YEAR 5 ANNUAL REPORT
REPORTING PERIOD
JANUARY 1, 2020 TO DECEMBER 31, 2020

Award Number: OIA1557349
PI/PD: Gwen Jacobs
June 1, 2016 to May 31, 2021
# Table of Contents

I. 'Ike Wai Year 5 Annual Report Information ........................................................................................................ 1

II. Overview .......................................................................................................................................................... 1
   A. Vision, mission, and goals of the project ........................................................................................................ 1
   B. Accomplishments achieved during the reporting period .................................................................................. 2
   C. Intellectual merit and broader impacts .......................................................................................................... 4
   D. Challenges, novel opportunities, and changes in strategy ............................................................................. 5

III. Research and Education Program ................................................................................................................ 7
   A. Goal 1. Develop and validate improved conceptual models of subsurface water distribution and flow within and through Pearl Harbor and Hualālai aquifers systems (in order to develop a framework to sustainably manage groundwater resources in regions) .................................................. 9
   B. Goal 2. Develop a new data and modeling platform for Hawai‘i volcanic hydrogeology, economic modeling and decision support ........................................................................................................................................ 26
   C. Goal 3. Education and Workforce Development Focus: Establish an integrated set of pathways to train and develop a diverse cohort of students, post-doctoral and faculty researchers at UHM and UHH to address Hawai‘i’s water challenges ........................................................................................................ 50

IV. Solicitation-Specific Project Elements ........................................................................................................... 55
   A. Workforce Development ................................................................................................................................. 55
   B. Diversity .......................................................................................................................................................... 56
   C. Partnerships .................................................................................................................................................... 56
   D. Collaborations ................................................................................................................................................. 57
   E. Sustainability .................................................................................................................................................. 58

V. Broadening Participation ................................................................................................................................... 59

VI. Expenditures and Unobligated Funds ................................................................................................................ 59

VII. Special Conditions .......................................................................................................................................... 59

VIII. Response to External Evaluation Recommendations .................................................................................. 59

IX. Tabular/Graphic Representation of Progress to Date ....................................................................................... 66

X. Appendix A: Abbreviations and Hawaiian Language Terms ................................................................................. 67
I. ‘Ike Wai Year 5 Annual Report Information

RII Track-1: ‘Ike Wai: Securing Hawai'i’s Water Future
NSF Award Number: OIA-1557349

Award Start Date: June 1, 2016
Principal Investigator: Gwen Jacobs, University of Hawai'i

Reporting Period: January 1, 2020 to December 31, 2020

II. Overview

A. Vision, mission, and goals of the project

Vision: Water resource management in Hawai'i is sustainable, responsible and data-driven. Scientific, cultural and social dimensions to the problem of water security are integrated in a transparent, stakeholder-driven and rigorous water research enterprise in Hawai'i.

Mission: To ensure Hawai'i’s future water security through an integrated program of research, education, community engagement and decision support.

Goals: ‘Ike Wai has the potential to be a transformational project for the University of Hawai'i, the state, and for organized research units such as the University's Water Resources Research Center (WRRC). The project's promise is to be transformative scientifically in terms of the knowledge base of a critical resource, to transform capacity, in terms of the human, physical and computational capital to perform cutting-edge water research, and socially, to threshold a new level of partnership between the academic community and stakeholders in Hawai'i. The specific goals of the ‘Ike Wai project are:

Goal 1: Collect new hydrological and geophysical data on the two study sites to address data gaps in our understanding of subsurface structure and flow.

Goal 2: Develop a new data and modeling platform for Hawai'i volcanic hydrogeology, economic modeling and decision support.

Goal 3: Establish an integrated set of pathways to train and develop a diverse cohort of students, post-doctoral, and faculty researchers at UHH and UHM to address Hawai'i’s water challenges.

Participating Units: ‘Ike Wai is a complex project with multiple internal and external participants. Two campuses, UH Mānoa (UHM) and UH Hilo (UHH) are the key institutional participants. At UHM, the units include Water Resources Research Center (WRRC; for overarching water resource management), Hawai'i Institute of Geophysics & Planetology (HIGP; for geophysics and geology), UH Economic Research Organization (UHERO; for water economics), Dept. Civil and Environmental Engineering (for groundwater modeling), the College of Social Sciences (CSS) for stakeholder engagement and the Laboratory for Advanced Visualization and Applications (lava.manoa.hawaii.edu), led by Jason Leigh, for visualization. At the UH System level, Information Technology Services (ITS) provides senior leadership (PI, Jacobs) and the computing, data management, analysis and dissemination software infrastructure. The Hawai'i Data Science Institute, co-directed by PI Jacobs and Leigh, serves as a nexus for Data Science Education, Research and Partnerships. UHH houses education efforts in Data Science across four participating departments: Computer Science, Mathematics, Marine Science and Economics and Business.
Leadership: The Leadership Team is comprised of senior personnel that represent and steer the project sciences, education, community engagement and cyberinfrastructure teams, as well as representatives from senior campus leadership that manage the project.

Gwen Jacobs: PI, Cyberinfrastructure
Nicole Lautze: Co-I Geochemistry, Geophysics
Barbara Bruno: co-PI, Workforce & Education
Matthew Platz: Data Science, UH Hilo
Helen Turner: co-PI, Diversity Equity and Inclusion, Chaminade University
Gregory Chun: Community Engagement
Aly El-Kadi: Groundwater Modeling
Thomas Giambelluca: Geography, Climate & Rainfall
Velma Kameoka: UH Mānoa Vice Chancellor for Research
Michelle Choe: EPSCoR Program Administrator
Kaiwipuni Punihei Lipe: Native Hawaiian Affairs Program Officer and Interim Director Inst. for Hawaiian Language Research & Translation (IHLRT)
Donald Thomas: Geology, Geochemistry, UH Mānoa

B. Accomplishments achieved during the reporting period

Capacity Building (2020 Graduates):
This year 2 PhD and 1 Master’s degree students graduated from the project.
Nathan DeMaagd, Ph.D. Economics, Kimberly Burnett, Advisor
Trista McKenzie, Ph.D. Geology and Geophysics, Henrietta Dulai, Advisor
Thomas Pi’ilani Smith, M.A. Urban and Regional Planning, Greg Chun, Advisor

Awards and Recognition:

Faculty Awards and Recognition:

Nicole Lautze, UHM associate researcher in the Hawai‘i Institute of Geophysics and Planetology (HIGP) received a promotion to full professor with tenure in 2020.

Jonghyun Harry Lee, UHM faculty was the symposium organizer for a machine learning symposium entitled ‘Combining Artificial Intelligence and Machine Learning with Physical Sciences’ for the Association for the Advancement of Artificial Intelligence Conference Spring Symposium 2020.

John Burns, UHH faculty was co-PI on a National Fish and Wildlife Foundation Award for $300k (Award # 6109878) with several collaborators from UHM and UHH titled “Mitigating impacts from environmental stressors: early response to the Chondria outbreak at Pearl and Hermes Atoll, and Hurricane Walaka impacts at French Frigate Shoals.” Burns was PI on a cooperative agreement with the National Park Service (Award # P20AC01074) for $200k for a project titled “Evaluate coral reef, marine fish, and benthic monitoring protocol in Pacific Island and South Florida Caribbean Inventory and Monitoring Networks.”

Postdoc/Student Awards:

Eric Attias, a postdoctoral researcher with ‘Ike Wai authored a publication titled ‘Marine electrical imaging reveals novel freshwater transport mechanism in Hawai‘i’ in Science Advances with Don Thomas. This publication included collaborators D. Sherman, K. Ismail and S. Constable and received both local and national media coverage.

Sofia Ferreira, a UHH undergraduate student won the award for Outstanding Undergraduate
Student Oral Presentation for her project “Examining coral community composition and 3D habitat structure on shipwrecks in Apra Harbor, Guam”. She presented this work at the 2020 Hawaii Conservation Conference. John Burns, UHH served as her advisor.

Trista McKenzie, a UHM graduate student won the L&O Letters Early Career Publication Honor (ASLO Limnology & Oceanography (L&O) Letters) and Toby Lee ARCS Award in Earth Sciences (ARCS Foundation Honolulu Chapter) in 2020. Henrietta Dulai (UHM) served as their advisor.

Brytne Okuhata, a UHM graduate student won the Stefan Seyb Award in SOEST for her graduate work. This award recognizes excellent students who measure, analyze and/or model geophysical observations of Earth and Environmental processes. Aly El-Kadi (UHM) served as her advisor.

Theodore Brennis, a UHM graduate student received a funding award from the Science Mathematics and Research for Transformation (SMART) Department of Defense (DoD) Service for Scholarship program. The program webpage can be found at: https://www.smartscholarship.org/smart?id=smart_index. Nicole Lautze (UHM) served as his advisor.

PEARC20 Best Paper Awards: Several team members won recognition for their work at the Practice and Experience in Advanced Research Computing Conference, July 2020.


Awards Included:

Best Paper in Machine Learning and Artificial Intelligence Track: “Exploring collections of research publications with human steerable AI” Alberto González Martínez, Billy Troy Wooton, Nurit Kirshenbaum, Dylan Kobayashi and Jason Leigh


Key Research and Education Accomplishments:

Key research accomplishments this year include achievements in geophysics, both marine and terrestrial and in the development of the Hawaiʻi Climate Data Portal.

Eric Attias’ ground-breaking discovery of a new transport mechanism of fresh groundwater may represent a new mechanism and resource for volcanic islands worldwide. These potentially new renewable offshore reservoirs are considered more resilient to climate change-driven droughts. The results of this study were recently published in Science Advances (Attias et al., 2020).

Nicole Lautze and Stéphanie Barde-Cabusson made excellent progress on acquiring geophysics data from the Dole Plantation property in October 2020, despite restrictions due to COVID19 safety precautions. They were able to collect AudioMagnetelluric (AMT) and gravity data from the property. The new data overlaps with Seismic and Self Potential (SP) data acquired in 2019 from the same locations completing a fully integrated dataset. Lautze and Barde-
Cabusson have since analyzed this data and the results are described in more detail below.

**Sean Cleveland, Jennifer Geis and Jared McLean** worked with Tom Giambelluca’s group to develop a new data portal to host all of the meteorological data compiled for the state of Hawaiʻi within the ‘Ike Wai Gateway. The Hawaiʻi Climate Data Portal (HCDP) will host both daily and monthly rainfall data from over 1000 meteorological stations across the State spanning the period 1920 to present day. The HCDP hosts daily observations of other meteorological variables including relative humidity, solar radiation, and wind speed. In addition to station-based climate data, the HCDP hosts 100 years of monthly rainfall maps and 30 years of daily rainfall maps, both of which are updated in near-real-time. Users will have the ability to query specific data products, including quality-controlled observations as well as serially complete versions of this data, for specified time periods.

**Travis Mandel** developed and led an innovative summer research experience for undergraduates at UH Hilo entitled "Human-in-the-Loop Research Experience." Students learned in a hands-on manner while working on their cutting-edge research projects. Travis successfully delivered this course with COVID safe social distancing. The students pursued three interrelated projects in teams of two. Projects included topics such as how can AI help scientists collect better data in domains like psychology and ecology, developing methods for identification of invasive plans using AI and improving on tracking methods for marine science with sparse data sets. All of these projects used principles of human-in-the-loop artificial intelligence and are highly accessible to undergraduate students.

**Publications:**

‘Ike Wai participants published a total of 55 peer reviewed publications and conference proceedings in 2020.

**C. Intellectual Merit and Broader Impacts.**

**Intellectual Merit:** This project has collected new geological, hydrological, and geophysical data at previously unavailable spatio-temporal resolution to develop actionable models of Hawaiʻi’s aquifers, water flow, and transport processes (Objective 1). Geophysical imaging will provide new high-resolution 3D maps of geologic structures. Real-time down-well monitoring will support analysis of aquifer volume and hydraulic conductivity estimations. Flow and aquifer connectivity measurements will integrate three approaches: submarine groundwater discharge (SGD) analysis, geochemistry and, innovatively, the use of microbial diversity as a groundwater tracer.

