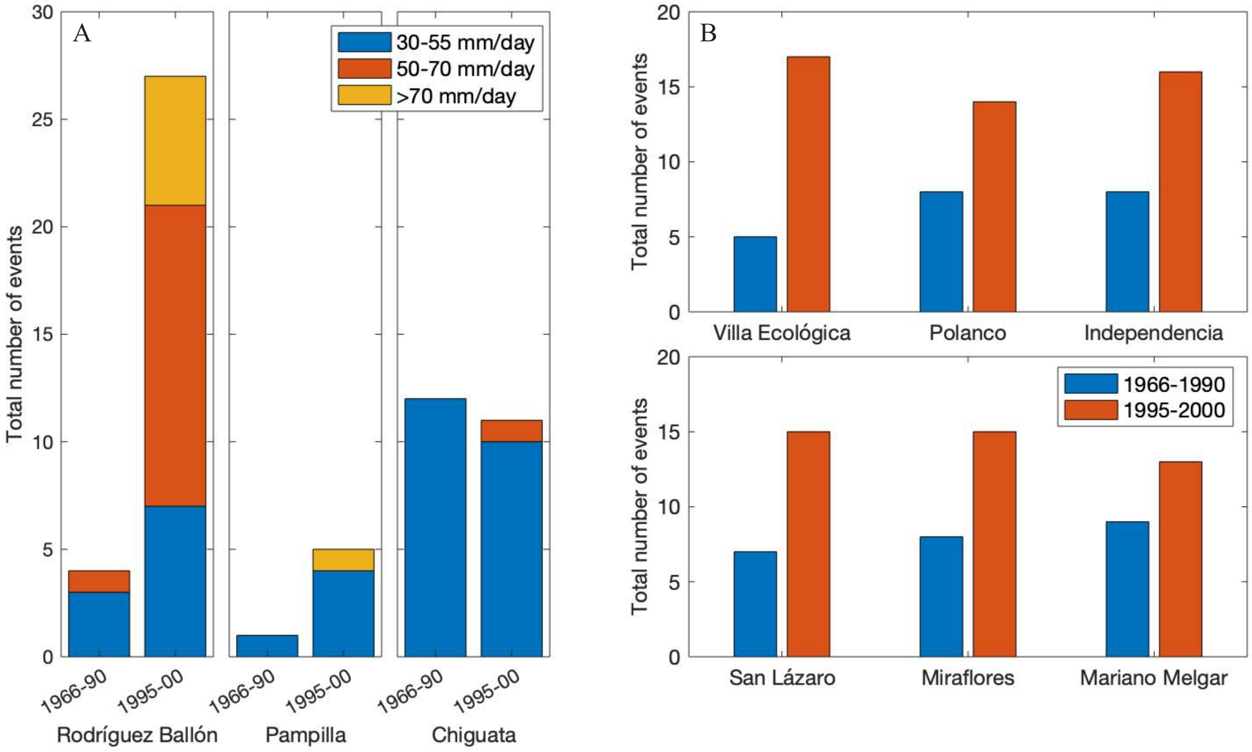
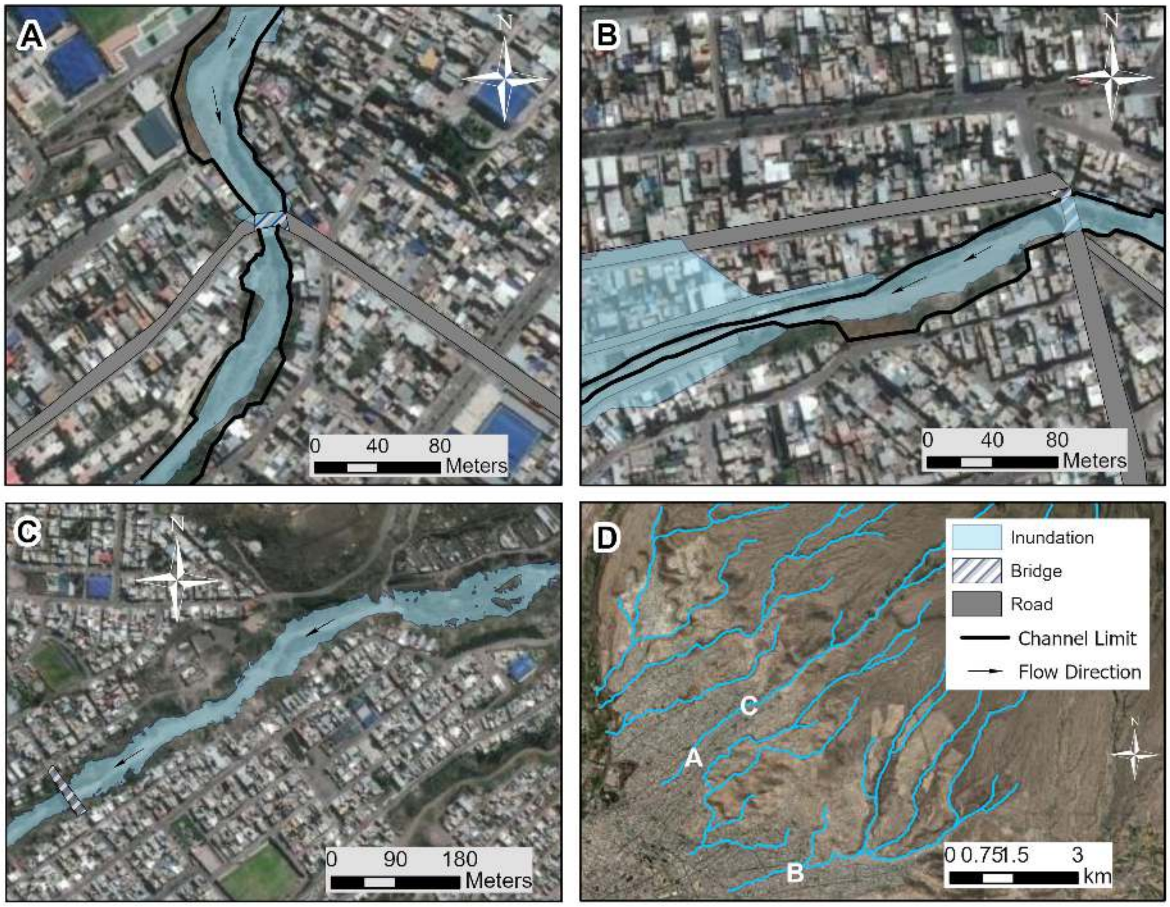


Figure 4. Hydrologic changes in Arequipa. A) Number of extreme precipitation events (> 30 mm/day) for the three weather stations closest to the *torrenteras.* B) Number of peaks over a threshold (two-year return period) in each of the six *torrenteras*.

were highly channelized, i.e., constricted within a constructed, concrete channel, like in Mariano Melgar (Figure 5B). In channelized areas with overbank flow, flooding was also simulated at bridges, which were even more constricted than the channels themselves. Flooding was of least concern in upstream areas where development did not encroach on the channel, the floodplain was accessible to floodwater, and bridge locations were wider and larger resulting in limited flow constriction. A good example for this is in the upstream area of San Lázaro (Figure 5C).

Velocity Hazard. Velocity hazard analysis for HEC-RAS outputs from the 100-year flow event are shown in Figure 6. Locations shown in Figure 6A, 6B, and 6C are the same as those shown in Figure 5A, 5B, and 5C, respectively. Most of the inundated area had high velocity hazard values that would cause an adult to topple over in the floodwater. Locations in Figure 6A and 6B are in the downstream, urbanized portion of the torrenteras and are heavily channelized with smaller flow areas. This led to greater velocities, deeper water, and therefore, increased velocity hazards compared to the upper portions of the torrenteras (Figure 6C). Location A also shows inundation of a road next to Mariano Melgar, where the velocity hazard exceeded thresholds for destabilizing adults and vehicles. Debris in floodwaters, like vehicles, also increases the velocity hazard and the likelihood of destabilizing other objects downstream (Jonkman and Penning-Rowsell 2008).

Slope Instability Hazard. Unstable slopes that could lead to failure occur when the slope FS is



Service Layer Credits: World Imagery: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 5. Flood inundation extents of 100-year peak flows in A) Bridge Cahuide in San Lázaro, B) Bridge 8 de octubre and overland flow in Mariano Melgar, C) a less developed area upstream in San Lázaro with no overbank flow, and D) a location map for all aforementioned hazard sites.

less than 1.0. Figure 7 shows slope instability (as defined by the FS) and stream power in the upstream portion of San Lázaro (Figure 6C), as well as drone imagery of the bridge in this section of the torrentera. Since stream power indicates the work a stream is capable of doing, such as sediment transport, areas with high stream power and high slope instability are areas with high slope failure potential. In the middle portion of Figure 7A (location 1), slopes surrounding the channel are unstable and the stream power is high. Areas like this of high instability and high stream power are most susceptible to slope failure. In the upper portion (location 2) of Figure 7A, San Lázaro is wider and the floodwater has more area in which to disperse, lowering the stream power. This area could have a lower slope instability hazard than location 1 because, although the slopes are still steep and unstable, the floodwater has less power to destabilize the sediment. Immediately above the bridge (location 3), the slope instability and stream power are lower, meaning this area would have a lower slope instability hazard.

Discussion

Applications of Flood Hazard Information

Though estimated 100-year peak flows have not increased over the period of study in all *torrenteras*, our analysis demonstrated that moderate flood events are becoming more frequent. Hydrologic analysis shows that stormflow is unpredictable, flashy, and can be very isolated. These flows, though infrequent, happen very quickly, reaching peak flow in an hour or less. Arequipa is growing, and urban development near and into the *torrenteras* is increasing (Figure 8A). Hazard maps show that many areas in and around the *torrenteras*

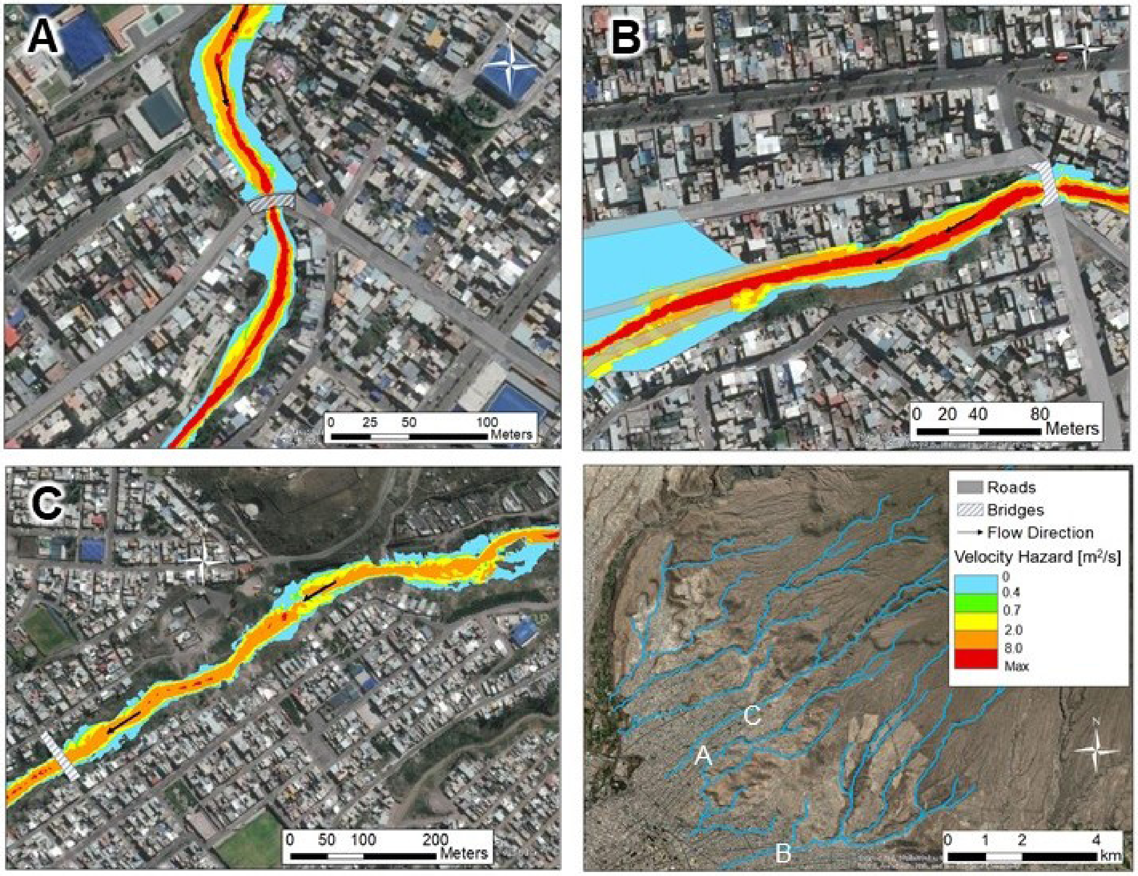


Figure 6. Velocity hazard maps for the case studies using HEC-RAS outputs from the 100-year peak flow for water velocity and depth at A) Bridge Cahuide in San Lázaro, B) Bridge 8 de octubre and overland flow in Mariano Melgar, C) a less developed area upstream in San Lázaro, and D) a location map for all aforementioned hazard sites.