We will create a transformative knowledge resource and modeling platform for water research and decision support (Objective 2). The ‘Ike Wai Integrated Knowledge Environment (IKE) supports numerical modeling with High Performance Computing, and advanced data visualization, creating a decision support tool for our water enterprise. IKE has been populated with new data, previously untapped legacy/historical agency data, and indigenous Hawaiian knowledge. As an integral part of the field data collection, sensor fabrication, and data analysis, our education program will build an inclusive and diverse pipeline of future water researchers and policymakers (Objective 3). Our Pacific island culture and Hawaiʻi’s pressing water issues frame multi-level efforts in diversity and community engagement that span these objectives. ‘Ike Wai assembles a diverse team of hydrogeophysicists, modelers, volcanologists, engineers, visualization experts, social scientists, and educators, including seven strategic new faculty hires in the University of Hawaiʻi (UH) System. The three objectives will be accomplished through five focal activities: (a) Develop new conceptual models of water distribution and flow within the aquifers that account for Hawaiʻi’s volcanic geology; (b) Identify fundamental data and knowledge gaps about water that will impact economic growth and development; (c) Develop tools to allow decision makers to make informed choices about water resource management; (d) Provide an inclusive STEM pipeline to develop diverse water scientists, data scientists, and policymakers;
(e) Provide an improved model for volcanic island hydrology and water resources in Hawai‘i that is extensible to other Pacific volcanic islands.

Broader Impacts: Hawai‘i depends exclusively on local water. ‘Ike Wai will provide data and models that address the grand challenge of water sustainability. A diverse workforce of data scientists and water researchers will work in concert with the community, government and business to inform decision makers with high-quality data and predictive capacity. The resulting new data-to-knowledge paradigms for volcanic island sustainability will be extensible to other Pacific locales. The project incorporates indigenous and local communities, and its robust, inclusive and diverse human capital pipeline of undergraduates, graduate students, postdocs and junior faculty will address water challenges at the academic and policy level.

**Advance discovery and understanding while promoting teaching, training, and learning.** Research activities in geophysics, geochemistry, traditional/historical knowledge and sensor development have involved fifteen graduate students and four post-doctoral trainees. Each trainee position (including junior faculty) has an active role in a mentoring cascade and frequent professional development opportunities offered by the Education team (Bruno). Junior faculty are mentored both scientifically and in skills sets such as laboratory management, proposal writing, and navigation of university systems and the tenure process. Teaching is being actively promoted by ‘Ike Wai. All UHH and most UHM ‘Ike Wai faculty have active teaching loads and several (Grobbe, Lee, Weyenberg, Burns, Mandel, Hong) incorporated ‘Ike Wai related materials and concepts in their classes.

**Broadening participation of under-represented groups** (See Section IV.B Diversity). A key focus of ‘Ike Wai has been partnering with Native Hawaiian-serving organizations to build pathways for Native Hawaiian and other diverse local students interested in STEM careers.

**Broaden dissemination to enhance scientific and technological understanding.** The ‘Ike Wai Science Gateway (Objective 2.1) serves as the central location for data management, computation, analysis, visualization, and dissemination of all data and data products generated by the ‘Ike Wai project. The Hawai‘i Climate Data Portal is designed to disseminate high resolution (250- m) monthly gridded rainfall and estimated uncertainty maps from up-to-date, quality controlled, tabular rainfall data. The EPSCoR Website ([http://www.hawaii.edu/epscor/](http://www.hawaii.edu/epscor/)) and Social Media (Objective 2.4): Maria Dumanlang, our communications director continues to disseminate project accomplishments through multiple communication channels. In addition to our website and Facebook pages, the project’s social media presence has expanded to include more content on Instagram, Twitter and LinkedIn. Internally, University of Hawai‘i (UH) News produced 21 EPSCoR-focused stories.

D. Challenges, novel opportunities, and changes in strategy

**Specific challenges:**

**COVID-19:** The COVID-19 pandemic impacted personnel, fieldwork, interisland and mainland travel from mid-March through December 2020. The University of Hawai‘i closed the campus to the public and all in-person meetings and courses were moved to remote interactions. The largest impact to the project was the cancellation of inter-island travel, which impacted the team’s ability to continue fieldwork and community meetings on Hawai‘i Island. Fortunately, the team had completed almost all of the data collection for the project on Hawai‘i Island, with the exception of additional geophysical data. Team members continued geochemical sampling on O‘ahu, with the observance of COVID-19 safety protocols.

In August 2020, Niels Grobbe resigned his faculty position at UHM to return to the Netherlands to take a new professional position. He resigned for personal reasons and to be closer to his family. He has an affiliate faculty appointment in both the Water Resources Research Center and in the
Hawai‘i Institute of Geophysics and Planetology and continues to collaborate with project faculty and students. Following his departure, Nicole Lautze and Stéphanie Barde-Cabusson developed a geophysics field plan to collect data on the Dole Property on O‘ahu. Their fieldwork campaign was very successful, and they were able to collect an extensive set of measurements using two additional geophysical techniques. These results are summarized in Activity 1.1.2 below.

**Novel Opportunities:**

**Hawai‘i Data Science Institute (HIDSI) Activities:** The HIDSI is a UH System-wide virtual institute focused on data science education, multidisciplinary research and building industry partnerships. It serves as the primary locus for collaborative work between ‘Ike Wai faculty at UH Hilo and their colleagues at UH Mānoa. Our weekly Data Science Friday seminar series draws 30-50 attendees each week from UH Mānoa, UH Hilo and local business and industry. In 2020 HIDSI hosted 18 events including seminars, workshops, two research showcases and a collaboration with Stanford and IBM to host the Women in Data Science Honolulu Conference resulting in approximately 780 participants across all events. The Data Science Fellows program is a one-year fellowship for graduate students and advanced undergraduates. Students are recruited from a broad range of domain science and data science. The program includes a mentored research project, training in cyberinfrastructure skills and professional development activities. Sofia Ferreria, a student in John Burns’ lab is a member of the Fellows program currently.

**PEARC20:** Several members of ‘Ike Wai had significant roles in the planning and execution of the annual Practice and Experience in Advanced Research Computing (PEARC) meeting. This meeting is the go-to annual conference for cyberinfrastructure professionals and researchers. PI Jacobs served as General Chair, Sean Cleveland as Technical Program Co-Chair, and Jason Leigh as the Visualization Chair. Michelle Choe and Maria Dumanlang provided administrative and social media support.

**Faculty hiring update:** All of the faculty hiring proposed for the ‘Ike Wai project was completed in Year 4 (Objective 3.5). UH Hilo completed its final faculty recruitment commitment with the hiring of Dr. Sukhwa Hong into the College of Business and Economics last year. Dr. Niels Grobbe resigned his position in August 2020 for personal reasons related to COVID-19. Nicole Lautze was awarded a promotion to Full Professor with tenure in 2020. This promotion reflects her significant research accomplishments and her growing national and international reputation in geosciences, geothermal science and energy research. Travis Mandel was awarded an NSF Career Award for his research and teaching in artificial intelligence and human-in-the-loop AI.

New faculty were highly productive this year, authoring 38 publications and 4 conference proceedings in 2020. Several faculty also were involved with new NSF awards in 2020. These include:

Travis Mandel: CAREER: Accelerating Scientific Data Collection through Human-in-the-Loop Artificial Intelligence #1942229; Principal Investigator: Travis Mandel; University of Hawai‘i, $210,545.00.

Travis Mandel: SCC-PG: Big Island Drink Smart: #1952263; Principal Investigator: Karen Pellegrin; Co-Principal Investigator: Shihwu Sung, Mazen Hamad, Ryan Perroy, Travis Mandel; Organization: University of Hawai‘i; $149,961.00.

Harry Lee: Elements: ALE-AMR Framework and the PISALE Codebase: #2005259; Principal Investigator :Alice Koniges; Co-Principal Investigator: Jonghyun Lee; Organization: University of Hawai‘i, $599,996.00.

Leah Bremer: CoPe EAGER - Identifying Multiple Values for Beaches and Coastlines Under Sea
III. Research and Education Program

Here we describe the major accomplishments and research findings during the reporting period organized by the major goals or focus areas of the project, as put forth in the original proposal and approved strategic plan.

Goal 1: Develop and validate improved conceptual models of subsurface water distribution and flow within and through Pearl Harbor and Hualālai aquifers systems (in order to develop a framework to sustainably manage groundwater resources in both regions).

Objective 1.1: Image subsurface geologic structures and/or the location of groundwater in 3 to 4 target areas of Hualālai and Pearl Harbor aquifers systems using geophysical techniques.

Our geophysical study sites focus on three science questions (Q1-Q3):
1) What is the nature of the high/low divide (Hawai‘i Island and O‘ahu)?
2) What spatial hydrogeological variations exist along the western boundary of the Keauhou aquifer systems?
3) What are the characteristics of the valley fills on O‘ahu and their impact on local hydrology?

Activity 1.1.1: Perform synthetic simulations of MT, gravity, ERT/IP, SP, and seismic geophysical techniques for 3 to 4 target areas in the Pearl Harbor and Hualālai aquifer systems in order to identify optimal field method(s). (Lautze, Barde-Cabusson)

Results: The majority of this task was completed in prior years. In 2020 Lautze and Barde-Cabusson developed a plan to obtain audio-magnetotelluric (AMT) and gravity data on the Dole property, as further work on Hawai‘i Island was rendered infeasible due to COVID-19. The new data overlaps with seismic and self-potential (SP) data on Dole property obtained in 2019, thus enabling a fully-integrated dataset. This plan was approved by the NSF Program Officers and carried out in Oct 2020 (see Activity 2.1.2).

As a result of the work done in the previous reporting period, developing and testing our one-dimensional (1D) MT forward modeling and inversion code, we used the ‘R’ programming language and STAN to expand the capabilities of the software to not only invert for the 1D subsurface electrical resistivity distribution with uncertainty quantification (e.g. per station) but also to enable inference of hydrogeological parameters of interest, such as rock formation porosity and pore fluid salinity.

Activity 1.1.2: Design geophysical survey, obtain land access permissions, and acquire field data. (Lautze, Barde-Cabusson)

Results: West Hawaii: In 2020, we had planned to investigate the high/low divide in Keauhou, Hawai‘i Island using a three-dimensional (3D) ambient seismic noise and self-potential (SP) study on land owned by Queen Lil‘uokalani Trust, which traverses the divide (Figure 1). However, inter-island travel and field work restrictions due to Covid-19 has made it impossible to acquire this dataset to date.
In 2020, we collected new SP data at Queen Liliʻuokalani Trust land (QLT, Big Island) with the goal of understanding spatial hydrogeological variations along the western boundary of the Keauhou aquifer system. The new data was combined with that of the 2019 survey, referenced to the ocean, and corrected to create an extended SP map (Figure 2.a.). This map shows the results of our measurements, where the blue colors show negative SP anomalies, which we interpret as vertical infiltration along the path of the groundwater and the blue tones show the main groundwater flows. The blue region next to the Wastewater Treatment Plant could be associated with infiltration from the plant, however only part of this area is constrained by data. Alternatively, this anomaly and several others coincide with a lava tube visible at the surface (white dashed line in the northern part of the map). Water flowing inside this lava tube could also explain this anomaly.

Further analysis of the initial SP survey performed at QLT land, focusing on the anchialine pond (white star; Figure 2.b.), determined that even if the main groundwater path leads to the anchialine pond itself, there may be minor paths along the coastal area (dashed arrows along the coast). These multiple groundwater paths could be associated with various lava tubes. A publication including those geophysical results and cultural significance of anchialine ponds in the Hawaiian culture, is currently in preparation. (Barde-Cabusson et al., in prep.).

**Results:** Pearl Harbor, Oʻahu: Land access at Dole Fruit Company on Oʻahu was obtained to study the nature of the hydrogeological structures that cause an abrupt change in water level, considered to be an analog to the high/low divide on Hawaiʻi Island. We studied the potential impact this structure could have on the characteristics and distribution of the groundwater system feeding into the Pearl Harbor aquifer.

Based on the results obtained with the SP and seismic ambient noise methods (see Activity 1.1.3.), additional and complementary geophysical surveys were planned and conducted in October 2020 (Figure 3). 31 AMT measurements were performed to help confirm the nature and extent of the Northern Schofield dam at greater depth. A total of 88 gravity measurements were also obtained and will allow for a future comparative study of the Southern
Outputs: Keahou, Big Island: Extended Self-Potential (SP) data was collected at Queen Lili'uokalani Trust with additional interpretations of groundwater/SGD system at the coast. A publication is currently in preparation (Barde-Cabusson et al., intended for early 2021) MT and gravity data collected at Dole Plantation land is currently being processed for analysis and will be published in 2021.