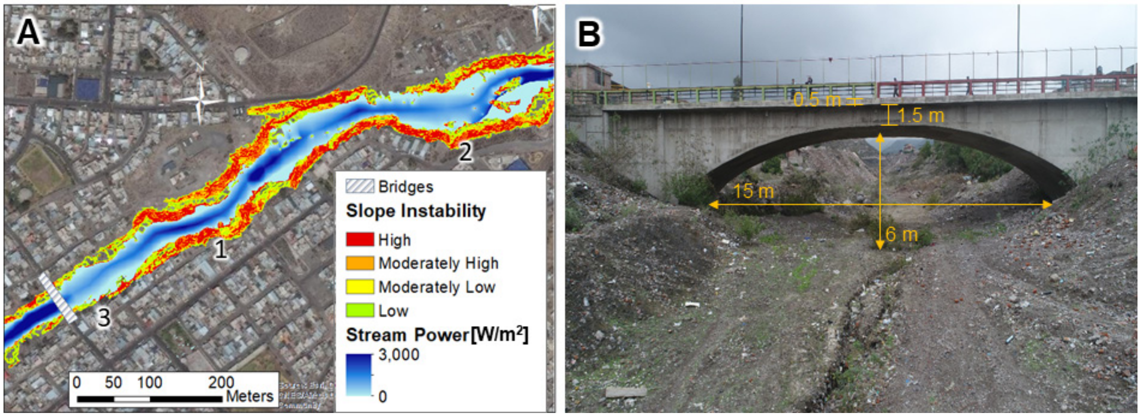


Figure 7. A) Slope instability and stream power of San Lázaro at three selected locations (1, 2, and 3). B) Drone footage of the bridge over San Lázaro depicted in A (location 3) and how it was used to get bridge dimensions. Slope instability is considered high when FS is less than 1, moderately high when FS is between 1 and 1.25, moderately low when FS is between 1.25 and 1.5, and low when FS is greater than 1.5.

can be dangerous, but these issues are exacerbated as development encroaches on the channels, putting more people and property at risk from flood hazards (Figure 8B). Hydraulic modeling and analysis of inundation, velocity, and slope instability give examples of hazards during the most extreme events, which can provide guidance for dealing with other, less severe floods. It is becoming increasingly important that stakeholder groups utilize hazard mapping information to make decisions about disaster mitigation strategies and future development. We provide considerations for each stakeholder group based on hazard locations, such as those shown in Figure 8B for a section of Mariano Melgar.

Use by Stakeholders

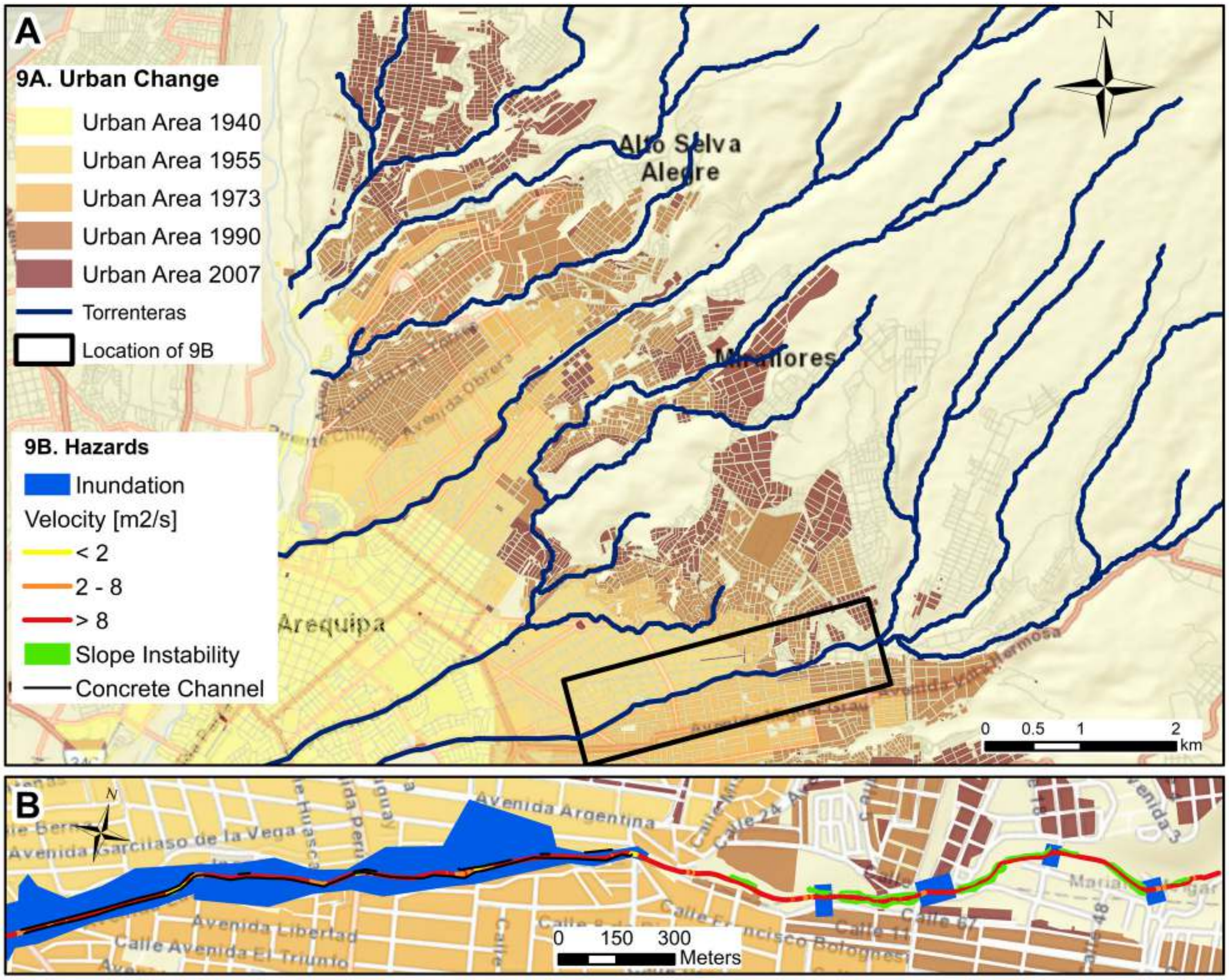
Reliable hazard maps could enhance flash flood mitigation strategies already in place in Arequipa. Currently, a rudimentary early warning system exists, relying on those living in upstream areas to report landslides and floods (Andina 2013). There are plans to add advanced weather prediction to the warning system, making it more robust and allowing for more time to evacuate (Del Mar 2019). Different mitigation strategies have been used in flash flood-prone areas to increase channel stability. Concrete reinforcement has been used in *torrenteras* to increase stability based on site observation. Colombo et al. (2002) created an extensive list of structures that have been effective in managing flash floods throughout Europe, including the use of gabion walls and natural materials for bank erosion protection. Land use control, like leaving vulnerable floodplains undeveloped or converting them into flood tolerable green spaces, has been utilized to mitigate flood damage in arid regions around the world (Abdrabo et al. 2020).

Information on flood boundaries where streamflow leaves the channel can help disaster risk managers and emergency responders make decisions about which bridges to close first, areas to prioritize for evacuation because of higher hazard probabilities, and optimal routes for evacuation. Velocity hazards can be used to issue warnings of areas to avoid during storm events because the storm duration and rapidly rising waters characteristic of flash floods give emergency responders little time to prepare and respond to extreme events. Lastly, areas where banks of the *torrenteras* have the highest slope instability hazards can be monitored more closely during storm events when soil saturation increases the probability of failure.

Water authorities can use this information about high hazard zones to establish limits for flood boundaries and, therefore, development, in currently less-developed, upstream areas. These boundaries can be based on identified floodplains and unstable slopes, minimizing hazards caused by channelization and floodplain encroachment. Although these regulations may be difficult to enforce as informal settlements encroach on *torrentera* channels, this study, with both hydrologic and hydraulic analysis of peak flows in *torrenteras,* provides scientific guidance on where and how to set development limits.

Though it is difficult to alter existing infrastructure in developed areas without large investment and displacement of people, municipalities and planners can prioritize areas in which to work with vulnerable people to utilize measures at the home-scale to mitigate flood risk, which can be much more cost-effective (Holub and Fuchs 2008).

While hazard mapping provides planners with limits for regulating development, for these *torrenteras*, there is no guarantee that community groups will not create "informal settlements" in high hazard zones. To increase the likelihood of community acceptance, community education of these hazards and consequences of floodplain encroachment is key (Zeballos-Velarde et al. 2017). In addition, upstream areas with more open and available space could be used to mitigate flooding effects farther downstream. Streamflow can be slowed or diverted to reduce downstream impact, through methods like creating check dams and step pools (Norman et al. 2016), offline detention (Ngo et al. 2016), and diverting water to spreading grounds that allow for sedimentation and infiltration (Wohlgemuth and Lilley 2018). Costs



Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 8. A) Development of Arequipa over time near the *torrenteras* indicates the importance of understanding flood hazards. B) Identified hazards have been compiled in a section of Mariano Melgar, showing areas of highest concern. These areas identify zones of flood hazard rather than exact flood extent.

of maintenance, like removal of heavy sediment loads, should be considered when implementing any of these options (Aerts 2018). With decreased velocity hazard and because they only convey water two months per year, there may be opportunities to use *torrenteras* for recreational infrastructure as a community amenity (Remón Royo 2018). The *torrenteras,* like other ephemeral streams, may also be enhanced to provide ecosystem services, including cultural services for nearby communities (Koundouri et al. 2017; Datry et al. 2018).

Conclusions

Intense peak flows, combined with channelization and development near or into the *torrenteras* of Arequipa, cause hazards for both human life and infrastructure. The city's ability to mitigate damage from these events has been limited due to a lack of both meteorological and topographical information. In this study, we had access to high-resolution spatial data and were able to synthesize sub-daily precipitation using a combination of datasets, which allowed us to assess hydrologic and hydraulic impacts from storm events over the last 60 years in the *torrenteras*. Storms are short and intense, resulting in high peak flows and short time to peak. The intensity of precipitation is increasing in some parts of the city, and the frequency of moderate flood peaks is increasing.

Hydraulic analysis revealed flood hazards related to inundation, velocity, and slope instability. Flooding was an issue in all modeled channels, particularly at bridges and culverts in downstream, channelized sections of the *torrenteras*. When channelization was very extreme, like in areas where development abutted concrete-reinforced channels, there was even inundation on roads and around houses. All *torrenteras* had large stretches where the velocity hazards were large enough to destabilize both humans and vehicles, and these flows become more extreme in channelized sections of the *torrenteras*. Development has also moved into unstable channel sections, encroaching on the channel floodplain, and putting these buildings in danger of collapse.

This analysis of hazards can be used for multiple stakeholder groups in Arequipa. This method can be used to create extensive, detailed maps for all *torrenteras*, thus providing these groups with specific information on hazard areas. Using this information, disaster risk managers can create evacuation routes, prioritize road closures, and create warnings of high hazard zones. Water authorities, municipalities, and planners can work together to create development boundaries based on hazard maps. Planners can also engage with community members to build understanding of where hazards exist in the *torrenteras* and the importance of respecting development boundaries.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín. The DEM was provided by the "Costuras Urbanas: Red de Centralidades Barriales en la Periferia de Arequipa como alternativa Socio Ambiental al Cambio Climático en Poblaciones Vulnerables" research project, funded by the Universidad Nacional de San Agustín.

Author Bio and Contact Information

Katy Mazer (corresponding author) is coordinator of the Sustainable Water Management team of The Nexus Institute at Purdue University. She engages with stakeholder groups in Arequipa, Peru to coproduce water management decision-making tools. She can be contacted at kmazer@purdue.edu or 920 W. State St., West Lafayette, IN 47907.

Abigail Tomasek is a Postdoctoral Research Associate in Agricultural and Biological Engineering at Purdue University. Her research broadly focuses on how anthropogenic activities have affected water quality and flow using a combination of experimental and field-based methods. She can be contacted at atomasek@purdue.edu.

Fariborz Daneshvar is a Postdoctoral Research Associate in the Department of Agricultural and Biological Engineering at Purdue University. He conducts watershed hydrology research with respect to environmental and socioeconomic impacts. He can be contacted at fdaneshv@purdue.edu or 225 S. University St., West Lafayette, IN 47907.

Laura Bowling is a Professor of hydrology in the Department of Agronomy at Purdue University. Her research investigates the water resources impact of environmental change across multiple scales, climate

regimes, and ecosystems and communicates these findings to stakeholders. She can be contacted at bowling@purdue.edu or 915 W. State St., West Lafayette, IN 47907.

Jane Frankenberger is a Professor of Agricultural and Biological Engineering at Purdue University. She conducts model-based analyses and engages stakeholders to improve management of watersheds and water quality. She can be contacted at frankenb@purdue.edu or 225 S. University St., West Lafayette, IN 47907.

Sara McMillan is an Associate Professor of Agricultural and Biological Engineering at Purdue University. Her research on ecological restoration uses experimental and modeling approaches to develop solutions to water quality problems. She can be contacted at smcmillan@purdue.edu or 225 S. University St. West Lafayette, IN 47907.