Outcomes:
Keahou, Hawai'i Island: The self-potential data collected at the anchialine pond identifies the dominant and preferred groundwater flow paths feeding into this ecosystem and in the coastal area. The data demonstrates anomalies in hydraulic conductivity, related to geological structures such as lava tubes. The site is located at the western boundary of the Keahou aquifer system, Kona, Hawai'i Island, and our findings provide information on this important boundary condition for the West Hawai'i groundwater modeling efforts (Q2).

Pearl Harbor, O'ahu: The complementary geophysical studies (AMT and gravity measurements) provided us with subsurface information necessary to understand the nature of the high/low divide and its impact on the hydrogeological system at the Northern Schofield Dam. This serves as an analogy to the high/low divide that we are studying on the Big Island (Kona), and enables compare and contrast studies between the two sites (Q1). Furthermore, the Southern Schofield dam forms an important hydrological boundary condition for the Pearl Harbor models. Due to the challenging conditions to acquire geophysical data in this area (density of the population/infrastructures), only gravity measurements will be possible. The hydrogeophysical information gathered at the Northern dam will thus also serve as a base to identify similar structures at the Southern dam. The data acquired will provide insight into the flow paths and groundwater distribution at this boundary, serving as important input data as well as a means to calibrate and validate hydrological models for the Pearl Harbor aquifer system.

Activity 1.1.3: Model and invert newly obtained geophysical data. (Lautze, Barde-Cabusson)

Results: Kaiwi Coast (Valley fill analog) O'ahu: Last year we acquired a multi-geophysical dataset, including SP, seismic ambient noise, and a small, preliminary 3D ERT/IP data as part of the hydrogeophysics summer field school program at UH Mānoa. This class, hosted in the summer of 2019, allowed us to acquire the SP and seismic ambient noise. Processing has been fine-tuned and an interpretative model proposed and formatted for publication (Grobbe et al., submitted). Figure 4 shows the ambient noise surface wave tomography final results. The data was processed via cross-correlation interferometry and subsequent surface wave group velocity dispersion analysis of the recorded noise data (after pre-processing) and the tomography was obtained via a Monte Carlo-type inversion using a neighborhood algorithm. This figure displays two-dimensional (2D) vertical slices of the seismic shear wave velocities localized on a map of the same tomography results at about 80 m depth. We can clearly identify the contact between the deeper bedrock (velocities > 1400 m/s) underlying the sediment infill of the old stream valley and coastal plain (velocities < 1400 m/s). Joint interpretation using ambient noise surface wave tomography (ANSWT) and SP data allowed us to identify the regions of dominant ground-water flow in the old stream valley at the Kaiwi Coast, O'ahu. The SP data nicely displays the distribution of groundwater in the region and zones of higher infiltration and/or flow rates. The ANSWT
identifies the erosional contact between the older Ko'olau basaltic formation and the younger post-erosional Honolulu volcanics, as well as the distribution of valley fill alluvium, Honolulu volcanics, and sedimentary water-saturated deposits near the coast. The integration of SP and seismic data suggests that significant groundwater flow occurs in the deeper parts of the identified paleo-channels on the erosional surface between the Ko'olau basaltic bedrock and the overlying formations, roughly at 100-200 m (Figure 5).

Figure 4: Vertical cross-sections through the 3D shear-wave velocity model of Kaiwi (O'ahu). The locations of the sections are shown in the left panel, which is a horizontal slice of the shear wave velocity model at 80 m below the surface.

Figure 5: Schematic interpretation of the hydrogeophysical results at Kaiwi (O'ahu). SP map draped on the topography of the studied area with blue arrows showing the preferential groundwater flow paths. Dotted paths are uncertain. Below is a 3D representation of the depth of the iso-shear-wave-velocity of 1400 m/s interpreted to be the depth of the old eroded Ko'olau volcano. The main groundwater flow paths are taking place in the deeper parts of the paleo-channels (in green).
Our results are consistent with the literature-based hypothesis that the dominant aquifer flow occurs in basaltic ridges and bedrock with higher hydraulic conductivity than the valley fill material for watersheds on the leeward side of the island of O‘ahu. However, we cannot exclude the presence of groundwater flow in the shallow valley fill material.

Pearl Harbor Aquifer, Schofield Dam, O‘ahu: SP and seismic surveys were conducted crossing the Northern Schofield dam. Data acquired through November/December 2019 consisted of 2027 SP measurements along ~ 40 km of profile (20 m spacing) to study the groundwater distribution and flow, and to explain the variations of the hydraulic heads levels between the wells. We processed the SP and seismic datasets this year and present preliminary interpretations here. The final results will be presented in a publication currently in preparation (Barde-Cabusson et al., in prep.). Figure 6 shows the results of the inversion for the Schofield Northern dam (Dole Plantation, O‘ahu) seismic ambient noise data.

The shallower part of the model shows the lower velocities (< 1000 m/s), likely reflecting the saprolite with intercalated weathered Ko‘olau basalts layer visible at the surface and in the nearby gulches. According to the bibliographic information, the saprolite layer is less than 55 m thick in this area, which is not resolved by the seismic tomography, but it likely has an impact on the velocity of the shallower part of the model. The velocity contrasts observed in the model from 300 m below the topographic surface, range from 1400 m/s to about 1900 m/s, highlighting a sharp limit between the northwestern and southeastern parts of the study area. We proposed three preliminary hypotheses to interpret this limit:

Hypothesis 1: The sharp limit could highlight a fault. The contact between low and high velocities is very sharp in the first 300-400 m below the surface. Below this depth, the transition from NW to SE is more "blurred" because at depth, the contact would be between lava flow layers and other lava flow layers with a distinct level of alteration. In the shallower part, saprolite and highly altered lava flows would be in contact with the more massive bedrock.

Hypothesis 2: This limit could represent the contact between a swarm of dykes associated with hydrothermally altered material and/or associated with groundwater trapped in the structure. This hypothesis is compatible with the alleged position of the Waianae Northeast rift zone. These preliminary interpretations will be compared to the available geological and structural information of nearby drillings and wells.
This structure has a notable impact on the groundwater distribution, as shown by the dense SP dataset that we acquired in the same area (Figure 8). Higher SP values have been detected in the Southeast of the study area, which would be explained by (1) a shallower impermeable surface (e.g. the contact between the saprolite and altered basalts, with the less/unaltered lava flows of the bedrock) guiding underground water circulation or (2) a thinner vadose zone with less infiltration compared to the northwestern part of the map.

The thicknesses of the vadose zone at each well in the study area does not support the second hypothesis. However, this variation in head levels may be due to the time periods when the measurements were made (Helemano in 1972, Waialua Pump in 1975, and Kaheaka Obs. in 1994). Unfortunately, only few wells have been monitored along the years in this area. The closest is the Helemano Deep Monitor (3-3405-005), located 2.4 km to the north of Kaheaka Obs. and it registered a maximum variation of 51 cm during the period 01/24/03 to 10/08/18. This low variation may suggest that no substantial change of the aquifer depth occurred at the nearby wells on the Dole property since they were drilled. If so, the thickness of the vadose zone is not the cause of the SP map zonation and instead, a contrast in the underground structure/lithology affecting underground water circulation may be a preferred hypothesis. A SP/elevation plot of the 2027 SP measurements and elevation extracted from a high-resolution DEM can be used to highlight different hydrogeological domains. Each domain, defined by different geology or hydrogeology, usually displays distinct SP gradients (in mV/m). This might explain the hydrogeological contrast marked by the wells as, even if the vadose zone thickness appears to be relatively constant across the North Schofield Dam, the head of the aquifer above sea level is not, with the following head values above sea level: Helemano = 80.8 m, Waialua pump 26 = 50.44 m, and Kaheaka Obs. = 3.8 m.

**Outputs:** *Keaouhou, Hawai‘i Island:* Inversions of the 2D magnetotelluric field data, as well as 1D Bayesian inversions and parameter estimations, hydrogeological interpretation of the high-level aquifer system and the transitioning via the high/low divide to the low-level aquifer system.

*Kaiwi Coast, O‘ahu:* Joint interpretation of ambient noise surface wave tomography and Monte-Carlo-based depth inversions interpreted with SP data.

*Schofield Dam, O‘ahu:* Processing of seismic ambient noise dataset and joint interpretation of the SP dataset acquired on Dole Plantation property.

**Publications and Papers:**


S. Barde-Cabusson, N. Grobbe, A. Mordret, D. Dores, et al., Geophysical characterization of the Northern Schofield ground-water volcanic dam (O’ahu, Hawaii). In Prep.

Outcomes:

Keauhou, Big Island: We obtained insight into the impact of the high/low divide geological structure on the distribution of groundwater in West Hawai’i, Kona and information on the depth to the fresh/salt water interface, and an estimate of the depth of the aquifer system. This information serves as input data, validation and calibration constraints to the hydrological models and conceptual models (Q1).

Kaiwi Coast, O’ahu: Results lead to imaging of an impermeable surface guiding the main subterranean groundwater discharge (SGD) associated with an old stream valley on O’ahu. We found that the main groundwater circulation is not concentrated in the valley itself but instead it is guided by deeper geological surfaces (i.e. here the Ko’olau basalts). This information serves to improve the conceptual models for O’ahu, as well as constrain hydrological models in volcanic environments, particularly in light of providing an improved understanding of the role of chemically altered valley fills vs. bedrock flow on O’ahu.

Schofield dam, O’ahu: Geophysical characterization and preliminary geological interpretation of the North Schofield Dam. Serving as an analog to other sites of interest for ‘Ike Wai, these results will help understanding the nature of hydrogeological barriers in the islands and in other volcanic contexts.

Activity 1.1.4: Continuation of geophysical data acquisition based on key gaps identified from prior work. (Lautze, Barde-Cabusson)

Results: The AMT and gravity measurements acquired across the Northern Schofield dam (Dole Plantation, O’ahu) are expected to characterize this hydrogeological border with a methodology that can be reproduced in the densely inhabited area of the Southern Schofield dam. Priority should be given to gravimetry measurements across this limit, for future geophysical investigations to compare both limits.

Activity 1.1.5. Marine Geophysics (Attias)

Results: (1) In this marine geophysics study, we revealed a novel transport mechanism of freshwater moving from onshore to offshore through a multilayer formation of water-saturated layered basalts with interbedded low-permeability layers of ash/soil (Figure 8). Our Marine electromagnetic imaging shows ~35 km of laterally continuous resistive layers that extend to at least 4 km from west of Hawai’i’s coastline (Figure 9), containing about 3.5 km3 of freshened water. We propose that this newly discovered transport mechanism of fresh groundwater may be the governing mechanism in other volcanic islands. In such a scenario, volcanic islands worldwide can utilize these renewable offshore reservoirs as new water resources, which are considered more resilient to climate change-driven droughts. The results of this study were recently published in Science Advances (Attias et al., 2020). Additionally, (2) Our water column electromagnetic imaging detected large freshwater plumes in high-resolution (Figure 10), offshore west of Hawai’i island. Electrical resistivity models present multiple vertical freshwater plumes extending from the seafloor to the ocean surface.
**Figure 8:** Fresh groundwater onshore to offshore transport mechanism. Illustration showing a multilayer conceptual model of the transport mechanism of fresh groundwater from onshore to offshore in Hawai‘i (Attias et al., 2020). Fresh groundwater recharge from rainfall infiltrates to the sub-surface basalts and migrate toward the coastline. Low-permeability ash/soil layers intercept and perch the downslope migration (hydrostatic head driven) of freshwater in case that the freshwaters are above the water table. Below the water table, the low-permeability ash/soil layers act as confining formations. The freshwaters trapped below the confining formations flow thorough permeable fractured basalts and mix with seawater to form refreshed groundwater while displacing gravitationally denser seawater. At the shelf edge, the refreshed groundwater flows are released to the ocean as springs. Above and below the refreshed water-saturated basaltic formations, seawater-saturated basalts exist as a result of seawater intrusions from the ocean towards the land.