Hector Novoa is a professor of fluid mechanics, hydraulics and hydrology in the Faculty of Civil Engineering at the Universidad Nacional de San Agustín in Arequipa, Peru. He has over 25 years of experience in environmental issues, including water and sewer systems, surface water hydrology, and design of hydraulic structures. He can be contacted at hnovoa@unsa.edu.pe.

Carlos Zeballos-Velarde is an architect, urban planner, and professor in the Faculty of Architecture and Urbanism at the Universidad Nacional de San Agustín in Arequipa, Peru. He conducts GIS analyses about various topics related to environmental urban planning and works on several research projects about participatory risk management with different communities. He can be contacted at czeballos@unsa.edu.pe or Urb. Las Begonias F-1, JLByR. Arequipa, Peru.

References

Abdrabo, K.I., S.A. Kantosh, M. Saber, T. Sumi, O.M. Habiba, and B. Alboshy. 2020. The Role of Urban Planning Tools in Flash Flood Risk Reduction for The Urban Arid and Semi-Arid Regions. DOI:10.13140/RG.2.2.31397.12000.

Aerts, J.C.J.H. 2018. A review of cost estimates for flood adaptation. *Water* 10(11): 1646. Available at: https://doi.org/10.3390/w10111646. Accessed November 24, 2020.

Aguirre-Pe, J. and R. Fuentes. 1990. Resistance to flow in steep rough streams. *Journal of Hydraulic Engineering* 116(11): 1374-1387. Available at: https://doi.org/10.1061/(ASCE)0733-9429(1990)116:11(1374). Accessed March 19, 2020.

Andina. 2013. Instalan sistema de alerta temprana en Arequipa para prevenir desastres por lluvias. Agencia Peruana de Noticias. Available at: https://andina.pe/agencia/noticia.aspx?id=487435. Accessed November 23, 2020.

Arnold, J.G., J.R. Kiniry, R. Srinivasan, J.R. Williams, E.B. Haney, and S.L. Neitsch. 2013. Soil & Water Assessment Tool. Input/Output Documentation Version 2012. Texas Water Resources Institute, TR-439. Available at: https://swat.tamu.edu/media/69296/swat-io-documentation-2012.pdf. Accessed April 30, 2020.

ASTM D2487-17e1. 2017. Standard Practice for Classification of Soils for Engineering Purposes (United Soil Classification System). ASTM International, West Conshohocken, PA. Available at: https://www.astm.org/Standards/D2487.htm. Accessed May 1, 2020.

Boithias, L., S. Sauvage, A. Lenica, H. Roux, K.C. Abbaspour, K. Larnier, D. Dartus, and J.M. Sánchez-Pérez. 2017. Simulating flash floods at hourly time-step using the SWAT model. *Water* 9(12): 929. Available at: https://doi.org/10.3390/w9120929. Accessed March 13, 2020.

Bowling, L.C., D.P. Lettenmaier, B. Nijssen, L.P. Graham, D.B. Clark, M. El Maayar, R. Essery, S. Goers, Y.M. Gusev, F. Habets, B. van den Hurk, J. Jin, D. Kahan, D. Lohmann, X. Ma, S. Mahanama, D. Mocko, O. Nasonova, G.Y. Niu, P. Samuelsson, A.B. Shmakin, K. Takata, D. Verseghy, P. Viterbo, Y. Xia, Y. Xue, and Z.L. Yang. 2003. Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS Phase 2(e) 1: Experiment description and summary intercomparisons. *Journal of Global and Planetary Change* 38(1-2): 1-30. Available at: https://doi.org/10.1016/S0921-8181(03)00003-1. Accessed March 13, 2020.

Bricker, J.D., W. Schwanghart, B.R. Adhikari, S. Moriguchi, V. Roeber, and S. Giri. 2017. Performance of models for flash flood warning and hazard assessment: The 2015 Kali Gandaki landslide dam breach in Nepal. *Mountain Research and Development* 37(1): 5-15. Available at: https://doi.org/10.1659/MRD-JOURNAL-D-16-00043.1. Accessed November 30, 2020.

Cacya, L., P. Meza, V. Carlotto, and L. Mamani. 2013. Aluvión del 8 de Febrero del 2013 en la ciudad de Arequipa. In: *Foro Internacional Peligros Geológicos,* INGEMMET, Arequipa, Peru, pp. 195-200. Available at: https://hdl.handle.net/20.500.12544/1132. Accessed November 30, 2020.

Colombo, A.G., J. Hervas, and A.L. Vetere Arellano. 2002. *Guidelines on Flash Flood Prevention and Mitigation*. European Commission Joint Research Centre, Report number EU-NA-20-386-EN-C. Available at: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.13140%2FRG.2.1.4234.2480. Accessed December 2, 2020.

Daneshvar, F., J.R. Frankenberger, L.C. Bowling, K.A. Cherkauer, and M.J. Villalta Soto. 2020a. Estimated Soil Physical Properties for Hydrologic Modeling in Arequipa, Peru. Purdue University Research Repository. DOI: 10.4231/N5MX-9W30.

Daneshvar, F., J.R. Frankenberger, L.C. Bowling, K.A. Cherkauer, and J.A. Vera Mercado. 2020b. Estimated Land Cover Properties for Hydrologic Modeling in Arequipa, Peru. Purdue University Research Repository. DOI: 10.4231/GYN8-W684.

Daneshvar, F., J.R. Frankenberger, L.C. Bowling, K.A. Cherkauer, and A.G.D.L. Moraes. 2020c. Development of strategy for SWAT hydrologic modeling in data-scarce regions of Peru. *Journal of Hydrologic Engineering* (Under Review).

Datry, T., A.J. Boulton, N. Bonada, K. Fritz, C. Leigh, E. Sauguet, K. Tockner, B. Hugueny, and C.N. Dahm. 2018. Flow intermittence and ecosystem services in rivers of the Anthropocene. *Journal of Applied Ecology* 55(1): 353-364. Available at: https://doi.org/10.1111/1365-2664.12941. Accessed April 17, 2020.

Del Mar, J. 2019. Arequipa: El radar de 3 millones de soles que financiaría Cerro Verde permitirá pronosticar lluvias. *El Búho*. Available at: https://elbuho.pe/2019/03/arequipa-radar-metereologico-senamhi-lluvias-cerro-verde/. Accessed November 23, 2020.

Gobierno Regional Arequipa. 2016. Elaboración del Estudio de Suelos y la Clasificación de Tierras por su Capacidad de Uso Mayor en la Región Arequipa. Proyecto Desarrollo de Capacidades en Zonificación Ecológica Económica para el Ordenamiento Territorial en la Región Arequipa, Autoridad Regional Ambiental de Arequipa, Gobierno Regional Arequipa, Arequipa, Perú. 1,152 pp. (Reg.# 1782331, Doc.# 1775929).

Gourley, J.J., Z.L. Flamig, H. Vergara, P.E. Kirstetter, R.A. Clark III, E. Argyle, A. Arthur, S. Martinaitis, G. Terti, J.M. Erlingis, and Y. Hong. 2017. The FLASH project: Improving the tools for flash flood monitoring and prediction across the United States. *Bulletin of the American Meteorological Society* 98(2): 361-372. DOI:10.1175/BAMS-D-15-00247.1.

He, B., X. Huang, M. Ma, Q. Chang, Y. Tu, Q. Li, K. Zhang, and Y. Hong. 2018. Analysis of flash flood disaster characteristics in China from 2011 to 2015. *Natural Hazards* 90(3): 407-420. DOI:10.1007/s11069-017-3052-7.

Helsel, D.R., R.M. Hirsch, K.R. Ryberg, S.A. Archfield, and E.J. Gilroy. 2020. Statistical methods in water resources. In: *U.S. Geological Survey Techniques and Methods, book 4, chapter A3*, Reston, VA. Available at: https://doi.org/10.3133/tm4a3. Accessed November 30, 2020.

Holub, M. and S. Fuchs. 2008. Benefits of local structural protection to mitigate torrent-related hazards. In: *Risk Analysis VI: Simulation and Hazard Mitigation*, C.A. Brebbia and E. Beriatos (Eds.). WIT Press, Southampton, UK, pp. 401-411.

Huffman, G., D. Bolvin, D. Braithwaite, K. Hsu, R. Joyce, and P. Xie. 2019. Integrated Multi-satellite Retrievals for GPM (IMERG), version 6. NASA's Precipitation Processing Center. Available at: https://giovanni.gsfc.nasa.gov/giovanni/. Accessed October 31, 2019.

Jeong, J., N. Kannan, J. Arnold, R. Glick, L. Gosselink, and R. Srinivasan. 2010. Development and integration of sub-hourly rainfall–runoff modeling capability within a watershed model. *Water Resources Management* 24(15): 4505-4527. Available at: https://doi.org/10.1007/s11269-010-9670-4. Accessed March 13, 2020.

Jonkman, S.N. and E. Penning-Rowsell. 2008. Human instability in flood flows. *Journal of the American Water Resources Association* 44(5): 1208-1218. Available at: https://doi.org/10.1111/j.1752-1688.2008.00217.x. Accessed March 15, 2020.

Karvonen, R.A., A. Hepojoki, H.K. Huhta, and A. Louhio. 2000. *The Use of Physical Models in Dam-break Analysis*. RESCDAM Final Report of Helsinki University of Technology, Helsinki, Finland. Available at: https://www.google.com/search?q=The+use+of+physical+models+in+dam-break+analysis%2C+RESCDAM+Final+Report%2C+Helsinki+University+of+Technology&rlz=1C1CHBF_enUS798US798&oq=The+use+of+physical+models+in+dam-break+analysis%2C+RESCDAM+Final+Report%2C+Helsinki+University+of+Technology&aqs=chrome..69i57j69i64.318j0j7&sourceid=chrome&ie=UTF-8#. Accessed December 2, 2020.

Koundouri, P., A.J. Boulton, T. Datry, and I. Souliotis. 2017. Ecosystem services, values, and societal perceptions of intermittent rivers and ephemeral streams. In: *Intermittent Rivers and Ephemeral Streams*, Academic Press, pp. 455-476. Available at: https://doi.org/10.1016/B978-0-12-803835-2.00018-8. Accessed April 17, 2020.

Magilligan, F.J., E.M. Buraas, and C.E. Renshaw. 2015. The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding. *Geomorphology* 228: 175-188. Available at: https://doi.org/10.1016/j.geomorph.2014.08.016. Accessed March 15, 2020.

Magirl, C.S., J.W. Gartner, G.M. Smart, and R.H. Webb. 2009. Water velocity and the nature of critical flow in large rapids on the Colorado River, Utah. *Water Resources Research* 45(5): W05427. Available at: https://doi.org/10.1029/2009WR007731. Accessed March 19, 2020.

Martelli, K.M. 2011. The physical vulnerability of urban areas facing the threat of inundation from lahars and floods: Application to the city of Arequipa, Peru. Dissertation, Université Blaise Pascal, Clermont-Ferrand, France. Available at: https://tel.archives-ouvertes.fr/tel-00881754/. Accessed November 16, 2019.

Martinez-Gomariz, E., M. Gomez Valentin, B. Russo, and S. Djordjevic. 2016. Stability criteria for flooded vehicles: A state of the art review. *Flood Risk Management* 11(1). Available at: https://doi.org/10.1111/jfr3.12262. Accessed March 15, 2020.

Ministerio de Ambiente (MINAM). 2017. Zonificación Ecológica y Económica (ZEE). Available at: https://www.minam.gob.pe/ordenamientoterritorial/zonificacion-ecologica-y-economica-zee/. Accessed November 26, 2019.

Moraes, A.G., K.A. Cherkauer, L.C. Bowling, and C.R. Zeballos Velarde. 2019. Arequipa Climate Maps-Normals. Purdue University Research Repository. DOI: 10.4231/490D-HC66.

Moraes, A.G.L., E. Bocardo-Delgado, L. Bowling, F. Daneshvar, J. Pinto, A.H. Watkins, and K.A. Cherkauer. Assessment of Arequipa's Hydrometeorological Monitoring Infrastructure to Support Water Management Decisions. *Journal of Contemporary Water Research and Education* 171: 27-48. Available at: https://onlinelibrary.wiley.com/journal/1936704x. Accessed December 22, 2020.

Muller, M. 2007. Adapting to climate change: Water management for urban resilience. *Environment and Urbanization* 19(1): 99-113. Available at: https://doi.org/10.1177%2F0956247807076726. Accessed November 16, 2020.

Munir, B.A., S.R. Ahmad, and S. Hafeez. 2020. Integrated hazard modeling for simulating torrential stream response to flash flood events. *ISPRS International Journal of Geo-Information* 9(1): 1. Available at: https://doi.org/10.3390/ijgi9010001. Accessed December 2, 2020.

NASA Earth Data. 2019. ASF Data Search Vertex. Available at: https://search.asf.alaska.edu/#/?flightDirs=. Accessed October 10, 2019.

The National Centers for Environmental Prediction, Climate Forecast System Reanalysis (NCEP CFSR). 2019. Global Weather Data for SWAT. Available at: https://globalweather.tamu.edu. Accessed October 29, 2019.

Ngo, T.T., D.G. Yoo, Y.S. Lee, and J.H. Kim. 2016. Optimization of upstream detention reservoir facilities for downstream flood mitigation in urban areas. *Water* 8(7): 290. Available at: https://doi.org/10.3390/w8070290. Accessed April 17, 2020.

Norman, L.M., F. Brinkerhoff, E. Gwilliam, D.P. Guertin, J. Callegary, D.C. Goodrich, P.L. Nagler, and F. Gray. 2016. Hydrologic response of streams restored with check dams in the Chiricahua Mountains, Arizona. *River Research and Applications* 32(4): 519-527. Available at: https://doi.org/10.1002/rra.2895. Accessed April 29, 2020.

Parhi, P.K. 2013. HEC-RAS model for Manning's roughness: A case study. *Open Journal of Modern Hydrology* 3: 97-101. Available at: http://www.scirp.org/journal/ojmh. Accessed March 19, 2020.

Pisaturo, G.R., M. Righetti, C. Castellana, M. Larcher, A. Menapace, and G. Premstaller. 2019. A procedure for human safety assessment during hydropeaking events. *Science of the Total Environment* 661: 294-305. Available at: https://doi.org/10.1016/j.scitotenv.2019.01.158. Accessed December 2, 2020.

Prellwitz, R., T. Koler, and J. Steward. 1994. *Slope Stability Reference Guide for National Forests in the United States – Volume II*. Engineering Management Report EM-1710-13, U.S. Department of Agriculture, Forest Service, Washington, D.C. Available at: https://www.google.com/books/edition/_/KpFedYt9r7oC?gbpv=1. Accessed December 2, 2020.

Ramesh, R., B. Datta, S.M. Bhallamudi, and A. Narayana. 2000. Optimal estimation of roughness in open-channel flows. *Journal of Hydraulic Engineering* 126(4): 299-303. Available at: https://doi.org/10.1061/(ASCE)0733-9429(2000)126:4(299). Accessed March 19, 2020.

Reid, D.E. and E.J. Hickin. 2008. Flow resistance in steep mountain streams. *Earth Surface Processes and Landforms* 33(14): 2211-2240. Available at: https://doi.org/10.1002/esp.1682. Accessed March 19, 2020.

Remón Royo, R. 2018. Basureros transformados en jardines públicos: Medellín, Colombia. *Arquitectura y Empresa*. Available at: https://www.arquitecturayempresa.es/

noticia/basureros-transformados-en-jardines-publicos-medellin-colombia. Accessed April 26, 2020.

Republica de Perú. 2016. Reglamento para la Delimitación y Mantenimiento de Fajas Marginales. Resolución Jefatural No 332-2016-ANA. Available at: http://www.osterlingfirm.com/Documentos/webma/normas/RJ-332-2016-ANA.pdf. Accessed December 2, 2020.

Rodriguez-Iturbe, I., D.R. Cox, and V. Isham, 1987. Some models for rainfall based on stochastic point processes. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 410(1839): 269-288. Available at: https://doi.org/10.1098/rspa.1987.0039. Accessed December 2, 2020.

Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI). 2019. Ministerio del Ambiente. Available at: https://www.senamhi.gob.pe/. Accessed October 29, 2019.

Sistema Nacional de Defensa Civil Peru (SINPAD). 2013. Fuertes Precipitaciones Pluviales Afectaron la Ciudad de Arequipa. Estado Situacional de la Emergencia. Available at: http://sinpad.indeci.gob.pe/sinpad/emergencias/Evaluacion/Reporte/rpt_eme_situacion_emergencia.asp?EmergCode=00056271. Accessed April 30, 2020.

Skempton, A.W. and F.A. DeLory. 1957. Stability of natural slopes in London clay. In: *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering 2*, Thomas Telford Publishing, London, England, pp. 378-381. Available at: https://doi.org/10.1680/sposm.02050.0011. Accessed December 2, 2020.

Stoleriu, C.C., A. Urzica, and A. Mihu-Pintilie. 2019. Improving flood risk map accuracy using high-density LiDAR data and the HEC-RAS river analysis system: A case study from north-eastern Romania. *Journal of Flood Risk Management* 13(3): e12572. Available at: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1111%2Fjfr3.12572. Accessed December 2, 2020.

Teutschbein, C. and J. Seibert, 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology* 456-457: 12-29. Available at: https://doi.org/10.1016/j.jhydrol.2012.05.052. Accessed December 2, 2020.

Thouret, J.-C., S. Ettinger, M. Guitton, O. Santori, C. Magill, K. Martelli, G. Zuccaro, V. Revilla, J.A. Charca, and A. Arguedas. 2014. Assessing physical vulnerability in large cities exposed to flash floods and debris flows: The case of Arequipa (Peru). *Natural Hazards* 73: 1771-1815. Available at: https://doi.org/10.1007/s11069-014-1172-x. Accessed November 16, 2019.

Thouret, J.-C., G. Enjolras, K. Martelli, O. Santoni, A. Luque, M. Nagata, A. Arguedas, and L. Macedo. 2013. Combining criteria for delineating lahar- and flash-flood-prone hazard and risk zones for the city of Arequipa, Peru. *Natural Hazards and Earth Systems Science* 13: 339-360. DOI: 10.5194/nhess-13-339-2013.

U.S. Army Corps of Engineers (USACE). 2016. HEC-RAS River Analysis System. Hydraulic Reference Manual, Version 5.0, CPD-69. U.S. Army Corps of Engineers Hydraulic Engineering Center, Davis, California. Available at: https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%20Reference%20Manual.pdf. Accessed December 2, 2020.

Wohlgemuth, P.M. and K.A. Lilley. 2018. Sediment delivery, flood control, and physical ecosystem services in southern California Chaparral Landscapes. In: *Valuing Chaparral*, E. Underwood, H. Safford, N. Molinari, and J. Keeley (Eds.). Springer, Cham, pp. 181-205. Available at: https://doi.org/10.1007/978-3-319-68303-4_7. Accessed November 17, 2020.

Zeballos-Velarde, C., M.Á. Huamaní, J.Q. Valdivia, S.C. Alejo, and C.M. Espinoza. 2019. An environmental atlas as a tool for improving local environmental education and awareness in Arequipa. In: *Proceedings of the International Congress on Educational and Technology in Sciences*, Arequipa, Peru, December 10-12, 2019, pp. 191-200. Available at: http://ceur-ws.org/Vol-2555/paper17.pdf. Accessed April 13, 2020.

Zeballos-Velarde, C., R. Gonzalez-Salinas, and J. Urquizo Angulo. 2017. Urban linkages: A methodological framework for a network neighbour centralities in the periphery of Arequipa, Peru, as a social-environmental alternative to climate change in vulnerable settlements. In: *Proceedings of the UIA 2017 Seoul World Architects Congress*, September 3-7, 2017, Seoul, Korea. Available at: http://www.uia2017seoul.org/P/assets/html/5-2-paper.html. Accessed December 2, 2020.

Zimmerman, A. 2010. Flow resistance in steep streams: An experimental study. *Water Resources Research* 46(9): W09536. Available at: https://doi.org/10.1029/2009WR007913. Accessed March 19, 2020.

UNIVERSITIES COUNCIL ON WATER RESOURCES
JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION
ISSUE 171, PAGES 111-126, DECEMBER 2020

Coproduction Challenges in the Context of Changing Rural Livelihoods

*Ruxandra Popovici[1], Katy E. Mazer[2], Anna E. Erwin[1], Zhao Ma[1], José P. Pinto Cáceres[3], Laura C. Bowling[2], Edwin F. Bocardo-Delgado[4], and Linda S. Prokopy[1]

*[1]Forestry and Natural Resources, Purdue University, West Lafayette, IN, USA; [2]Department of Agronomy, Purdue University, West Lafayette, IN, USA; [3]Department of Agronomy, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; [4]Department of Biological Sciences, Universidad Nacional de San Agustín de Arequipa, Arequipa, Peru; *Corresponding Author*

Abstract: Coproduction is a process that involves scientists and citizens engaging throughout the production of knowledge, decisions, and/or policies. This approach has been widely applied in an international context for addressing global environmental issues. It is customary for scientists to travel to rural communities, where both scientists and local knowledge holders work together and jointly design solutions to pressing problems. Such collaboration, however, often involves high costs for both residents and scientists, which can reduce project effectiveness. This study examines the challenges associated with coproduction in the context of changing rural livelihoods in beneficiary communities. We specifically conduct a self-analysis of the coproduction process led by our own university team, where scientists designed tools for water and crop management together with community members in Peru's Caylloma province. We collected qualitative data on the coproduction challenges in five local districts in Caylloma, using focus groups and semi-structured interviews. Our results indicate that changing socioeconomic conditions in rural communities undermined the long-term sustainability and effectiveness of the coproduction efforts and deliverables. These included increased migration, market integration, and reliance on regional institutions for water and crop management.

Keywords: *agriculture, Peru, Latin America, participation, governance, community-based natural resource management*

Coproduction is an approach that has been increasingly used to address natural resource management challenges. Coproduction involves collaboration between different stakeholders, such as external experts and local resource users, to jointly determine the problems to be addressed, as well as their solutions (Beier et al. 2017). This approach is often suitable for addressing complex issues, such as climate change adaptation and watershed management, requiring complementary knowledge types (Leimona et al. 2015; Wall, Meadow, and Horganic 2017). Individual stakeholder groups rarely have the full range of knowledge, experience, and expertise required to tackle complex social, economic, and environmental problems (Berkes 2010). Through coproduction, multiple stakeholder groups can discuss, negotiate, and co-create practical solutions to their identified problems (Pohl et al. 2010). Such a process is believed to be more effective than top-down or bottom-up decision making alone (Beier et al. 2017).

Coproduction was originally designed as a mechanism to include citizens in the design and delivery of public services that were traditionally created and provided by government alone (Ostrom 1996; Bovaird 2007). However, the concept and related practices have evolved into a highly participatory and collaborative process that can involve multiple stakeholders (government, civil society, private sector) and have been expanded to areas such as watershed management (Leimona et al. 2015) and climate policy (Lövbrand 2011). Currently, coproduction is seen as a process that promotes intensive and repeated collaboration between external experts and local experts, as well as other stakeholders such as governments, nongovernmental organizations (NGOs), and businesses, with the specific goal of informing better decisions, management practices, and policies (Prokopy et al. 2017; Djenontin and Meadow 2018; Vincent et al. 2018). Figure 1 describes the coproduction cycle in more detail.

In the university research context, coproduction is closely related to Participatory Action Research (PAR), an approach where the research objectives, methods, and outcomes are co-developed by researchers and study participants (Baum et al. 2006). PAR involves the acknowledgement of different values and different forms of knowledge as valid and important and seeks to empower study participants to design projects that are most beneficial to them (Dudgeon et al. 2017). In an international development context, coproduction is also used in more applied projects and for the generation of specific deliverables, such as educational programs for farmers and technologies for soil and plant management (Almekinders 2011; Dalton et al. 2011; Davis et al. 2012; Akpo et al. 2015). Scholars have indicated that there are different types and levels of engagement between researchers, community members, and other stakeholders, as shown in Table 1 (Biggs 1989; Higginbottom and Liamputtong 2015; Meadow et al. 2015). Using the modes of engagement presented in Table 1 as a reference, the coproduction process represents a move away from top-down, contractual, or consultative relationships and toward more collaborative, collegial, equitable, and inclusive forms of interaction (Ahmad, Kyratsis, and Holmes 2012; Akpo et al. 2015; Higginbottom and Liamputtong 2015; Meadow et al. 2015).

When it comes to the actual interaction between different stakeholders, Pohl et al. (2010) outline two spaces for coproduction: the *agora* and the boundary organization. In the *agora*, researchers, community members, and other stakeholders gather and interact in a common space where they deliberate and negotiate various aspects of the proposed project. In such spaces, the "quality of dialogue" is particularly important, especially when stakeholders hold different views (King and Gillard 2019, 702). It is thus necessary for researchers to take on the role of facilitators and mediate between the different stakeholder interests in a way that promotes fairness, sharing, learning, and joint problem-solving (Akpo et al. 2015). Coproduction efforts can also be led by boundary organizations, whose members are professionals that engage with the different stakeholders and facilitate cross-group discussions and negotiation (Pohl et al. 2010). Boundary organizations can include NGOs, university extension offices, and some local or regional government branches. It is important to note that, while the *agora* and the boundary organizations are presented as separate

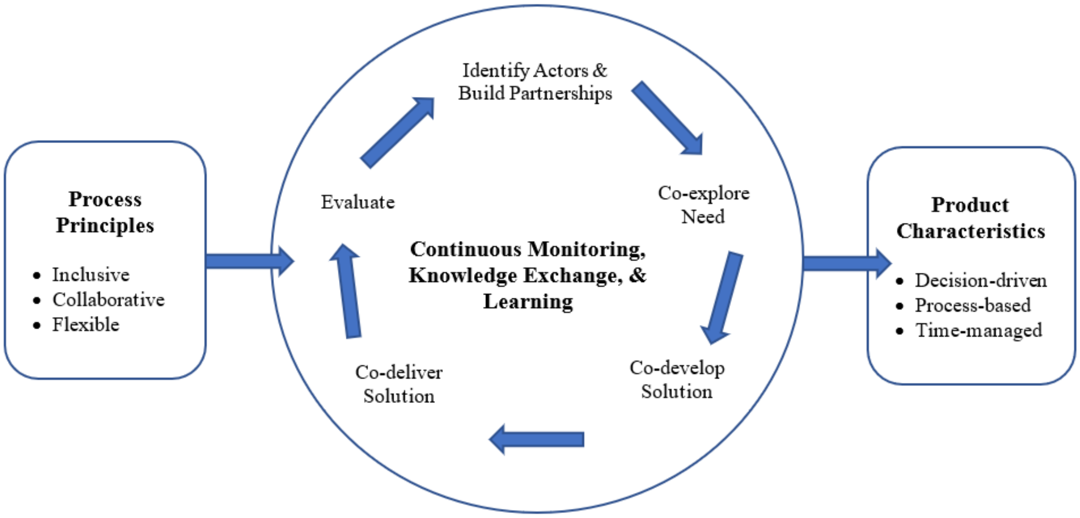


Figure 1. The cycle of coproduction. Source: Adapted from Vincent et al. 2018, 49.