**Figure 9:** Multilayer electrical resistivity formation offshore the Island of Hawai‘i. Fence diagram showing 2-D isotropic CSEM inversion models of 20 discretized survey lines parallel to the Kona coastline and two crosslines (Attias et al., 2020). The color scale gives $\log_{10}[\rho(\Omega m)]$, with blue and red colors corresponding to resistive and conductive features, respectively. Blue shaded areas start ing at ~100 meters depth denote horizontal layers of resistive anomalies that represent fresh- ened water-saturated basalts, confined by low-permeability horizons of ash/soil (black-dashed lines). White lines denote the deeper boundary of these refreshed horizontal layers. Spatially extensive and highly resistive area (~1000 $\Omega m$) offshore Kailua-Kona represents a large-scale freshwater reservoir that extends from ~250 to ~500 depth.

**Figure 10:** Two-dimensional inversion model derived from the CSEM data acquired in survey line 3d. The color scale presents the electrical resistivity in $\log_{10}[\rho(\Omega m)]$. The grey dashed line represents the seafloor, positioned at a water depth of ~95 m. For enhanced visuality of the water column resistive anomalies, the resistivity shading thresholds are $\geq 1.7$ $\Omega m$ and $\leq 8$ $\Omega m$ for the plume and surface freshwater body, respectively. Distinctive freshwater plume imaged at a towline distance of ~1–1.1 km. This inversion converged to an RMS of 1.0 after 15 iterations, with error floors of 9% and 7% for the amplitude and phase data, respectively. Black rectangular represents the water column plume area selected for salinity calculation. (b) Line 3d water column salinity distribution. The black line encompasses low salinities (~10) within the plume, calculated from the resistivity model. The average plume salinity is 4.4, with ~87% of freshwater.

**Figure 11:** Two-dimensional inversion model derived from the CSEM data acquired in survey line 3d. The color scale presents the electrical resistivity in $\log_{10}[\rho(\Omega m)]$. The grey dashed line represents the seafloor, positioned at a water depth of ~95 m. For enhanced visuality of the water column resistive anomalies, the resistivity shading thresholds are $\geq 1.7$ $\Omega m$ and $\leq 8$ $\Omega m$ for the plume and surface freshwater body, respectively. Distinctive freshwater plume imaged at a towline distance of ~1–1.1 km. This inversion converged to an RMS of 1.0 after 15 iterations, with error floors of 9% and 7% for the amplitude and phase data, respectively. Black rectangular represents the water column plume area selected for salinity calculation.
Furthermore, our models image extensive spatially distributed surface SGD (Figure 11). The resistivity of these freshwater plumes and surface SGD ranges from ~1 to 30 Ωm. Our resistivity-to-salinity calculation presents a plume-scale salinity range of ~0.3–9.9, containing up to 87% of freshwater (Figure 11). Thus, we suggest that substantial volumes of freshwater occupy water column plumes in Hawai‘i. These findings provide valuable information to elucidate hydrogeologic and oceanographic processes affecting biogeochemical cycles in coastal waters worldwide. Lastly, (3) Our offshore 3-D magnetic imaging presents multiple magmatic intrusive structures (Figure 12), which might be the governing features that dictate the flow path of submarine freshwater across the submerged flank of Hualalai, from the coastline to the shelf edge.

Outcomes: (1) The results of this study were recently published in Science Advances (Attias et al., 2020). (2) The manuscript that describes these findings is currently in review at Geophysical Research Letters. (3) The manuscript that describes these findings is currently in prep.

Publications:


Chase, B., and E. Attias. 3-D magnetic imaging of intrusive structures offshore Hawai‘i, (in prep).

Objective 1.2: Geochemistry, Microbial Tracers, and Submarine Groundwater Discharge (SGD):
Map groundwater flow paths and improve estimates of connectivity and flux in the Pearl Harbor and Hualalai aquifer systems using integrated isotope, biogeochemical, and submarine groundwater discharge data by the end of Year 5.

The results we report here for Activity 1.2.2 and 1.2.3 are integrated across the geochemistry, microbial tracers and submarine groundwater discharge group as we synthesize our results in preparation for manuscripts and community stakeholder workshops and reports.

Activity 1.2.1: Obtain geochemical data (major ions, trace elements, isotopes) to improve models of flow and connectivity. (Dulai, Lautze, Tachera)

The goal of this activity is to use water chemistry as a natural tracer. To do so, we collected data on the chemistry of precipitation as well as water in groundwater wells across West Hawai‘i Island and O‘ahu. This has enabled us to define the chemistry of the source of groundwater to aquifers and to infer connectivity among aquifers. Using precipitation data, specifically the isotopes of oxygen and hydrogen, we are able to define a local meteoric water line (LMWL) for each island over the time period of collection, which can be used to illustrate variable climate patterns (e.g. La Nina, El Nino) and to analyze a change in surface temperature over time.
West Hawai‘i. This effort focuses on the isotopic and chemical compositions of rainfall and groundwater from central to leeward Hawai‘i Island. This region is characterized by the interactions of Pacific trade wind flow with two 4,000-meter high mountains as well as one of the largest natural emitters of sulfur dioxide on the planet – Kilauea volcano. Cumulative rainfall samples were collected at regular intervals from 20 stations over a 28-month period, at sites shown in the previous annual report. Sites cover a range of elevations across this region, and were used to determine average isotopic and dissolved ion compositions. The study period included an extreme weather event (Hurricane Lane), a major volcanic eruption at Kilauea in 2018 and the nearly complete cessation of long-term volcanic emissions following that eruptive event. Building on the work of previous studies, results demonstrate long-term variability through the establishment of a second, enhanced local meteoric water line (LMWL) for West Hawai‘i. Comparison of results with prior studies shows that episodic changes in regional climate conditions (e.g. El Nino and the Southern Oscillation) can produce distinct and statistically different LMWL for the duration of those climate conditions. Additionally, effects on the chemistry of precipitation due to extreme events such as volcanic eruptions and hurricanes are highlighted in the stable isotope and bulk ion deposition compositions. Sulfate concentrations in bulk precipitation decreased by a mean of 70% (p = 0.032) after the 2018 Kilauea eruption ceased. The results from this study can be used to better quantify and characterize precipitation, which is the ultimate source of Hawai‘i’s groundwater.

Results:
Precipitation results for West Hawai‘i (Figure 13):

Figure 13: The precipitation sites are broken up into three columns: low elevation sites less than 500 meters (n=7), mid elevation sites 500 to 2,000 meters (n=7), and high elevation sites above 2,000 meters (n=6). The first row shows the precipitation accumulated in both figures, the second row shows the d18O isotopic composition (left figure) and the chloride concentration (right figure), and the third row shows the dD isotopic composition (left figure) and the sulfate concentration (right figure). The shaded region represents the duration of the 2018 Kilauea eruption, dashed vertical lines represent each sample collection, and the red vertical dashed line represents the Hurricane Lane event and sample collection.
Figure 14: (Left figure) Volume-weighted averages for the twenty sites are shown as red points. Various local meteoric water lines (LMWL) are displayed: the West Hawai‘i LMWL conducted by this study as a solid red line, the West Hawai‘i LMWL defined by Fackrell et al. (2020) as a black dot-dash line, the East Maui LMWL defined by Scholl et al. (2002) as a black dotted line, the East Hawai‘i LMWL defined by Scholl et al. (1996) as a black dashed line, and the global meteoric water line defined by Craig (1961) as a solid black line. (Right figure) Comparison of the LMWL defined by Fackrell et al. (2020) in black, the LMWL defined by this study in red, a combined VWA of overlapping sites in white circles, and groundwater collected and analyzed by Fackrell et al. (2020) as white triangles. (length in Tachera et al (2021)).

Figure 15: Chloride-corrected groundwater well data plotted on a Piper diagram, showing groupings of wells with similar chemistry, indicating flow/connectivity among each group but subdued or no flow across groups. The groundwater samples are separated into four groups: NRZ = north of the rift zone wells in Waimea, ʻAnaeho‘omalu, and Kīholo aquifers, RZ = rift zone wells that fall along the rift zone of Hualālai, SRZ HL = south of the rift zone high-level wells in the Keauhou and Kealakekua aquifers, and SRZ Basal = south of the rift zone basal wells in the Keauhou and Kealakekua aquifers.

Figure 16: Groundwater well isotope data are shown as varying blue circles. The summits of the three mountains are shown as triangles, Hualālai as white, Mauna Kea as gray, and Mauna Loa as black. Recharge elevations were calculated using the precipitation isotope data, the local meteoric water line, and the isotope-elevation relationship produced during ʻIke Wai. Solid lines represent the elevation at which point-source recharge would need to fall (point-source meaning once the precipitation falls at that elevation, it enters the groundwater system and does not mix with any other water or isotopic values as it travels to the groundwater well). Dashed lines represent the elevation at which fully-integrated recharge would need to fall (fully-integrated meaning the precipitation that falls at this elevation mixes with groundwater and other recharge as it flows down to the groundwater well).
In Figure 14, the LMWL from this study is nearly identical to the East Hawai‘i LMWL, δD = 8.0 δ18O + 12, defined by Scholl et al. (1996), suggesting similar source and climatic conditions for rainfall sampled in both periods. There is a distinct difference between the LMWL produced by the data of Fackrell et al. (2020) versus this study over a similar collection area, which potentially addresses the discrepancy of 18O enrichment in groundwater samples observed in previous studies (Tillman et al., 2014; Kelly and Glenn, 2015). We postulate that Fackell’s data and the data collected in this study represent two ends of a spectrum in the precipitation chemistry to West Hawai‘i, which mixes in the groundwater (more below).

Groundwater results for West Hawai‘i: Figures 15 is a preliminary figure that relates the location of the groups.

Outputs: In West Hawai‘i, the project deployed 20 precipitation collectors in the field, and collected oxygen and hydrogen isotope, major ion, and trace metal data for >400 samples from a combination of collectors, water wells, and anchialine ponds. All data is in the ‘IkeWai.org. We anticipate at least three publications stemming specifically from this work, one which is accepted to be published in 2021, and the second which is in preparation. The first paper focused specifically on the precipitation results. The second focuses primarily on the groundwater well/pond results and discusses evidence for water-rock interaction including due to seawater infiltration and hydrothermal activity and the effect of such interactions on groundwater chemistry and quality. The third paper will integrate both datasets in terms of groundwater source, flow path, and implications for water management.

Publications and Papers:

Tachera, D., Lautze, N., Dulai, H., and Thomas, D. Characterization of seawater circulation and water-rock interactions in West Hawai‘i aquifers (in prep, to be submitted to Hydrogeology Journal)

Tachera, D., Lautze, N., Dulai, H., Burnett, K., and Thomas, D. Identifying water sources and reassessing aquifer boundaries in West Hawai‘i (in prep)

Results Pearl Harbor, O‘ahu: Preliminary analysis of the precipitation chemistry data from O‘ahu reveals zonal trends and a reasonably strong orographic elevation effect on stable isotope concentration. The local meteoric water line (LMWL) for O‘ahu was determined by compiling all known precipitation δD and δ18O (DnO) datasets (Dores 2020; Booth [in-progress]) with the present research. The LMWL was determined to be δD = 7.6 δ18O + 11.3 (r² = 0.90). The global meteoric water line (GMWL), currently accepted as δD = 8.2 δ18O + 11.3, fell within the 95% probability interval for points used to determine the LMWL (Figure 18). Elevation trends suggest precipitation, though not the extent seen on the orographic effect on O‘ahu is strong enough to
have an appreciable impact on DnO in Maui (Scholl et al. 2002) and Hawai‘i Island (Scholl et al. 1995; Fackrell et al. 2020; Figure 19). Some zonal trends in both the LMWL and the δ18O vs. elevation data suggest that weather patterns have a measurable effect on the chemical composition of precipitation. The volume weighted average (VWA) precipitation DnO from drier, leeward areas was generally more depleted in the heavy stable isotopes of water, whereas that of windward areas tended to be more enriched, closer to the DnO signature of evaporated ocean water (Figure 18). Precipitation collected from valleys also seems to have a distinct DnO signature, possibly indicating that microclimates within valleys on O‘ahu are important drivers of precipitation chemistry in those areas (Figure 18). In terms of elevation, the strongest orographic effect was seen in precipitation collected from the leeward areas of the Ko‘olau Range, the area estimated to provide the majority of recharge to the Pearl Harbor Aquifer (Engott et al. 2015). DnO from this area showed a 1‰ enrichment of δ18O per every 460m in elevation gain (Figure 19). The elevation signature in the Wai‘anae Range was more muted, showing approximately 1‰ enrichment of δ18O per every 1300m of elevation gain. Precipitation DnO from the Wai‘anae Range was uniformly more depleted in heavy isotopes of water.

Preliminary estimates of the DnO of recharge within the Pearl Harbor Aquifer indicate land cover, and seasonal weather patterns are important controls on the chemical composition of groundwater recharge. The DnO of recharge for O‘ahu was estimated using a water budget model to account for spatio-temporal heterogeneity in evapotranspiration, precipitation, runoff and recharge processes. Thirty-year average monthly

![Figure 18: Local Meteoric Water Line (LMWL) for O‘ahu.](image18)

![Figure 19: Plot of δ18O vs. precipitation collector elevation for O‘ahu.](image19)

![Figure 20: Estimated δ18O of recharge for O‘ahu based on past and current work. Green circles and purple squares show the location of precipitation collectors deployed in this project, with orange circles deployed collaboratively by the Hawaii Dept of Health. These data were used to estimate the δ18O of recharge islandwide, as shown by the color scale in the legend.](image20)
precipitation and evaporation maps from Frazier et al. (2016) and Giambelluca et al. (2014) were combined with seasonal runoff estimates from Engott et al. (2015) to estimate monthly recharge at 250m spatial resolution. Monthly precipitation DnO coverages were interpolated via kriging, and then weighted using the monthly recharge estimates to produce an estimate of the mean annual δ18O of recharge (Figure 20). Estimates of recharge δ18O in the Koʻolau range varied from approximately -3.3 to -2.0, whereas those within the Waiʻanae Range tended to be more depleted (-4.6 to -2.5). The recharge DnO signal in three areas seemed to be dominated by land cover type: the North Shore (Waialua - Pūpūkea), south central Oʻahu (Kapolei - Kunia - Mililani), and Waiʻanae. Estimates of recharge δ18O were substantially more enriched in these areas, approaching the chemical composition of ocean water. Generally, recharge DnO estimates in the Pearl Harbor Aquifer were more enriched than well samples from previous studies (Lautze et al. 2017; Hunt 2004). *This suggests that disturbance-based weather patterns, like cold fronts, Kona storms, upper-tropospheric disturbances, and tropical systems - all typically more depleted in heavy isotopes of water - play a more important role in determining recharge chemistry than previously thought (Dores 2020).* The improved understanding stemming from this work will assist regulators in sustainably managing Oʻahu’s fresh groundwater supply.

**Outputs:** On Oʻahu, of 17 precipitation collectors deployed 15 were sampled regularly at eight-ten week intervals through 2020. Access to two collectors was restricted due to COVID-19 precautions. In addition to precipitation sampling, four West Oʻahu wells were sampled in cooperation with the Board of Water Supply.

**Publications and Papers:**

Theodore Brennis; “Spatio-temporal variations in runoff coefficients derived from daily rainfall data”, projected Spring 2021 (MS thesis)

Theodore Brennis, Nicole Lautze, Robert Whittier, “An Examination of Soil Infiltration and Recharge Processes within the Waimano-Manana Catchment, Oʻahu”, projected Winter 2021-2022

Theodore Brennis, Nicole Lautze, Robert Whittier, “Characterization of the isotopic and bulk ion deposition of precipitation the island of Oʻahu”, projected Spring 2022

Theodore Brennis, Nicole Lautze, Robert Whittier; ”Examination of groundwater source and flow path in South Central O‘ahu through O and H isotope analyses”, projected Summer 2022

**Activity 1.2.2:** Characterize temporal and spatial distribution of microbial communities within wells at Pearl Harbor and Hualālai as a novel method for exploring water flow and source.

Postdoctoral researcher Sheree Watson and PhD candidate Cédric Arisdakessian are currently preparing collaborative manuscripts between the microbe and geochemistry research groups and some preliminary results from the first manuscript are discussed here.

*Research question 1. How does aquifer geochemistry differ in the Hualālai watershed across spatial and temporal changes?*

The focus of this analysis was on freshwater samples (wells) located in both Kīholo and Keauhou aquifers of the Hualālai watershed. Groundwater samples were collected from both private (wells #1-8) and publicly owned (wells #9-20) production wells in quarterly intervals from November 2017-March 2019 (Figure 21 – Map). Sample sites (wells) in the figures are color coded in the figures by PCA groups including A) well #1-red, B) wells #2-4-blue, C) wells #5-9-green, and D) wells #10-20-purple.
Results: A principal component analysis (PCA) model was performed to explore spatial geochemical differences between objects (well samples) and measured geochemical variables (total phosphorus, TP; orthophosphate, PO₄; silica, Si; sulfate, SO₄; Magnesium, Mg; Molybdenum, Mo; Boron, B; Chloride, Cl; Vanadium, V; Chromium, Cr; Nitrate+Nitrite, NOₓ; and total nitrogen, TN; (Figure 22 – PCA). The dominant Eigenvalue (PC1) was explained by variation in concentrations of Mg (34.9%), and secondarily by Cr (26.3%), which together explained 61.2% of the variation observed in samples. The tertiary (PC3) Eigenvalue (not graphed) was TN (15.0%). An ordination biplot scaled on intersample relationships demonstrates correlative relationships among hydrochemistry and spatial locations of groundwater samples. For example, samples from wells located along the rift zone between Kīholo and Keauhou aquifers were associated with increasing concentrations of Mg and SO₄. Concentrations of Mg and SO₄ in these wells was highly variable ranging from 0.25 - 7.40μM (average 1.79±2.4μM), and 0.10 - 3.51μM (average 0.75±0.99μM) respectively with the highest values of both major ions occurring in well #5. In contrast, the samples from wells along the high-low divide in the Keauhou aquifer are associated with varying concentrations of TN and NOₓ. Concentrations of dissolved organic nitrogen (DON) calculated as TN – (NH₄ + NO₃) were highly variable amongst samples along the high-low divide ranging from -180.4 -174.8μM (average 20.3±84.6μM). A Canonical correspondence analysis (CCA) was performed to test the hypothesis that groundwater geochemistry structure observed by PCA would drive microbial community structure. A CCA produces a multivariate ordination showing associations between explanatory variables (dissolved oxygen, DO; pH; specific conductivity, SPC; sulfate, SO₄; and nitrate+nitrite, NOₓ) and response variables (individual microbe relative abundances from each sample site; Figure 23-CCA). The plot demonstrated that high DO, pH, and NOₓ drives microbial community differences in groundwater along the Keauhou high-low divide (wells #10-20). By contrast, high SO₄ and SPC differentiate community structure in the sample sites (wells #5-9) along the Kīholo and Keauhou rift zone. The constrained axes combined to explain 60.1% of the pattern variation observed in microbial community structure and the model was statistically significant (p<0.001) in explaining covariance of microbial communities by geochemistry.

Outputs: Exploratory and multivariate statistical analyses/visualizations demonstrate geochemistry of groundwater aquifers drives spatial and temporal microbial community structure in the Hualālai watershed. For example, sample sites (wells# 5-9) along the Kīholo and Keauhou rift zone have high concentrations of sulfate which drives differentiation of microbial community structure specifically sulfate reducers.

Publications and Papers:
Sheree J. Watson, Cédric Arisdakessian, Diamond Tachera, Brytne Okuhata, Maria Petelo, Ku‘i Keliipuleole, Nicole Lautze, Henrietta Dulai, Kiana L. Frank. Functional diversity of
groundwater/subsurface microbial communities driven by spatial and temporal geochemistry in volcanic aquifers. (In preparation), ISME (June 2021).

Sheree J. Watson, Cédric Arisdakessian, Diamond Tachera, Brytne Okuhata, Maria Petelo, Ku‘i Keliipuleole, Nicole Lautze, Henrietta Dulai, Kiana L. Frank (potential community partners Keith Olsen, Pam Madden, Kimber Deverse, Darren Okimoto), Biogeographical and biogeochemical drivers of microbial dynamics in groundwater ecosystems. (In preparation), PNAS (August 2021).

**Outcomes:** Microbial functional diversity indicates that nitrogen and sulfate cycling communities are major drivers of ecosystem functions in groundwater aquifers in the Hualālai watershed. Functional microbial diversity indicates ecosystem functions differ spatially across the Kīholo and Keahou aquifer. For example, variable concentrations of nitrogen appear to drive microbial structure across the high-low divide in the Keahou aquifer, contrasted by high variable concentrations of sulfate influencing sulfate microbial cycling along the rift zone.

**Impacts:** The results demonstrate that microbial community structure can be utilized to further explore groundwater aquifer flow, and connectivity to reveal expanded information gathering about the Hualālai watershed/aquifer.

**Activity 1.2.3:** Quantify microbial water quality of well samples to identify pathogenic contaminants and microbial indicators for chemical contamination.

**Question 2:** Do abundances of key functional microbial groups correspond with geochemical spatial differences observed in the Hualālai watershed?
**Results:** Abundances of 16S rRNA (proxy for bacteria and archaea) varied widely across sample sites (Log16S; Figure 24 - boxplots). Average abundances of 16S rRNA was $3.53 \times 10^{4} \pm 1.28 \times 10^{5}$ copies ml$^{-1}$ across all samples. Comparisons are made here for samples from PCA groups C (green, wells #5-9), and D (purple, wells #10-20) as majority of samples were collected from these sites (162 out of 189 samples). One-way ANOVA results were significant for PCA groups (F (3,185) = 6.25; p<0.001) and results from Tukey HSD post hoc analysis revealed groups C and D were significantly different (p<0.001). Groundwater samples from group D averaged $4.83 \times 10^{4} \pm 1.56 \times 10^{5}$ copies ml$^{-1}$, compared with group C of $2.46 \times 10^{3} \pm 1.68 \times 10^{3}$ copies ml$^{-1}$ of 16S rRNA indicating a greater biomass in well sites from group D (wells#10-20). Further, copy numbers for 16S rRNA at each sample site were used to normalize denitrification (nirS) and sulfate reduction (dsrAB) abundances (dsr, nirS; ; Figure 24 - boxplots).

Sulfate reductase (dsr gene) abundances varied widely across sites, however abundances were three orders of magnitude less than 16S rRNA and nirS averaging $5.51 \times 10^{2} \pm 2.02 \times 10^{3}$ copies ml$^{-1}$ (dsr, Figure 24 - boxplots). One-way ANOVA exhibited significant differences between well groups for dsrAB (F (3,185)=44.51; p<0.001). A further Tukey HSD post hoc analysis showed significant differences (p<0.001) between wells in groups C and D for. Abundances of dsrAB averaged $4.55 \times 10^{2} \pm 1.61 \times 10^{3}$ copies ml$^{-1}$ in group C compared with $1.89 \times 10^{2} \pm 3.33 \times 10^{2}$ copies ml$^{-1}$ in group D.

Denitrification (nirS gene) abundances varied spatially with an average value of $1.53 \times 10^{4} \pm 5.64 \times 10^{4}$ copies ml$^{-1}$ (nirS, Figure 24 - boxplots). One-way ANOVA was significantly different at the p<0.01 level (F (3,185) = 3.91; p<0.01) and results from Tukey HSD post hoc analysis indicated that nirS abundances were significantly different in groups C and D (p<0.01). Abundances of nirS averaged $3.88 \times 10^{3} \pm 9.01 \times 10^{3}$ copies ml$^{-1}$ for group C. Group D wells averaged lower abundances at $2.19 \times 10^{4} \pm 6.97 \times 10^{4}$ copies ml$^{-1}$ of nirS, however the largest abundance measured was observed in group D (well #19) at $3.00 \times 10^{5}$ copies ml$^{-1}$.

**Outputs:** Results quantify biomass differences of bacteria and archaea in groundwater samples across the Hualālai watershed. In addition, quantification of key microbial function genes (denitrification, nirS; sulfate reduction, dsrAB) are indicators of geochemical cycling and key ecosystem functions in the groundwater aquifers.

**Publications and Papers:**

Sheree J. Watson, Cédric Arisdakessian, Diamond Tachera, Brytne Okuhata, Maria Petelo, Kuʻi Keliipuleole, Nicole Lautze, Henrietta Dulai, Kiana L. Frank. Functional diversity of

**Outcomes:** Quantification of key microbial functional groups (denitrification, sulfate reducers) further support our findings that spatial geochemical differences in aquifers drive quantifiable differences in microbial communities. For example, abundances of sulfate reducers are significantly different in wells that exhibit higher and variable concentrations of sulfate (wells #5-9, group C).