Table 1. Modes of interaction between researchers and other stakeholders.

Mode	Objective	Type of Relationship	Stakeholder Involvement
Contractual	Test applicability of new technology or knowledge	Unidirectional flow of information from researchers to stakeholders	Primarily as passive recipient of new knowledge or technology
Consultative	Use research to solve real-world problems	Researchers consult with stakeholders, diagnose the problem, and try to find a solution	At specific stages of research such as problem definition, research design, diffusion of findings
Collaborative	Learn from stakeholders to guide applied research	Stakeholders and researchers are partners	Continuous with emphasis on specific activities, depending on joint diagnosis of the problem
Collegial	Understand and strengthen local research and development capacity	Researchers actively encourage local research and development capacity	Variable, but ongoing

Source: Adapted from Biggs 1989, 3-4 and Meadow et al. 2015, 183.

elements, they are located on a continuum and can also happen simultaneously. For example, a boundary organization can hold an open discussion in a public space with a wide range of stakeholders (Lemos et al. 2014).

Coproduction, however, is not easy. It is a complex, iterative process that requires time and effort from scientists, local residents, and other stakeholders involved (Lemos and Morehouse 2005). It often requires capacity-building at multiple scales to enable collaboration and knowledge sharing between different actors with different experiences and areas of expertise (van Kerkhoff and Lebel 2015). Stakeholders need to build trusting relationships in order to coproduce, which takes time and effort (Lemos and Agrawal 2006; Bowen et al. 2015; Prokopy et al. 2017), and often includes travel to the sites where coproduction deliverables are implemented (Schuttenberg and Guth 2015). Scholars also advocate for the creation of a coproduction "culture" where collaborative decision making becomes a common approach to solving environmental problems (Lebel, Wattana, and Talerngsri 2015). The literature shows that, when done right, coproduction can be a highly effective and rewarding process, producing benefits that are both tangible (i.e., specific tools or deliverables) and intangible (i.e., new relationships and values) (Alford 2002; Poocharoen and Ting 2015). At the same time, coproduction can be undermined by several obstacles. These include uneven power relations (Bowen et al. 2015; Wyborn 2015; Farr 2018), failure to build trusting relationships (Bowen et al. 2015; Schuttenberg and Guth 2015), lack of support by the larger-scale political or institutional climate (Lebel, Wattana, and Talerngsri 2015), as well as differences in cultural and organizational norms (Castellanos et al. 2013; Campbell, Svendsen, and Roman 2016; Cvitanovic, McDonald, and Hobday 2016).

In this paper, we assess the coproduction challenges that arise in the context of changing rural livelihoods due to shifting socioeconomic conditions, a topic that has been less explored in the literature. Many coproduction initiatives seeking to address issues related to climate change or natural resource management are conducted with local resource users in rural communities (Homsy and Warner 2013; Shaffer 2014; Bremer and Meisch 2017; Laursen et al. 2018). Rural communities are also targeted by coproduction efforts aiming to provide services such as drinking water, electricity, and healthcare to marginalized and underserved populations (Sternberg 2011; Munoz 2013; Brandsen, Steen, and Verschuere 2018; Hutchings 2018). However, rural communities around the world are undergoing rapid transformations caused by globalization, market integration, and migration, among other factors (Aggarwal 2006; Chimhowu 2019). It is unclear how these socioeconomic stressors affect the coproduction process. We specifically analyze these issues in a coproduction project conducted by our own team in the Caylloma province of Peru. The project is part of a partnership between two universities in which scientists attempted to coproduce tools for water and crop management together with local water users. This paper is a self-analysis of the coproduction process, reflecting on how the process was implemented by our research team and the extent to which coproduction was beneficial for community members in the five districts.

Study Context and Methods

This study examines the difficulties encountered in a coproduction effort led by our own Sustainable Water Management (SWM) team, composed of faculty, staff, and students from Purdue University in Indiana, USA and the Universidad Nacional de San Agustín (UNSA) in Arequipa, Peru. The SWM team is one of several research groups that are part of the Arequipa Nexus Institute for Food, Energy, Water, and the Environment, which is a partnership between the two universities. Over 2018 and 2019, SWM members conducted 144 semi-structured interviews, primarily with community members who earn their livelihood through farming and pastoralism in the districts of Caylloma, Lari, Yanque, Cabanaconde, and Majes in the province of Caylloma, Department of Arequipa, Peru (see Figure 2 for their geographical location and the Appendix for more detailed characteristics). Five of these interviews were conducted with personnel in regional water management agencies in order to obtain contextual information; however, agencies were not the focus of this study. The purpose of this initial qualitative research phase was to both collect qualitative data to understand the context of watershed management in the region and to gather data about community needs as a first step of our coproduction process. Specifically, our interview goals were to: 1) assess the formal and informal institutions for watershed management and 2) identify community needs in terms of water, crop, and pasture management. The interview questions centered around past and present water management practices for agriculture and pastoralism specifically. Participants were asked questions about the formal and informal rules of the local irrigation commission, government regulations for irrigation water, and other laws or organizations that regulated water use for farmers.

As outlined in Table 2, interviewees in the five communities included both leaders (irrigation commission leaders, mayors) and individuals not holding leadership positions. The majority of our interviewees sustained their livelihoods through agriculture and/or pastoralism. As this study specifically targeted farmers, our research participants were relatively homogenous, from a livelihood perspective. All irrigation commission members were farmers, as were irrigation commission leaders who performed their duties without remuneration. Some community members had different professions such as healthcare workers, veterinarians, and tour guides; however, they also practiced some crop farming or pastoralism. The communities were all similar, as most of their residents engaged in crop farming or pastoralism. Because this study specifically targeted farmers, our research participants were relatively homogenous. As will become apparent in the results section, all community members who earned their livelihood through farming activity faced similar socioeconomic pressures.

Based on the information obtained from the interviews, SWM members then conducted focus groups with community members in the five Caylloma districts in 2019. These focus groups gathered feedback on proposed tools for addressing community water management needs, concerns, and priorities in a farming context, as identified in the interviews. As such, the coproduction process in the context of this study involved two phases: 1) semi-structured interviews, where researchers asked participants about their water management practices and their specific needs; and 2) focus groups, where participants were asked to provide feedback on specific tools for water and crop management. Focus groups were conducted using the *agora* approach (Pohl et al. 2010), where SWM researchers worked with local community leaders in each district to organize in-person meetings between the research team and the community members who had participated in the semi-structured interviews. A coproduction approach was considered most appropriate because SWM researchers wanted to receive as much feedback and participation as possible from farmers when designing the tools, to make sure they effectively addressed local needs.

To obtain feedback on the tools, SWM team members conducted a total of five focus groups, one in each of the study districts. During the focus groups, SWM members reported the needs identified through the semi-structured interviews (specific to that particular community) and sought feedback about whether these needs had been correctly identified. The team presented a preliminary set of tool ideas for water and crop management. These tools included calculation methods for estimating crop water use and irrigation scheduling, fact sheets on 30-year historic climate trends, information on regional crop quantities and growth stage using remote sensing, and water quality testing kits. About 15 people were invited to participate in each focus

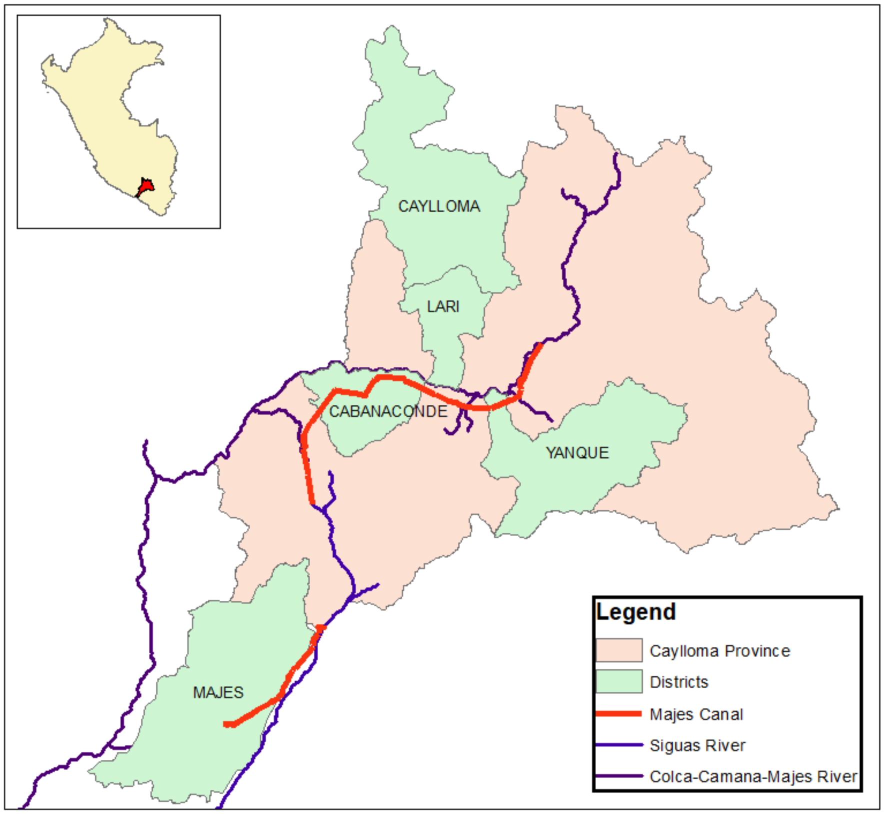


Figure 2. Study districts in the province of Caylloma, Peru.

Table 2. Number of community-level interviews, focus groups, attendees, and key informants.

Location	Interviews (n)	Focus Groups (n)	Focus Group Attendees (n)	Key Community Informants
Caylloma	32	1	1*	• Past and present district authorities (i.e., mayors) • Past and present irrigation commission leaders • Community members that did not hold leadership positions • Community elders
Lari	17	1	~40	
Yanque	25	1	~10	
Cabanaconde	30	1	~40	
Majes	35	1	~10	

*Only one person showed up for the focus group in the Caylloma district. We gave them a paper copy of our results summary, but we did not go through the entire presentation of the tools.

group, including some previously interviewed community members. Attendance ranged from one to about 40 participants (see Table 2).

Focus group participants were invited to provide feedback on the accuracy of the research findings, on the usefulness of the preliminary ideas identified by SWM, and on additional tools they would like the team to develop. SWM members facilitated an open conversation acknowledging the many community needs, the areas of expertise of the SWM team, and the areas of overlap where SWM experts could develop tools to address specific community needs. Figure 3 is an example of a PowerPoint slide that was presented during the coproduction focus groups. The star indicates the "sweet spot" where certain community needs intersected with the SWM team's areas of expertise. Based on information obtained during the initial focus group, the SWM team developed tools and then revised them following additional community feedback to ensure they adequately met community needs.

At the time of the study, SWM members had two additional visits planned to collect input on tool prototypes and to deliver final products. These additional visits were not yet completed and are not reported in this paper. As part of this research effort, SWM members also conducted focus groups with staff from regional water management agencies. However, the community and agency focus groups were conducted separately, and only the analysis of the information from focus groups conducted with community members is explored in this paper.

For this paper, we used the data collected in the first phase to discuss the specific difficulties encountered during the coproduction process, and to explain how these challenges contributed to rising coproduction costs. We analyzed the transcripts of 144 semi-structured interviews and five focus groups conducted by the SWM team during 2018 and 2019. Interview and focus group transcripts were analyzed in NVivo (version 12), a software for qualitative data analysis. We conducted thematic coding (Saldaña 2009), identifying commonly mentioned community needs and obstacles to coproduction. After the obstacles to coproduction were identified, we conducted process coding (Saldaña 2009) by tracing the chain of events and the underlying causes leading to those obstacles. The codebook was revised by two of the coauthors, who convened to discuss definitions and coding methods until agreement was achieved. Interviews were transcribed and analyzed in Spanish, and the quotes included in this paper were translated to English.

Figure 3. Coproduction focus group objective.