**Impacts:** The geochemical differences across space in the Hualālai watershed allow for a structured investigation of the specific taxonomic microbes involved in sulfate reduction and denitrification. Work is currently being done to identify specific taxonomic groups that may serve as indicators of increased sulfate and/or nitrogen in groundwater which may help resource managers detect harmful levels of sulfate and nitrogen in drinking water sources.

**Activity 1.2.4:** Link SGD to aquifer conditions at the two aquifer locations. (Dulai and McKenzie)

**Results:** (1) SGD sensor development: An upgraded version of the SGD Sniffer, an autonomous radon monitor, has been developed in Years 1 and 2 of the project. In Year 4 we tested the instrument and finalized its design. In addition, one of the two instruments was selected to be outfitted with wireless telemetry. Due to COVID-19, telemetry installation, which requires an upgrade of the software and some hardware parts has been put on hold.

**SGD sensor deployment:** Three deployment sites have been selected in Kona. Permits for deployment at 2 sites were obtained. We deployed 1 instrument at Queen Lili‘uokalani Trust (QLT) anchialine pond in November 2019. This instrument has been making hourly radon, salinity and temperature measurements through 2020. Data has to be retrieved manually and we will proceed with retrieval when travel restrictions due to COVID-19 are lifted. Future deployments of sniffers have been postponed due to COVID-19 but the permit for deployment at NELHA has been obtained.

**Data processing:** Radon, temperature and salinity time series analysis is being automated by developing a code for automated data processing and SGD calculation in Python. In addition, time series analysis and deep learning methods have been developed to further evaluate seasonal trends and drivers of SGD as well as to predict SGD. These are being combined with rainfall patterns and analyzed for spatial and temporal correlations between precipitation and SGD. Due to COVID-19 and associated travel and social distancing restrictions, our team has shifted to focusing on and broadened our work with data analyses and machine learning. The following outlines our progress and remaining goals:

**SGD Time Series Analysis:** Time series analysis of SGD Sniffer data is ongoing. Four years of data were collected and evaluated for relationships between SGD and its marine and terrestrial hydrological drivers (Figure 25). Our primary objectives are to (1) isolate hydrological drivers and their relative contribution to SGD, (2) constrain the relationship and lag between precipitation and SGD, and (3) establish criteria for impact to SGD from events (e.g., storm, hurricane, tsunami) and threshold effects.
Modeling SGD Using Deep Learning: This same data is being used in the development of a deep learning model to predict SGD. This model has been developed using Python and Tensorflow with Keras API and accurately models the SGD dataset from Kīholo Bay. The model, which has a Convolutional Neural Network (CNN) framework has a mean square error (MSE) of 10^-4 for both the training and validation sets (Figures 26A, 26B).

This model that was developed using the Kīholo Bay dataset was used on SGD time-series datasets from two sites in Maunalua Bay, O‘ahu to test its applicability to other locations. The model performed well (MSE = 10^-2) for both Maunalua Bay locations and now the model is being tested with an SGD dataset from Florida in collaboration with researchers from the University of Alabama.

We are also aiming to improve the SGD prediction for Maunalua Bay by developing a different deep learning model (with undergraduate researcher Brody Uehara) to improve data inputs from data-sparse areas (e.g., watersheds flowing into Maunalua Bay). This deep learning model will predict stream flow and baseflow (i.e., groundwater fluxes) from precipitation (‘Ike Wai product by...
The preliminary results from this effort (Figure 26C) show this being a promising method. These results will be applicable broadly around Hawai‘i (and elsewhere), addressing long-term issues with sparse stream discharge data availability for many areas.

**Outcomes:** The new version of SGD Sniffer is perfectly suited for pond and nearshore coastal region monitoring. Deep learning methods predict SGD trends and can be used to predict SGD and therefore developed to run future scenarios of SGD to aid stakeholder pond management.

**Risks and Mitigation Plan:** Trista McKenzie is working on SGD deep learning models and also refocused to use deep learning models to predict stream flow and baseflow from precipitation.

**Objective 1.3:** Produce datasets on physical and chemical parameters of groundwater by establishing novel sensor-based monitoring network in wells within targeted regions of the Pearl Harbor and Hualālai aquifer systems by the end of Year 3.

**Activity 1.3.1-1.3.2:** Build and deploy active well monitors. (Oyama)

This activity was completed in Year 3.

**Goal 2:** Develop a new data and modeling platform for Hawai‘i volcanic hydrology, economic modeling and decision support

**Objective 2.1:** ‘Ike Wai Gateway: Implement a fully featured data management, analysis, and visualization application based on the Agave software framework.

**Activity 2.1.1:** Hire Professional Staff: (Cleveland, Geis, Jacobs)

**Results:** This activity was completed in Year 4. In January of 2020 the CI team added Jared McLean to the project to work on gateway features. In January 2020 the CI team added Christopher Shuler to the project to assist researchers in documenting, annotating and publishing data products in the ‘Ike Wai gateway.

**Activity 2.1.2:** Setup Computation and Storage platforms.

**Results:** This activity was completed in Year 2.

**Outcomes:** Infrastructure is able to support research and computation for the project; Researchers can manage data, run analysis and compute on the platform.

**Activity 2.1.3:** Create training materials, documentation and train researchers on using the ‘Ike Wai Gateway. (Cleveland, Geis, Jacobs)

**Results:** All ‘Ike Wai Gateway documentation and training materials are published and updated on GitHub. All research teams have been trained on the Gateway on an as needed basis, in some cases a CI team member would assist researchers in uploading, annotating, and/or making their data public. CI team conducted two training sessions on the new data dissemination

![Figure 26C: Preliminary stream discharge deep learning results. Ongoing efforts include improving model results under high discharge conditions and expanding spatially to include additional streams.](image)
workflows to the entire ‘Ike Wai research team.

**Outputs:** All ‘Ike Wai Gateway documentation and training materials have been previously reported.

**Outcomes:** ‘Ike Wai researchers have used the gateway to upload data, annotate products, and publish datasets to Hydroshare and the public ‘Ike Wai data repository (ikewai.org).

**Activity 2.1.4: ‘Ike Wai Visualization (Leigh, McLean, Cleveland)**

**Results:** Hawai’i Rainfall Analysis and Mapping Application (HI-RAMA). The CI team and rainfall analysis teams worked to generate a user endpoint for visualizing and retrieving rainfall maps and other climatological data products.

**Features of HI-RAMA:** The application provides users the ability to visualize rainfall station data and generated rainfall maps as described by Activity 2.2.3. Users can step through the data over the period the data is available for or select a specific date of interest to view. Rainfall stations appear on the map at their geographical locations and are tabulated. These stations can be filtered on their associated metadata and specific stations be selected to view their value, metadata, and timeseries data (Figure 27 and 28). Several color schemes are built into the application, and users are able to import custom color mappings in an XML format. Users are able to export the map-based visualization as an image file.

This application will also serve as an endpoint for users to export the data displayed by the application, allowing users to select their period of interest and retrieve a set of data products including rainfall station data as a csv, rainfall maps, anomaly maps, standard error maps, and standard error anomaly maps as GeoTIFFs, and metadata on the map generation. These data products are available by county as well as for the whole state. This application is designed to accept variable data sets that follow a similar pattern and will be extended to include additional climatological data as it becomes available.

![Rainfall Station Filters](image)

**Figure 27: Rainfall mapping and display of a selected rainfall station’s metadata**
Publications and Papers:

Outcomes: The data constructed by the rainfall analysis team were packed into a set of JSON documents and stored using the UH Agave metadata service and source files will be stored using the files API. This data is used to generate the HI-RAMA visualization and source files will be retrievable through the application for public use.

Activity 2.1.5: ‘Ike Wai Gateway Dissemination. Development of dissemination platform. (Cleveland, Geis, Giambelluca)

Results: Over 3,500 data files/datasets have been made ready for dissemination. We developed a separate dissemination site, ikewai.org, to allow users from outside the ‘Ike Wai project a simple search and visualization interface for all available data and data products. We integrated dissemination of models and data with the community site, Hydroshare where DOIs can be assigned to data products.

A data platform has been developed to host all of the meteorological data compiled for the state of Hawai‘i within the ‘Ike Wai Gateway. The Hawai‘i Climate Data Portal (HCDP) hosts both daily and monthly rainfall data from over 1000 meteorological stations across the State spanning the period 1920 to present day. The HCDP hosts daily observations of other meteorological variables including relative humidity, solar radiation, wind speed, and many more. In addition to station-based climate data, the HCDP hosts 100 years of Monthly rainfall maps and 30-years of daily rainfall maps, both of which are updated in near-real-time. Users have the ability to query specific data products, including quality-controlled observations as well as serially complete versions of this data, for specified time periods.
Outputs: Feature update to dissemination workflows and public data repository interfaces. Annotation of datasets and publication to the research and stakeholder communities.

Outcomes: ‘Ike Wai researchers have used the gateway to upload data, annotate products, and publish datasets to Hydroshare and the public ‘Ike Wai data repository (ikewai.org).

Objective 2.2: Data Store Population: Aggregate, annotate, and store legacy, existing, and new scientific data.

Activity 2.2.1: Personnel & Training (Cleveland, Geis,)

All research groups have been trained on annotating data using the ‘Ike Wai platform. These users attended a training session or individual meeting that walked through the platform curation features and demonstrated how to curate and annotate project data products for large dissemination. All documentation and training materials on annotating data using the ‘Ike Wai platform are published to github.com and within the gateway itself. Materials that educate and demonstrate the use of the ‘Ike Wai platform for curating data products from the project have been integrated into the application as help documents.

Activity 2.2.2: Data Store & Curation (Cleveland, Geis, Jacobs)

Results: Over 300,000 files/data sets totaling almost 5T have been uploaded and ~3,500 have been curated. A data manager has been hired and has been meeting with groups and researchers individually to assist with uploading, curating, and annotating their data in the Gateway. New features make it easy for researchers to push their data and annotations to ikewai.org where everything is open and accessible to the public. Researchers can also push their annotations and links to the files to Hydroshare.org where they can obtain a DOI.

Outputs: 300k+ raw files and datasets, 3,500 curated.

Activity 2.2.3: Collate historical and current data from diverse agencies. This update includes all new data collections added this year. (Cleveland, Geis, Jacobs, Giambelluca)

Month-year rainfall mapping: Gridded rainfall datasets are essential for various applications in geosciences, including climate and hydrologic modeling, decision-making in environmental management, and water resource planning. Mapping monthly rainfall in Hawai‘i requires

Results: A 30-year (1990-2019), high resolution (250-m) gridded monthly rainfall time series was created for the State of Hawai‘i. An optimized geostatistical kriging approach is used to interpolate relative rainfall anomalies, which are then combined with long-term means to develop the gridded estimates. The optimization consists of the following: 1) determining the most appropriate offset (constant) to use when log-transforming data; 2) eliminating poor quality data prior to interpolation; 3) detecting erroneous maps using a machine learning algorithm; and 4) selecting the most appropriate parametrization scheme for fitting a model used in the interpolation. Leave one out cross-validation (LOOCV) is performed using an extensive network of 622 observation stations. LOOCV results are in good agreement with observations (Rsq = 0.79; Figure 29) across the entire dataset, however, predictions typically underestimate observations (~34 mm/month) due to a well-known smoothing effect that occurs with kriging. Rainfall maps, anomaly maps, standard error maps, station data, and LOOCV error metrics are available for each month over the period-of-record and are now available on the Hawai‘i Climate Data Portal. A sample of rainfall maps for August 2018 which was one of the rainiest months on the Island is shown for each county in Figure 30.
Results: A manuscript is submitted to the American Meteorological Society's "Journal of Hydrometeorology" that describes the methods and results of the mapping effort. This manuscript is developed in collaboration with a researcher at the East-West Center, Honolulu Hawaii.

Results: The mapping algorithm described here is also being used to produce near-real-time monthly rainfall maps that make use of an automated data collection from multiple public-facing weather stations data streams, archived climate data API and from several private servers. Rainfall maps, error maps and station data used to create each individual map are made available through the 'Ike Wai Gateway portal.

Quality Control Machine Learning Algorithm: Data quality can be compromised for a number of reasons, including instrument malfunction, poor data collection practices, or manual errors made in the data processing phase. To address these concerns, machine learning algorithms are tested to determine the most robust method for flagging erroneous values in the daily rainfall time series. Rainfall is probably the most difficult climate variable to screen due to its extremely high temporal and spatial variability.