Results

This section describes the challenges to coproduction encountered by the SWM team in the context of changing rural livelihoods. We identified two specific challenges, namely community members' declining ability to participate in ongoing coproduction efforts, as well as the transfer of local irrigation water management responsibilities to regional-level organizations.

Declining Ability to Participate in Ongoing Coproduction Efforts

While coproduction focus groups were well-attended in four of the five study communities, we found that community members had limited ability to participate in longer-term coproduction efforts that required follow up with key community contacts. In all five study districts, we found that community members were under economic pressure to work multiple jobs, reducing their capacity for continual participation in coproduction.

Interviewees in Caylloma, Lari, Yanque, and Cabanaconde told us that several decades ago, community members practiced subsistence pastoralism and crop farming. Farmers had few reasons to leave their communities. They would barter in local fairs to obtain food, clothes, and other items. Over time, the economic pressures created by globalization and market integration led many community members to abandon their farmland and migrate to larger cities or different countries. These pressures also pushed community members who chose to remain in their district of origin to commute and take on additional employment. Interviewees told us that the fluctuating prices of crops and the low price of alpaca meat and wool (usually sold to market intermediaries for a fraction of their market price) pushed them to seek other employment opportunities. As one farmer interviewee put it, "*It used to be possible to live from the farm alone. Now we need to work multiple jobs.*" Villagers supplemented their income by travelling outside their district to larger cities such as Arequipa, where they worked as farm laborers on other people's farms, tradesmen, shop owners, and miners, among other jobs. Some community members also held professional positions such as veterinarians, nurses, engineers, and crop advisors. It was also common for community members to own a house in their district of origin, as well as another one in a larger city such as Arequipa, and to commute between the two places for work. A second house in a larger city also enabled community members to send their children to better schools and ensure their employment opportunities outside the farm after graduation. In the coastal Majes district, formed in the more recent 1970s, the original settlers who migrated in the early 1980s practiced export-oriented agriculture from the onset. However, interviewees from Majes also reported an increase in out-migration and commuting.

In all five study districts, interviewees linked market pressures, out-migration, and commuting to decreased ability to organize and to participate in community meetings and events. As one community leader expressed, "*There is a lot of out-migration and it is difficult to get organized now. It is a lot more difficult, even though it's easier to communicate with technological advances. We have cellphones and communicating is faster than ever.*"

Specifically, community members in Caylloma, Lari, Yanque, Cabanaconde, and Majes reported decreased attendance in general assemblies organized by their local irrigation commissions and their municipalities. Interviewees also said there was less participation in community celebrations. Several interviewees made comments such as, "*Before we were more united, everyone attended meetings*" and "*Now, people are less available.*"

Reduced ability to participate in group activities affected the majority of our interviewees across communities. The pressure to commute and/or work multiple jobs affected community members whose income varied based on market fluctuations. Given that our study districts were populated by farming communities, almost all our interviewees and focus group participants were crop farmers and pastoralists. This included the leaders of the local irrigation commissions, who were farmers themselves and did not receive any monetary compensation, as well as some mayors and municipal workers. They reported that the low prices of crops and of alpaca meat and wool forced them to diversify their income by pursuing additional economic opportunities, leaving them with less time to participate in community activities. Even relatively wealthier community members, with professional degrees (i.e., veterinarians, healthcare workers) or employed in the local tourism market (i.e., tour guides, restaurant and hotel owners) told us that they worked long hours and/or multiple jobs which prevented them from attending community meetings. As one healthcare worker and part-time farmer put it, "*I don't really go to meetings because I'm busy working [in the health center]. [...] During my free time, I work on the farm. [...] I recently went to a community meeting after a year of not attending because I happened to be free that day.*" Community members receiving a fixed and regular salary included schoolteachers and principals, municipal workers (although their position was usually temporary, lasting until the new election cycle), priests, and healthcare workers. However, the wages paid to full-time workers were generally low, and it was very rare to find a person that did not have one or more side businesses in addition to their main job.

Declining community cohesion and participation in meetings and events posed obstacles for the coproduction initiative led by SWM. For example, the SWM team sent personalized invitation letters to key contacts interviewed during Phase 1 of the study. These key contacts included mayors, community leaders, and farmers who indicated interest in the coproduction process. Though they had initially agreed to participate and the focus groups were scheduled and confirmed several weeks in advance, many community members had to make last-minute trips to Arequipa to attend to other business. In the districts of Caylloma and Majes, none of the key contacts interviewed during Phase 1 were able to participate in the focus groups on specific dates that were set based on their own availability. In Caylloma, only one person showed up and SWM members gave him a pamphlet summarizing the research results but were forced to cancel the focus group. In Majes, SWM members managed to gather ten community members with the help of local contacts, moments before the focus group was scheduled to start. In the districts of Lari, Yanque, and Cabanaconde, a few community members that received invitation letters were present at the focus groups. Additional community members also became interested and decided to attend once the focus group started, a common occurrence in smaller villages. However, members of SWM were not able to follow up with many of their original key contacts. Thus, while some focus groups were well-attended, they were not always attended by the original contacts, making it difficult to establish the ongoing relationships necessary to the coproduction process.

An additional coproduction challenge was that most of the tools developed by SWM were designed to address discrete and specific challenges related to water and crop management. These included apps for selecting an appropriate crop mix given water limitations or monitoring the water demand of currently growing crops. As such, the tools only addressed one part of community members' increasingly diversified livelihoods. Furthermore, the issues that were listed as most pressing by farmers were economic in nature, including fluctuating crop prices and the lack of agricultural insurance. Not only were SWM members not qualified to address economic issues, but these issues were too broad in scope to be addressed by a single team of university researchers. With today's globalized economy, farmers need cross-cutting solutions that address the issues created by markets. While the economic issues that emerged from the qualitative interviews with community members were discussed among SWM members, it was decided that the scope of coproduction would be limited to the specific water- and crop-related issues that fell within the expertise of SWM researchers.

To generate effective solutions, the coproduction process would have ideally included members from regional water agencies and NGOs. Personnel in these regional organizations have a deep understanding of farmer livelihoods and might have been able to brainstorm potential ideas. Therefore, successful coproduction not only depends on creating an *agora* where stakeholders can deliberate, but it is also important to include boundary actors that have the power and resources to address community concerns. In fact, the inclusion of boundary organizations in the coproduction process might be increasingly important as rural communities become more globalized and integrated into regional markets.

Local Responsibilities are Increasingly Transferred to Regional Organizations

An additional reason limiting community members' long-term participation in coproduction is that watershed management responsibilities, previously localized, are increasingly being transferred to regional organizations. While community members agreed to participate in the coproduction process, many saw water management as the responsibility of regional officials.

Before the 1990s, water management for farming practices in Peru was mainly carried out through local irrigation commissions, which were the main bodies governing the allocation of irrigation water. Their boards of directors, composed of elected community members, were responsible for overseeing the irrigation schedule, the amount of water used on each plot, sanctioning for irrigation-related infractions, and irrigation infrastructure maintenance, among other tasks. Irrigation commissions are still in place today[1],

---

[1] At the time of our study, crop farmers in the districts of Lari, Yanque, Cabanaconde, and Majes were organized in irrigation commissions operating at the sub-district level. In the Caylloma district, pastoralists did not have formal irrigation commissions because their irrigation needs were minimal compared to crop farming. However, they were in the process of forming them at the time of our study.

but they operate in conjunction with regional-level watershed management institutions, which gradually took on some water management tasks.

In the 1990s, the World Bank funded the development and strengthening of regional-level Water Users' Associations (*Juntas de Usuarios*), which are organizations that represent all water users (and multiple irrigation commissions) in a particular region (Vera Delgado and Vincent 2013). In 2009, the Peruvian government adopted a new Water Resources Law (*Ley de Recursos Hídricos*) and established the National Water Authority (ANA, *Autoridad Nacional del Agua*), a central organization with local branches, overseeing water management and distribution throughout Peru (Filippi et al. 2014). Water Users' Associations and local ANA branches took on some responsibilities that were previously conducted by irrigation commissions for which farmers now pay a water fee. Specifically, decisions regarding the irrigation water amount to be used by each farmer are now determined by ANA. Interviewees explained that in the past, they had district-level waterkeepers that allocated water. One interviewee told us that "*My grandfather was a waterkeeper […] He made sure that everyone had sufficient water and that everyone finished irrigating on time. The waterkeeper worked for free […] It was a form of service to the community. We didn't pay […] Now, we no longer have waterkeepers.*"

Now, the irrigation water amount to be used by each farmer is determined by the ANA; however, local irrigation commission authorities still set the irrigation schedule and ensure that farmers do not irrigate past their allocated window. In addition, local conflicts that are difficult to resolve can be elevated to the Water Users' Associations, and then to the ANA, which reviews the case and applies the necessary sanctions. An additional responsibility transferred to the Water Users' Association is the oversight of irrigation infrastructure maintenance and repair. This organization collects annual watershed management plans from irrigation commissions, who are given the option of paying a higher water fee in exchange for help with irrigation infrastructure repair and maintenance. In the past, community members organized regular *faenas* (groupwork days), where they gathered to perform canal maintenance and infrastructure repairs. Now, interviewees report a decline in this practice. One farmer said that "*Now, group work is diminishing, little by little.*" Furthermore, community members made comments such as "*Irrigation canal maintenance and repair are the responsibility of the Water Users' Association*" and that "*ANA should come and see what infrastructure we are missing. For example, [ANA should] help us build reservoirs*."

This upward delegation of water management responsibilities (Popovici et al. in press) has made it more difficult to coproduce directly with communities because community members now rely on and expect regional organizations to solve water-related problems. In fact, several interviewees reported that "*ANA and the Water Users' Association should be more present in [their] community*" in order to help resolve conflicts and repair irrigation infrastructure. In theory, the tools could be distributed by local Water Users' Associations and ANA branches, which would involve training their personnel in the coproduction process. In practice, however, these organizations are understaffed and lack the necessary time and resources to participate in the necessary trainings and to take over tool distribution. This was especially true for the Water Users' Association located in Chivay, which represented water users in Lari, Yanque, and Cabanaconde. The manager of the Water Users' Association in Chivay told us that "*According to the 2009 Water Resources Law, Water User Associations are supposed to have nine full-time technical staff. But here, we only have three.*"

Thus, we are witnessing a shift in Caylloma's rural areas where community members are increasingly busy, reducing their ability to participate in community gatherings and efforts to manage their local water resources. At the same time, government agencies are stepping in and taking on some of the local water management responsibilities, although these efforts are incomplete due to lack of capacity. To address the gap between local needs and incomplete assistance from regional water agencies, community leaders in some local districts decided to hire experts such as lawyers, hydrologists, engineers, and business experts, to provide technical and targeted advice in exchange for payment (Popovici et al. in press). At the time of our study, irrigation commissions in two of the five districts had hired engineers and hydrologists to design blueprints for a small dam that would increase water supply for agriculture. Furthermore, leaders in two other districts had hired lawyers to advocate for a change in ANA water regulations on their behalf. Therefore, we are seeing the emergence of contractual relationships between experts and community members, which, according to interviewees, were less common over ten years ago.

During the coproduction focus groups, some of the community members made comments that suggested they expected to form similar consultant-client relationships with SWM researchers. For example, some community members expected us to give them a diagnosis along with proposed solutions to some of their water-related issues (i.e., what should be the optimal water quality or optimal irrigation schedule). While SWM researchers strived to take on a facilitator role and encouraged brainstorming and open discussion about potential solutions to water-related issues, some community members made comments such as "*We don't have enough knowledge. You're the experts*" and "*What do you think we should do?*" While a top-down transfer of ideas is assumed to produce less effective and less equitable outcomes, there nevertheless seems to be a demand for quick and expedient solutions from busy community members. Such transfer of knowledge would ease their participation burdens and free up their time to be spent on economically productive activities.

Discussion and Conclusions

Coproduction is already recognized as a complex and time-consuming process (Lemos and Morehouse 2005; Briley, Brown, and Kalafatis 2015). This is because coproduction often requires capacity-building to enable stakeholders to build relationships with each other, address power imbalances, and engage with stakeholders in different areas (van Kerkhoff and Lebel 2015). In this paper, we have outlined additional factors that complicate the coproduction process in rural areas, namely the decline in community members' ability to participate in long-term coproduction efforts and the transfer of water management responsibilities from local to regional organizations. Together, these two processes mean that successful coproduction requires additional elements in order to be successful.

Indeed, coproduction must account for community members' changing livelihoods and priorities, posing some obstacles to the iterative and intensive relationship-building needed for this process to be successful. In particular, it was difficult for community members to participate in coproduction because attending a focus group to provide input might result in missed travel or work opportunities. Furthermore, community members had multiple occupations and were becoming less dependent on crop farming and pastoralism, a trend that has been documented in Peru and other parts of the world (Bryceson 2002; Desta and Coppock 2004; Popovici et al. in press). In contrast, the tools presented by SWM in the coproduction focus groups with community members (most of whom were farmers) were mainly focused on improving water management for agriculture. Thus, community members may derive fewer benefits from coproduction focus groups because they only relate to a part of their livelihoods.

Specifically, it might be necessary to involve organizations that can play a boundary role between different stakeholders. This could ease some of the participation burden for community members, as well as some of the travel and other relationship-building costs for researchers. To date, much of the coproduction efforts presented in the literature have focused on empowering community members to be able to participate in the process. However, it might be equally important (if not more so) to focus on building the capacity of regional institutions to conduct coproduction efforts or other appropriate forms of participation. In fact, given the socioeconomic pressures faced by community members, the arena of coproduction might have to shift from in-person meetings with community members to meetings with boundary organizations, whose members can represent various stakeholders, including local communities.

Furthermore, the livelihood changes observed in rural communities pose a new set of challenges when it comes to managing power relations between researchers and community members. In particular, the heavy participation requirements in the form of an *agora* may be a burden for research participants who are increasingly outsourcing some of their water management responsibilities to regional organizations. Thus, there seems to be a local demand for transactional relationships with experts, as opposed to intensive collaboration that relies on in-person participation. In contrast to these trends, SWM researchers assumed that a collaborative coproduction approach would be the most empowering for community members. Nevertheless, the coproduction process imposed costs on both researchers and community members (Oliver et al. 2019). This indicates that even a collaborative approach can be harmful if it is led by a stakeholder group that is well-meaning but operating on assumptions about collaboration and participation that might not match local preferences for more expedient solutions based on more transactional relationships.

Given these challenges, it might be beneficial for the organizers of coproduction focus groups or other participatory efforts to offer monetary compensation to community members for attending. In addition, coproduction efforts need to consider and accommodate diversified lifestyles. Initially, SWM researchers attempted to identify a subset of community representatives that would be best suited to participate in coproduction, namely local leaders and individuals that expressed an interest in participating in our study. However, these individuals also faced the pressure to travel for work and coproduction inevitably became less of a priority. For this reason, allowing more time for the coproduction process might be necessary in order to identify the community members that have the most time, interest, and ability to participate.

Another strategy for approaching busy individuals, particularly farmers, is through individual interviews, rather than focus groups. In this study, both interviews and focus groups were conducted in each community. Interviews better accommodated schedules of the participants because they could be working in the fields during the process. Interviews were also generally shorter than focus group meetings, taking up less time of each individual. However, this method may be more time-consuming for the interviewer, as they have to repeat the process many times.

The transfer of water management responsibilities for irrigation to regional water agencies further complicates the coproduction process, and changes its focus. The fact that local community members have less decision-making power over the management of their irrigation water makes it difficult for them to take full ownership of the tools developed in the coproduction focus groups. Furthermore, it becomes necessary to involve regional water agencies in the coproduction process. A possible way to do this is to conduct coproduction focus groups with both community members and agency personnel as participants, present in the same room. This way, participants can be prompted to discuss who will be responsible for distributing the tools as well as strategies for maintaining tool continuity after they have been developed.

However, researchers need to be mindful that regional water agencies might not be able to take on additional responsibilities due to limited funding and high staff turnover (Rahmani 2012), among other issues. Coproduction projects thus need to find a way to build capacity without increasing the burden for regional water agency staff members. A possible solution might be to use project funds to hire a local consultant who could work under the supervision of regional organizations and ensure the tools developed through coproduction are distributed to community members. Another solution may be to create a local partnership with in-place institutions that can serve as boundary institutions in the coproduction process. This could provide a level of understanding local norms and information-gathering, as well as ensure distribution of final products developed to community members.

In sum, successful coproduction must operate across multiple scales while at the same time accommodating community members' changing livelihoods. Such efforts are likely to require more funds, time, and effort (Bidwell, Dietz, and Scavia 2013; Briley, Brown, and Kalafatis 2015), as well as a different model of engagement with stakeholders. Rather than relying on a prescriptive manual of who to engage in a coproduction process and a rigid set of procedures of how to engage stakeholders, it is important to recognize that the coproduction approach itself needs to be responsive and adaptive to the context within which it is applied (Bremer and Meisch 2017). Additionally, with increased globalization and market integration in rural societies, we see less demand for co-creation and more demand for expert consultation. In such a context, a traditional research method with deliverables developed through consultation might be more appropriate. Coproduction can still be pursued through boundary organizations, who could perform negotiations on behalf of community members and/or help build local capacity should communities wish to engage in coproduction through the *agora* method. Ultimately, researchers and practitioners who are interested in coproduction need to carefully consider the following questions before, as well as during, the recruitment and engagement of stakeholders: 1) who would receive direct benefits from engaging in coproduction?, 2) what capacity do different stakeholders have to engage in coproduction?, and 3) what can be done to contribute to stakeholders' agency to influence change as part of a coproduction process? Regularly reminding ourselves of these important questions and adapting our practices of engaging stakeholders accordingly can greatly improve the chance of success for all who are involved.

Acknowledgments

Funds to support research in the Arequipa Nexus Institute for Food, Energy, Water, and the Environment were provided by the Universidad Nacional de San Agustín. We would also like to thank our research participants in the districts of Caylloma, Lari, Yanque, Cabanaconde, and Majes.

Author Bio and Contact Information

Ruxandra Popovici (corresponding author) is a Postdoctoral Researcher in the Department of Forestry and Natural Resources at Purdue University. Her work focuses on environmental governance, where she researches the various rules and norms through which people on the ground manage their natural resources. She can be contacted at rpopovi@purdue.edu or 195 Marsteller St., West Lafayette IN 47907.

Katy E. Mazer is coordinator of the Sustainable Water Management team of The Nexus Institute at Purdue University. She engages with stakeholder groups in Arequipa, Peru to coproduce water management decision-making tools. She can be contacted at kmazer@purdue.edu or 920 W. State St., West Lafayette, IN 47907.

Anna E. Erwin is a Postdoctoral Research Associate in the Purdue University Department of Forestry and Natural Resources. She is a social scientist who conducts mixed-methods research on how to increase public engagement in climate change and agricultural policymaking at mulitple scales. She can be contacted at erwin9@purdue.edu or through www.annaerwin.com.

Zhao Ma is an Associate Professor of Natural Resource Social Science at Purdue University. Her research examines how individuals and organizations make natural resource decisions in the context of social-ecological change. She can be contacted at zhaoma@purdue.edu or 195 Marsteller Street, West Lafayette, IN 47907-2033, USA.

José P. Pinto Cáceres is a professor in the Department of Agronomy at the Universidad Nacional de San Agustín de Arequipa. He conducts agricultural research and connects with interested associations to improve natural resource management. He can be contacted at jpinto2@unsa.edu.pe or Urb. Aurora s/n (costado Estadio UNSA) Arequipa - Perú.

Laura C. Bowling is a Professor of hydrology in the Department of Agronomy at Purdue University. Her research investigates the water resources impact of environmental change across multiple scales, climate regimes, and ecosystems and communicates these findings to stakeholders. She can be contacted at bowling@purdue.edu or 915 W. State St., West Lafayette, IN 47907.

Edwin F. Bocardo-Delgado is a principal professor in the Department of Biological Sciences and a graduate Environmental Science professor at the Universidad Nacional de San Agustín de Arequipa. He also works as an environmental consultant for several companies and a natural resource management specialist. He can be contacted at ebocardo@unsa.edu.pe or Av. Sánchez Carreón s/n , Cercado Arequipa.

Linda S. Prokopy is a Professor in the Forestry and Natural Resources department at Purdue University. She conducts research on the social dimensions of watershed management. She can be contacted at lprokopy@purdue.edu or 195 Marsteller St., West Lafayette IN 47907.

References

Aggarwal, R.M. 2006. Globalization, local ecosystems, and the rural poor. *World Development* 34(8): 1405-1418. Available at: https://doi.org/10.1016/j.worlddev.2005.10.011. Accessed December 9, 2020.

Ahmad, R., Y. Kyratsis, and A. Holmes. 2012. When the user is not the chooser: Learning from stakeholder involvement in technology adoption decisions in infection control. *Journal of Hospital Infection* 81(3): 163-168. Available at: https://doi.org/10.1016/j.jhin.2012.04.014. Accessed December 16, 2020.

Akpo, E., T.A. Crane, P.V. Vissoh, and R.C. Tossou. 2015. Co-production of knowledge in multi-stakeholder processes: Analyzing joint experimentation as social learning. *The Journal of Agricultural Education and Extension* 21(4): 369-388. Available at: https://doi.org/10.1080/1389224X.2014.939201. Accessed December 16, 2020.

Alford, J. 2002. Why do public-sector clients coproduce? Toward a contingency theory. *Administration & Society* 34(1): 3256. Available at: https://doi.org/10.1177/0095399702034001004. Accessed December 9, 2020.

Almekinders, C.J.M. 2011. The joint development of JM-12.7: A technographic description of the making of a bean variety. *NJAS - Wageningen Journal of Life Sciences* 57(3-4): 207-216. Available at: https://doi.org/10.1016/j.njas.2010.11.007. Accessed December 16, 2020.

Baum, F., C. MacDougall, and D. Smith. 2006. Participatory action research. *Journal of Epidemiology and Community Health* 60(10): 854-857. Available at: https://doi.org/10.1136/jech.2004.028662. Accessed December 16, 2020.

Beier, P., L.J. Hansen, L. Helbrecht, and D. Behar. 2017. A how-to guide for coproduction of actionable science. *Conservation Letters* 10(3): 288-296. Available at: https://doi.org/10.1111/conl.12300. Accessed December 9, 2020.

Berkes, F. 2010. Devolution of environment and resources governance: Trends and future. *Environmental Conservation* 37(4): 489-500. Available at: https://doi.org/10.1017/S037689291000072X. Accessed December 9, 2020.

Bidwell, D., T. Dietz, and D. Scavia. 2013. Fostering knowledge networks for climate adaptation. *Nature Climate Change* 3: 610-611. Available at: https://doi.org/10.1038/nclimate1931. Accessed December 9, 2020.

Biggs, S.D. 1989. Resource-poor Farmer Participation in Research: A Synthesis of Experiences from Nine National Agricultural Research Systems. International Service for National Agricultural Research, OFCOR Series No. 3.

Bovaird, T. 2007. Beyond engagement and participation: User and community coproduction of public services. *Public Administration Review* 67(5): 846-860. Available at: https://doi.org/10.1111/j.1540-6210.2007.00773.x. Accessed December 9, 2020.

Bowen, K.J., F.P. Miller, V. Dany, and S. Graham. 2015. The relevance of a coproductive capacity framework to climate change adaptation: Investigating the health and water sectors in Cambodia. *Ecology and Society* 20(1): 13. Available at: https://doi.org/10.5751/ES-06864-200113. Accessed December 9, 2020.

Brandsen, T., T. Steen, and B. Verschuere (Eds.). 2018. *Co-Production and Co-Creation: Engaging Citizens in Public Services*. (*Routledge Critical Studies in Public Management*). Routledge, New York, New York.

Bremer, S. and S. Meisch. 2017. Co-production in climate change research: Reviewing different perspectives. *Wiley Interdisciplinary Reviews: Climate Change* 8(6): e482. Available at: https://doi.org/10.1002/wcc.482. Accessed December 9, 2020.

Briley, L., D. Brown, and S.E. Kalafatis. 2015. Overcoming barriers during the co-production of climate information for decision-making. *Climate Risk Management* 9: 41-49. Available at: https://doi.org/10.1016/j.crm.2015.04.004. Accessed December 9, 2020.

Bryceson, D.F. 2002. The scramble in Africa : Reorienting rural livelihoods. *World Development* 30(5): 725-739.

Campbell, L.K., E.S. Svendsen, and L.A. Roman. 2016. Knowledge co-production at the research–practice interface: Embedded case studies from urban forestry. *Environmental Management* 57: 1262-1280. Available at: https://doi.org/10.1007/s00267-016-0680-8. Accessed December 9, 2020.

Castellanos, E.J., C. Tucker, H. Eakin, H. Morales, J.F. Barrera, and R. Díaz. 2013. Assessing the adaptation strategies of farmers facing multiple stressors: Lessons from the coffee and global changes project in Mesoamerica. *Environmental Science & Policy* 26: 19-28. Available at: https://doi.org/https://doi.org/10.1016/j.envsci.2012.07.003. Accessed December 9, 2020.

Chimhowu, A. 2019. The 'new' African customary land tenure. Characteristic, features and policy implications of a new paradigm. *Land Use Policy* 81: 897-903. Available at: https://doi.org/10.1016/j.landusepol.2018.04.014. Accessed December 9, 2020.

Cvitanovic, C., J. McDonald, and A.J. Hobday. 2016. From science to action: Principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making. *Journal of Environmental Management* 183(3): 864-874. Available at: https://doi.org/10.1016/j.jenvman.2016.09.038. Accessed December 9, 2020.

Dalton, T.J., N.K. Lilja, N. Johnson, and R. Howeler. 2011. Farmer participatory research and soil conservation in southeast Asian cassava systems. *World Development* 39(12): 2176-2186. Available at: https://doi/org/10.1016/j.worlddev.2011.05.011. Accessed December 16, 2020.

Davis, K., E. Nkonya, E. Kato, D. A. Mekonnen, M. Odendo, R. Miiro, and J. Nkuba. 2012. Impact of farmer field schools on agricultural productivity and poverty in East Africa. *World Development* 40(2): 402-413. Available at: https://doi.org/10.1016/j.worlddev.2011.05.019. Accessed December 16, 2020.