Results: A machine learning data quality control algorithm is developed and tested to 1) screen extremely high rainfall values and 2) false zero rainfall values based on information from the 10 closest stations. At present the model is 90% accurate at detecting pseudo-bad data (a generated dataset that contains extreme outliers) at >15 mm and >10 mm for non-zero (>0 mm) station days and zero mm station days respectively (Figures 31 and Figures 32). The plots below show the effect of test data accuracy on introducing a minimal difference in RF in the pseudo-bad data used to train the random forest model (Breiman 2001) for each situation. This algorithm is tailored to each unique island.
Daily Temperature Dataset

Daily observations of average, maximum and minimum temperature are essential for many applications in the fields of climate science and ecological modeling. They can also be used as the basis for creating gridded products. To date, comprehensive datasets of these three variables, extending beyond 2014 do not exist.

Results: A 31-year (1990-2020) legacy collection of quality controlled temperature data (average, maximum and minimum temperature) from 186 climate stations has been compiled in Hawai‘i. These data are currently being used to develop a set of daily and monthly temperature (average, maximum and minimum) maps for the state of Hawaii.

Disturbance Driven Rainfall on O‘ahu

Hawai‘i: Undisturbed trade-wind conditions comprise the most prevalent synoptic weather pattern in Hawai‘i and produces a distinct pattern of orographic rainfall. Significant total rainfall contributions and extreme events are linked to four types of atmospheric disturbances: cold fronts, Kona lows, upper-tropospheric disturbances, and tropical cyclones (Figure 33). In this effort, a 20-year (1990-2010) categorical disturbance time series is compiled and analyzed in relation to daily rainfall over the same period. The primary objective of this research is to determine how disturbances contribute to total wet season rainfall on the Island of O‘ahu, Hawai‘i.

Results: We found that on average, 41% of wet seasonal rainfall occurs on disturbance days and 17% of seasonal rainfall can be directly attributed to disturbances (after a background signal is removed) and as much as 48% in a single season. The intensity of disturbance rainfall (mm/day)
is a stronger predictor ($r^2 = 0.49; p < 0.001$) of the total seasonal rainfall than the frequency of occurrence ($r^2 = 0.11; p = 0.153$). Cold fronts are the most common disturbance type. The rainfall associated with fronts that cross the island is significantly higher than rainfall produced from non-crossing fronts. In fact, non-crossing fronts produce significantly less rainfall than under mean non-disturbance conditions 76% of the time. One of the most interesting findings of this study was that fronts that are present in the region but do not cross the island can have a net drying effect, as these systems are close enough to disrupt normal trade-wind flow but far enough away to not cause any frontal rainfall on the island. While the combined influence of atmospheric disturbances can account for almost half of the rainfall received during the wet season the primary factor in determining a relatively wet or dry season/year on Oʻahu are the frequency and rainfall intensity of Kona Low events.

Results: A manuscript is submitted to the American Meteorological Societies “Monthly Weather Review” that describes the methods and results of this analysis. This manuscript is developed in collaboration with a Professor from the University of Albany’s Atmospheric Sciences department and a Research scientist from the Pacific Cooperative Studies Unit, University of Hawai‘i at Mānoa.

Publications and Papers:


Journal Articles In Review


Journal Articles In Preparation

Activity 2.2.4. Obtain historical land use data from Indigenous knowledge contained in Hawaiian newspapers and other cultural archives.

Results: No additional progress was made on this component of the project. Graduate student Kilika Bennet withdrew from the university without graduating in the summer of 2019. There are no plans to pursue further translations however the Community Outreach and Hawai‘i Island science teams have continued discussions with community members about various aspects of the 45 fully translated articles. These include the complete series of Nā Ho‘onanea o Ka Manawa and excerpts from Nā Hunahuna No Ka Mo‘olelo Hawai‘i.

Outcomes: The Hawaiian newspaper translations and storyboards produced under this component of the project were instrumental in building trust relationships with many community members and organizations both on Hawai‘i Island and O‘ahu. The conversations between community members and the ‘Ike Wai researchers have been invaluable in understanding the content of the translated articles.

Activity 2.2.5: Develop and parameterize coupled conceptual models of GW flow and chemical transport. (El-Kadi, Lee)

Results: The Keauhou basal aquifer (KBA) model, described in the previous year’s report, was further developed and calibrated to assess water management scenarios (Figure 35). Due to the complexities observed in the Keauhou aquifer, the eastern boundary of the KBA model was set at the high-low divide, and all upland recharge and pumping was applied to the eastern boundary. This reduced computational expenses and simplified uncertainties that exist in the upland Keauhou area due to sparse observation data. Geochemical tracers (14C, CFC/SF6, 3H) are being further assessed to estimate appropriate groundwater ages. Carbon isotope measurements were used to estimate the primary sources that would impact 14C ages. Although a few samples show clear sources, such as the rift zone samples (Figure 36), most samples are highly mixed between

Figure 35: Conceptualization of the Keauhou basal aquifer (KBA) model.
all three end-members. This demonstrates that the groundwater is likely influenced by seawater intrusion and volcanic CO₂ from Hualālai. When CFC measurements were compared to estimated recharge elevations (determined by D. Tachera), the fraction of young water present in a sample is inversely correlated with the elevation of recharge source. Additionally, older water (based on CFC-113 ages) is being pumped from deeper depths. In aggregate, this suggests that as water travels towards the coast, there is limited mixing of water sourced from different elevations.

Outputs: We updated the conceptual KBA model to best represent aquifer conditions based on field measurements and was used to develop a numerical groundwater model (Section 2.2.6).

The groundwater ages are continuously being assessed to help develop a conceptual model for the West Hawai‘i aquifer systems. Once the groundwater ages are refined, this conceptual model will be used to finalize the WHR numerical model calibration.

Publications and Papers:

Outcomes: The two conceptual models allow us to work at different scales using different datasets. This also allows us to focus on different research and management questions.

Activity 2.2.6: Based on model conceptualization, develop and apply suitable numerical groundwater models for use in developing comprehensive schemes for sustainable water use in West Hawai‘i. (El-Kadi, Lee)

Results: Using the conceptual model in Activity 2.2.5, a three-dimensional, density-dependent, multi-species baseline KBA model was developed using SEAWAT (Langevin et al., 2008). Following reliability assessment and sensitivity analyses, the KBA model was calibrated (Figure 37) by using observed head levels obtained from the Commission on Water Resource Management (CWRM) and salinity, NO₃⁻+NO₂⁻ (further referred to as N), and PO₄³⁻ (further referred to as P) concentrations measured at wells and SGD springs by ‘Ike Wai team members H. Dulai and D. Tachera.

Four preliminary example applications were tested to evaluate the model capabilities. These scenario applications include relative N source contributions, SGD spring modeling, aquifer response to sea level rise, and aquifer response to urban development and climate change. The following observations were made from each scenario application:
Relative N source contributions: Simulated N was primarily sourced from OSDS and the eastern boundary condition (Figure 38). SGD springs directly downgradient of the Kealakehe WWTP were significantly affected by N sourced from the WWTP. The simulated relative source contributions are supported by a nitrogen isotope mixing model, which produced a reasonable fit between measured and computed δ15N values (r²=0.76).

SGD spring modeling: SGD fluxes were best calibrated when simulated as drain points with conductance values varying from 550-33,000 m²/d to match the SGD discharge rates that vary from 360-22,000 m³/d (RMSE=1206 m³/d, r²=0.98). This allowed SGD to exit the coast as a point source following preferential flow rather than diffusively.

Aquifer response to sea level rise: Under sea level rise conditions, simulated heads uniformly and SGD spring fluxes increased since a significant head gradient was not encountered under flux-controlled conditions.

Aquifer response to urban development and climate change: Reduction of recharge caused by increased water demands and climate change most drastically impacted aquifer conditions, resulting in declining heads, increased salinity intrusion, and increased N and P concentrations (Figure 39).

Outputs: A paper outlining the baseline
KBA model, sensitivity analysis, and scenario applications has been written and will be submitted to Hydrogeology Journal for review in January 2021. The KBA model will also serve as the catalyst for several other projects, including economic assessment of pumping scenarios and an assessment of land-sea connection in Kona.

**Outcomes:** The KBA model integrates efforts from the modeling and management teams to assess pumping scenarios for water management purposes. Various scenarios developed by water managers can be simulated with this model to predict how the aquifer (and coastal ecosystems) may respond.

**Publications:**
Okuhata BK, El-Kadi AI, Dulai H, Lee J, Wada CA, Bremer LL, Burnett KM, Delevaux JMS, Shuler CK. A density-dependent multi-species model to assess groundwater flow and nutrient transport in the coastal Keauhou aquifer, Hawai‘i, USA. (Submitted and in review with Hydrogeol. J.)

**Risks and Mitigation Plan:** Groundwater ages will need to be further analyzed and refined in order to be included in the WHR model. To better understand the validity of the apparent 14C ages, a Bayesian mixing model will be used to estimate 14C sources based on end-member ranges. The WHR model will then be further calibrated with the ages.

**Activity 2.2.7:** Estimate model parameters, their spatial distribution, and boundary conditions by direct measurements or through inverse methods. (El-Kadi, Lee)

**Results:** For the KBA model, the number of parameters and other aquifer variables subject to calibration were minimized as much as possible by using independently estimated values based on a literature review. The calibrated parameters are horizontal hydraulic conductivity ($K_h$), vertical anisotropy ($K_h/K_v$), porosity ($\phi$), and longitudinal dispersivity ($\alpha_L$), and their values were constrained based on available literature ranges. Due to the extreme hydrogeologic heterogeneity observed across the islands and the lack of hydrogeologic data in this specific study area, four flow and transport parameters ($K_h$, $K_h/K_v$, $\phi$, $\alpha_L$) were tested to determine which is the most influential during the model calibration process. Additionally, since aquifer boundaries are being investigated, the assigned boundary condition flux was also tested. To maintain consistency for sensitivity analyses, all four of the flow and transport parameters were multiplied by factors of 0.5 and 2.0. Apart from the parameter tested, all others remained fixed at the values used for the control model. The relative sensitivity coefficient, $S$, was computed following the equation (Nearing et al. 1990), $S = \frac{[(O_2-O_1)/O_{avg}]/[(I_2-I_1)/I_{avg}]}$ where $I_2$ and $I_1$ are the highest and lowest model input parameter values, respectively, and $I_{avg}$ is the average of the two $I$ values. Similarly, $O_2$ and $O_1$ are the highest and lowest output values respective to the input values, and $O_{avg}$ is the average of the two $O$ values. Following a similar method performed by Shuler et al. (2017), the root-mean-square error (RMSE) computed from head, salinity, N, and P concentrations in wells were used as the respective O variables in order to investigate how changes in parameters can improve or degrade model calibration. The final $S$ is therefore normalized and can thus be compared across parameters (Nearing et al. 1990). This assessment deemed that $K_h$, $\alpha_L$, and the boundary condition flux are the most critical for calibration and should be further investigated (Figure 40).
The control model assumes a homogeneous/anisotropic K distribution, which is expected to introduce less reliable calibration results than those based on a heterogeneous distribution, due to the site’s well-known geological variability. To address this issue, Kh distribution was further calibrated (Figure 41) by using the Principal Component Geostatistical Approach (PCGA), a scalable inversion method for spatially distributed field characterization (Lee and Kitanidis 2014; Lee et al. 2016). Using both head levels and salinity measurements in wells for calibration, spatially distributed Kh points were estimated. A prior statistical correlation structure, modeled by an exponential covariance function with the scale length of 2000, 2000, and 200 m in the x, y, and z directions, respectively, was determined by a Bayesian hyperparameter optimization approach (Kitanidis 1996) and used as a constraint for the calibration. An open-source Python package (https://github.com/jonghyunharrylee/pyPCGA) was linked to the USGS SEAWAT model and approximately 200 SEAWAT model runs were needed to obtain calibration results. Accuracy of salinity calibration in wells improved but hydraulic head calibration slightly reduced (Figure 41). Additionally, N and P concentration accuracy worsened. It is clear that calibration based on head and salinity distributions is only useful if appropriate representation of various processes is included in the conceptual model. It can be concluded that, for this specific study site, and probably for many others, utilizing a simplified K distribution is preferred, considering the complications and computational expenses associated with developing more involved K distributions.