Desta, S. and D.L. Coppock. 2004. Pastoralism under pressure: Tracking system change in southern Ethiopia. *Human Ecology* 32: 465-486. Available at: https://doi.org/10.1023/B:HUEC.0000043516.56037.6b. Accessed December 9, 2020.

Djenontin, I.N.S. and A.M. Meadow. 2018. The art of co-production of knowledge in environmental sciences and management: Lessons from international practice. *Environmental Management* 61: 885-903. Available at: https://doi.org/10.1007/s00267-018-1028-3. Accessed December 9, 2020.

Dudgeon, P., C. Scrine, A. Cox, and R. Walker. 2017. Facilitating empowerment and self-determination through participatory action research: Findings from the National Empowerment Project. *International Journal of Qualitative Methods* 16(1): 1-11. Available at: https://doi.org/10.1177/1609406917699515. Accessed December 16, 2020.

Farr, M. 2018. Power dynamics and collaborative mechanisms in co-production and co-design processes. *Critical Social Policy* 38(4): 623-644. Available at: https://doi.org/10.1177/0261018317747444. Accessed December 9, 2020.

Filippi, M.E., M. Hordijk, J. Alegría, and J.D. Rojas. 2014. Knowledge integration: A step forward? Continuities and changes in Arequipa's water governance system. *Environment and Urbanization* 26(2): 525-546. Available at: https://doi.org/10.1177/0956247814539233. Accessed December 9, 2020.

Higginbottom, G. and P. Liamputtong (Eds.). 2015. *Participatory Qualitative Research Methodologies in Health*. SAGE Publications, London, UK. Available at: https://doi.org/10.4135/9781473919945. Accessed December 9, 2020.

Homsy, G.C. and M.E. Warner. 2013. Climate change and the co-production of knowledge and policy in rural USA communities. *Sociologia Ruralis* 53(3): 291-310. Available at: https://doi.org/10.1111/soru.12013. Accessed December 9, 2020.

Hutchings, P. 2018. Community management or coproduction? The role of state and citizens in rural water service delivery in India. *Water Alternatives* 11(2): 357-374.

King, C. and S. Gillard. 2019. Bringing together coproduction and community participatory research approaches: Using first person reflective narrative to explore coproduction and community involvement in mental health research. *Health Expectations* 22(4): 701-708. Available at: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1111%2Fhex.12908. Accessed December 16, 2020.

Laursen, S., N. Puniwai, A.S. Genz, S.A.B. Nash, L.K. Canale, and S. Ziegler-Chong. 2018. Collaboration across worldviews: Managers and scientists on Hawai'i Island utilize knowledge coproduction to facilitate climate change adaptation. *Environmental Management* 62: 619-630. Available at: https://doi.org/10.1007/s00267-018-1069-7. Accessed December 9, 2020.

Lebel, L., S. Wattana, and P. Talerngsri. 2015. Assessments of ecosystem services and human well-being in Thailand build and create demand for coproductive capacity. *Ecology and Society* 20(1): 12. Available at: https://doi.org/10.5751/ES-06527-200112. Accessed December 9, 2020.

Leimona, B., B. Lusiana, M. van Noordwijk, E. Mulyoutami, A. Ekadinata, and S. Amaruzaman. 2015. Boundary work: Knowledge co-production for negotiating payment for watershed services in Indonesia. *Ecosystem Services* 15: 45-62. Available at: https://doi.org/10.1016/j.ecoser.2015.07.002. Accesssed December 9, 2020.

Lemos, M.C. and A. Agrawal. 2006. Environmental governance. *Annual Review of Environment and Resources* 31: 297-325. Available at: https://doi.org/10.1146/annurev.energy.31.042605.135621. Accessed December 9, 2020.

Lemos, M.C. and B.J. Morehouse. 2005. The co-production of science and policy in integrated climate assessments. *Global Environmental Change* 15(1): 57-68. Available at: https://doi.org/10.1016/j.gloenvcha.2004.09.004. Accessed December 9, 2020.

Lemos, M.C., C.J. Kirchhoff, S.E. Kalafatis, D. Scavia, and R.B. Rood. 2014. Moving climate information off the shelf: Boundary chains and the role of RISAs as adaptive organizations. *Weather, Climate, and Society* 6(2): 273-285. Available at: https://doi.org/10.1175/WCAS-D-13-00044.1. Accessed December 9, 2020.

Lövbrand, E. 2011. Co-producing European climate science and policy: A cautionary note on the making of useful knowledge. *Science and Public Policy* 38(3): 225-236. Available at: https://doi.org/10.3152/030234211X12924093660516. Accessed December 9, 2020.

Meadow, A.M., D.B. Ferguson, Z. Guido, A. Horangic, G. Owen, and T. Wall. 2015. Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society* 7(2): 179-191. Available at: https://doi.org/10.1175/WCAS-D-14-00050.1. Accessed December 16, 2020.

Munoz, S.-A. 2013. Co-producing care services in rural areas. *Journal of Integrated Care* 21(5): 276-287. Available at: https://doi.org/10.1108/JICA-05-2013-0014. Accessed December 9, 2020.

Oliver, K., A. Kothari, and N. Mays. 2019. The dark side of coproduction: Do the costs outweigh the benefits for health research? *Health Research Policy and Systems* 17(33). Available at: https://doi.org/10.1186/s12961-019-0432-3. Accessed December 9, 2020.

Ostrom, E. 1996. Crossing the great divide: Coproduction, synergy, and development. *World Development* 24(6): 1073-1087. Available at: https://doi.org/10.1016/0305-750X(96)00023-X. Accessed December 9, 2020.

Pohl, C., S. Rist, A. Zimmermann, P. Fry, G.S. Gurung, F. Schneider, C.I. Speranza, et al. 2010. Researchers' roles in knowledge co-production: Experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. *Science and Public Policy* 37(4): 267-281. Available at: https://doi.org/10.3152/030234210X496628. Accessed December 9, 2020.

Poocharoen, O. and B. Ting. 2015. Collaboration, co-production, networks: Convergence of theories. *Public Management Review* 17(4): 587-614. Available at: https://doi.org/10.1080/14719037.2013.866479. Accessed December 9, 2020.

Popovici, R., A. Erwin, Z. Ma, L.S. Prokopy, L. Zanotti, E.F.B. Delgado, J.P. Pinto Cáceres, E.Z. Zeballos, E.P.S. O'Brien, L.C. Bowling, and G.R.A. Larrea. In press. Outsourcing governance in Peru's integrated water resources management. *Land Use Policy*. Available at: https://doi.org/10.1016/j.landusepol.2020.105105. Accessed December 9, 2020.

Prokopy, L.S., J.S. Carlton, T. Haigh, M.C. Lemos, A.S. Mase, and M. Widhalm. 2017. Useful to usable: Developing usable climate science for agriculture. *Climate Risk Management* 15: 1-7. Available at: https://doi.org/10.1016/j.crm.2016.10.004. Accessed December 9, 2020.

Rahmani, R. 2012. Donors, beneficiaries, or NGOs: Whose needs come first? A dilemma in Afghanistan. *Development in Practice* 22(3): 295-304. Available at: https://doi.org/10.1080/09614524.2012.664622. Accessed December 9, 2020.

Saldaña, J. 2009. *The Coding Manual for Qualitative Researchers*. Second edition. SAGE Publications, Thousand Oaks, CA.

Schuttenberg, H.Z. and H.K. Guth. 2015. Seeking our shared wisdom: A framework for understanding knowledge coproduction and coproductive capacities. *Ecology and Society* 20(1): 15. Available at: https://doi.org/10.5751/ES-07038-200115. Accessed December 9, 2020.

Shaffer, L.J. 2014. Making sense of local climate change in rural Tanzania through knowledge co-production. *Journal of Ethnobiology* 34(3): 315-334. Available at: https://doi.org/10.2993/0278-0771-34.3.315. Accessed December 9, 2020.

Stensrud, A.B. 2016. Dreams of growth and fear of water crisis: The ambivalence of 'progress' in the Majes-Siguas Irrigation Project, Peru. *History and Anthropology* 27(5): 569-584. Available at: https://doi.org/10.1080/02757206.2016.1222526. Accessed December 9, 2020.

Sternberg, H. 2011. Rural electrification: Towards an application of coproduction and its potential for the case of India. *International Journal of Regulation and Governance* 11(2): 77-111. Available at: https://doi.org/10.3233/IJR-120104. Accessed December 9, 2020.

van Kerkhoff, L.E. and L. Lebel. 2015. Coproductive capacities: Rethinking science-governance relations in a diverse world. *Ecology and Society* 20(1): 14. Available at: https://doi.org/10.5751/ES-07188-200114. Accessed December 9, 2020.

Vera Delgado, J. and L. Vincent. 2013. Community irrigation supplies and regional water transfers in the Colca Valley, Peru. *Mountain Research and Development* 33(3): 195-206. Available at: https://doi.org/10.1659/mrd-journal-d-12-00119.1. Accessed December 9, 2020.

Vincent, K., M. Daly, C. Scannell, and B. Leathes. 2018. What can climate services learn from theory and practice of co-production? *Climate Services* 12: 48-58. Available at: https://doi.org/10.1016/j.cliser.2018.11.001. Accessed December 9, 2020.

Wall, T.U., A.M. Meadow, and A. Horganic. 2017. Developing evaluation indicators to improve the process of coproducing usable climate science. *Weather, Climate, and Society* 9(1): 95-107. Available at: https://doi.org/10.1175/WCAS-D-16-0008.1. Accessed December 9, 2020.

Wyborn, C. 2015. Co-productive governance: A relational framework for adaptive governance. *Global Environmental Change* 30: 56-67. Available at: https://doi.org/10.1016/j.gloenvcha.2014.10.009. Accessed December 9, 2020.

Appendix: Characteristics of Our Five Study Districts

As shown in Table 3 below, our five study districts varied in terms of elevation, population, water source and water availability, land owned, and main income source. The district of Caylloma has an elevation of 4,310 meters above sea level, where most crops do not grow. Thus, agricultural producers interviewed were pastoralists raising alpacas, llamas, and some other livestock such as sheep. The districts of Lari, Yanque, and Cabanaconde are small villages largely populated by crop farmers who practice small-scale terraced agriculture. The main crops grown in these districts are maize, barley, garlic, broad beans, quinoa, and alfalfa. In addition to glacier melt and natural springs, the districts of Yanque and Cabanaconde receive irrigation water from the Majes Channel. The Majes Channel is a government-sponsored water diversion project constructed in the 1970s that brings water from the Condoroma Dam near the Tuti district (located upstream from the Yanque district but downstream from the Caylloma district) to the coastal Majes District (Stensrud 2016). Thus, the Majes district is a "new" community that does not have the same social history as the other study districts. The Majes Channel is the main source of irrigation water for the Majes district, where crop farmers practice larger-scale agriculture.

Table 3. Characteristics of the study districts.

Study Districts	Elevation (m)	Population	Water Sources	Average # Hectares per Household	Main Sources of Income
Caylloma	4,310	3,697	Glacier melt; Natural springs and rivers	100	Pastoralism; Mining industry
Lari	3,330	904	Glacier melt; Natural springs and rivers	1	Agriculture; Some pastoralism
Yanque	3,417	2,117	Glacier melt; Natural springs and rivers; Majes Channel	1	Agriculture; Some pastoralism; Tourism
Cabanaconde	3,296	2,096	Glacier melt; Natural springs and rivers; Majes Channel	1.5	Agriculture; Tourism; Remittances
Majes	1,410	60,108	Majes Channel	5	Agriculture

UNIVERSITIES COUNCIL
ON WATER RESOURCES

The National Institutes
for Water Resources

2021 UCOWR/NIWR
Annual Water Resources Conference

June 8-10, 2021
Hyatt Regency, Greenville, SC

The conference planning committee is busy planning the 2021 conference to be held June 8-10. Please note, the planning committee is aware of and carefully considering the potential pandemic impacts through June 2021. There will be a conference in June 2021!

Join us as we head to the Southeast in 2021. Nestled up against the foothills of the Blue Ridge Mountains in the heart of South Carolina's Upcountry, Greenville is a social distancing dreamland. The region's rich history, state parks, national forests, and wilderness areas provide endless opportunities for outdoor exploration. UCOWR is a family-friendly organization and we invite you to extend your conference participation and enjoy the abundance of opportunities a trip to Greenville offers.

Attendees will delve into current perspectives on a range of contemporary water resources challenges and solutions (at community, watershed, regional, national, and/or global scales). In addition to the vast range of water-related topics and disciplines that are typical of a UCOWR conference, a special focus will be on Water and Social-Environmental Justice. The Call for Abstracts will be sent out in January. Online abstract submission will open in January.

For more information on the conference, please visit https://ucowr.org/conference/.

General questions about the conference can be directed to Karl Williard (williard@siu.edu), Executive Director of UCOWR.

Contents

2021 UCOWR / NIWR
ANNUAL WATER RESOURCES CONFERENCE
GREENVILLE, SC
JUNE 8-10, 2021

UCOWR
UNIVERSITIES COUNCIL
ON WATER RESOURCES

Universities Council on Water Resources
Mail Code 4526
Southern Illinois University Carbondale
1231 Lincoln Drive
Carbondale, IL 62901
www.ucowr.org