Output: Sensitivity analysis determined that hydraulic conductivity, dispersivity, and mauka groundwater inflow (assigned at the upland boundary condition) are important parameters while assessing Keauhou’s groundwater resources.
Outcome: These findings highlight the parameters that need to be further investigated and can influence future groundwater model development.

We also investigated how geophysical surveys can improve the estimation of underlying subsurface structure, especially in field sites where only a few groundwater monitoring wells are available (e.g., Palani Ranch). Since the petrophysical relationship between geophysical properties (e.g., electrical conductivity) and hydrogeological parameters (e.g., hydraulic conductivity) is non-unique and uncertain, we proposed utilizing a self-potential (SP) survey to identify unknown subsurface structures without an explicit petrophysical relationship. Groundwater flow, MT, and SP were respectively simulated using the USGS MODFLOW model, MARE2DEM (Key, 2016), and a SP numerical model using a spectral approach (https://github.com/jonghyunharrylee/SP_forward_spectral written by Y. Seo). The inversion tests were carried out using the Python package described earlier. A notebook example is in https://nbviewer.jupyter.org/github/jonghyunharrylee/pyPCGA/blob/master/examples/mare2dem_MT/inversion_mare2dem.ipynb. A 2D cross-sectional model was designed for this experiment, as shown in Figure 42.

With two separate hydrological and geophysical calibrations using noisy head and MT measurements, hydraulic conductivity (K) and resistivity (ρ) were identified relatively well near the surface, up to the well penetration depth ~100 m for K and ~500 m for ρ (Figure 43). It is possible to improve the results by assuming a petrophysical relationship between K and ρ, but in practice, this information is not available and incorrect assignment of the petrophysical relationship would degrade the calibration results.
In the proposed approach, we used SP measurements to better correlate hydrogeological parameters and geophysical properties. Assuming we have additional SP surveys on the ground surface in addition to existing wells, the calibration can be performed jointly with the groundwater flow model, SP model, and MT model, without any petrophysical relationship. The calibration results in Figure 44 show that the proposed approach is promising and can be used in this volcanic island setting and for other aquifer characterization.

Figure 44: Preliminary results for joint calibration with additional SP data. Joint calibration identified high permeable $K$ structure below 100 m and $\rho$ becomes more accurate through multiphysics simulation and joint data inclusion

Outputs: A 2D cross-sectional model was developed to test joint calibrations and preliminary calibration results were obtained.

Publications and Papers:


Outcomes: The 2D cross-sectional model integrates efforts from the Modeling and Geophysics teams to characterize subsurface structures. Considering that well logs are not available to ground-truth the MT surveys conducted through Palani Ranch and other locations, the synthetic scenarios support teams’ efforts in identifying the relationship between certain hydrogeologic
parameters and electrical resistivity results.

**Activity 2.2.8:** Apply modeling tools to specific, pressing questions advanced by the hydrology community and stakeholders for the Pearl Harbor Aquifer. (Bremer, Burnett, Wada)

**Results:** We collaborated with the USGS Pacific Islands Water Science Center (PIWSC) to develop a simulation optimization methodology to estimate sustainable yield (maximum allowable withdrawal) in Hawai‘i, while taking into consideration several management objectives simultaneously: the reduction of salinization risk, minimization of head level drawdown and conservation of spring discharge. The USGS Hawaiian Water Budget Model (HWBM) was also used to generate recharge maps corresponding to different climate change and land-use scenarios. Simulation results are detailed in objective 2.3 for different (i) spring discharge thresholds, (ii) climate change futures, and (iii) watershed restoration and development scenarios.

**Outputs:** A general framework for estimating sustainable yield that incorporates important components of the Hawai‘i state water code, with particular emphasis on the protection of groundwater dependent ecosystems.

Maps of optimal pumping across Pearl Harbor Aquifer under varying climate and land use futures.

Maps of optimal pumping across Pearl Harbor Aquifer for a range of spring discharge constraints. Recommendations for updating the sustainable yield values currently used by state agencies overseeing the pumping of groundwater in the Pearl Harbor Aquifer.

**Publications and Papers:**


**Outcomes:** Recommendations for optimizing pumping across wells in the Pearl Harbor aquifer, if incorporated into groundwater management, can prolong the sustainable use of the aquifer and avoid high future freshwater provision costs, while protecting important and valued ecosystems that depend on the groundwater resource. We expect that continued communication of these types of results directly to stakeholders will help to improve coordination between groundwater modeling and groundwater management in Hawai‘i. This work has already stimulated a lot of interest from watershed partnerships and community organizations in the area.

**Objective 2.3:** Use economic modeling to forecast water availability and qualify economic impacts of aquifer utilization.

**Activity 2.3.1:** Develop site-specific land-use scenarios (Based on the stakeholder engagement process) (Bremer, Burnett, Wada)

**Results:** Pearl Harbor Aquifer: Land use and climate scenarios: Assuming (constant) baseline
land-cover, recharge declined by 16% under RCP 8.5 mid-century rainfall compared with baseline rainfall conditions. Land-cover change had a less significant impact on recharge than climate change; recharge was projected to be 1-7% lower in the future land-cover scenarios compared to the baseline land-cover. Recharge reductions were largest in scenario 6 (no forest protection and sprawl development) and smallest in scenario 1 (high forest protection and corridor development). Collectively, the projected benefits of informed land-cover planning, i.e., the difference in recharge between scenarios 1 and 6, was 43 million liters per day (MLD), or roughly 6%. The corresponding difference in estimated sustainable yield was 45 MLD (~10%). As was the case for recharge, the differences in sustainable yield estimates across different land use scenarios was driven much more by the level of forest protection than by urban development. We also found that pumping optimization increased the amount of freshwater that can be withdrawn compared to the current pumping allocation for any land use and climate scenario. For example, 390 MLD of pumped water would be below the salinity threshold after 50 years under the current pumping allocation and baseline climate, compared to 575 MLD in the optimized solution. Under RCP 8.5 mid-century, the numbers fell to 352 and 481 MLD for the current allocation and optimized pumping respectively. Changes in groundwater recharge and sustainable yield for different land cover scenarios under RCP 8.5 mid-century climate conditions are presented in Figure 45. Economic and management implications are detailed in Activity 2.3.2.

Spring scenarios: We found that over a 50-year period with salinity, drawdown and current levels of spring discharge constraints, the optimal maximum allowable withdrawal is 127 million gallons per day (MGD). For comparison, the current withdrawal rate of 117 MGD is already near the estimated optimal maximum, while the current designated sustainable yield value of 182 MGD using RAM2 is notably higher. We then defined additional spring discharge constraints as different percentages of the pre-development discharge level. Our simulation optimization results suggest that estimated optimal maximum allowable withdrawal changes from 127 to between 45 and 150 MGD, depending on the severity of the constraint (Figure 46c). More generally, the relationship between optimal maximum withdrawal and spring discharge is presented as a “tradeoff curve” (Figure 46d).

Hualālai Aquifer: Land use scenarios: We developed forest protection and restoration scenarios for the Kona area in collaboration with the Hawai‘i County Department of Water Supply. Results are described in detail in Activity 2.3.3. We also have been working with the stakeholders to develop future development and wastewater treatment scenarios for the Keauhou region. These scenarios have been linked to the KBA groundwater model, and results are described in Activity 2.2.6. Current efforts are focused on linking outputs of the KBA modeling of the development-wastewater scenarios to nearshore ecosystem health, including marine algae and coral reefs.

We also completed over 20 stakeholder interviews with resource managers and lineal descendants on the value of groundwater dependent ecosystems as a way to contextualize and link the hydrological and ecological analyses to human use and values. We have transcribed and analyzed the results of the interviews and will be submitting a manuscript (led by graduate student Veronica Gibson) this spring.

Outputs: Pearl Harbor Aquifer: Land use and climate scenarios: Six land use scenario maps developed in collaboration with the City and County of Honolulu and the State Office of Planning. Corresponding recharge and sustainable groundwater yield maps for each of the six land use scenarios, as well as maps illustrating the differences between scenarios (Figure 45). Estimated future freshwater replacement costs for each of the six land use scenarios (detailed in Activity 2.3.2)

Spring scenarios: Maps depicting optimal pumping patterns across the aquifer for four different spring discharge constraints (Figure 46c). Tradeoff curve developed to illustrate the relationship between optimal groundwater pumping and spring discharge (Figure 46d).
Hualālai Aquifer: Land use scenarios: Forest protection and restoration scenarios were developed for the Kona area in collaboration with the Hawaiʻi County Department of Water Supply.

Maps spatially prioritizing forest protection and restoration within the study region (detailed in Activity 2.3.3).

Maps illustrating groundwater quality implications of different development-wastewater scenarios (detailed in Activity 2.2.6)

~20 interviews with resource managers and lineal descendants complete and analyzed illustrating the uses and values of GDEs in Kona.

Publications and Papers:


**Outcomes:** The developed methodological framework and simulation results for Pearl Harbor aquifer will help to inform groundwater management planning. In particular, the optimization approach and results provide guidance for improving the accuracy of current sustainable yield estimates, while directly considering the tradeoff between pumping and maintenance of spring discharge in accordance with the state water code. Results from different land use scenarios also suggest that the negative effects of climate change on groundwater availability can be partially mitigated by targeted watershed management. Incorporating these results into water resource planning will benefit the community and environment through avoidance of over-pumping, reduction of future costs to water users, as well as protection of valued groundwater dependent ecosystems and native forests.

Research in the Hualālai aquifer area will be used by the Hawai‘i County Department of Water Supply to prioritize investments in forested watershed conservation overlying their managed aquifer units of interest. Such investments will benefit important forested ecosystems while simultaneously supporting continued groundwater use into the future. Results from the KBA modeling of development-wastewater impacts on groundwater quality may help to expedite the state-mandated conversion of existing cesspools. This would result in cleaner ground and coastal waters, which is important for both human health and groundwater-dependent ecosystems. Our qualitative research using interviews with lineal descendants and resource managers will also ensure that modeling results are salient and linked to the uses and values most strongly expressed by community members.

**Activity 2.3.2:** Evaluate economic and management implications of scenarios. (Bremer, Burnett, Results:

**Pearl Harbor Aquifer:** Figure 45 shows the implications for groundwater recharge and sustainable yield of different development and forest protection scenarios. As discussed in Activity 2.3.1, results suggest that targeted forest protection has a larger effect on the groundwater resource than urban development, and optimization increases sustainable yield relative to the value estimated under the current pumping allocations.

Figure 46 in Activity 2.3.1 presents optimal pumping patterns for different spring discharge constraints and depicts a tradeoff curve illustrating the relationship between sustainable yield and spring discharge. Unless recharge to the aquifer is increased, maintaining a higher rate of spring discharge requires reducing groundwater withdrawals.

We also estimated groundwater replacement costs for different land use and climate scenarios as the year 2070 shortfall (difference between our simulated sustainable yield and projected water demand) multiplied by $9 per thousand gallons, an estimate of the unit cost of desalination in Hawai‘i. Under RCP 8.5 mid-century rainfall projections, we estimated that targeted forest protection would avoid $6-10 million per year in future groundwater replacement costs, while high forest protection would avoid $33-39 million per year in future costs, which suggests that forest protection should be considered in water management planning. Results for all scenarios are summarized in Table 1.
We updated the mountain-to-sea resource management framework developed in Year 4 to include the possibility of removing invasive plant species that can uptake groundwater directly (in this case, *Prosopis pallida*), in addition to protecting existing native forest to enhance recharge. Our results suggest that protection of existing native forest tends to be more cost-effective than *P. pallida* removal if we are limited to selecting a single conservation tool. However, net present value was higher when both instruments were optimally used simultaneously. For example, forest protection alone reduced welfare loss (incurred as a result of limiting groundwater pumping to meet a submarine groundwater discharge constraint designed to protect nearshore ecosystems) by $86.87 million. But when both instruments were used simultaneously, total loss reduction improved to $93.44 million. Results were largely insensitive to variations in the invasive species uptake rate and coefficient values for the recharge benefit function.

We completed and published a spatial analysis of watershed investments in West Hawai‘i and finalized the results (detailed in Activity 2.3.3). As described in Activity 2.2.6, we have also been working to evaluate the water quality impacts of future development and cesspool conversions in the region. Within the next year, we plan to integrate conversion costs and nearshore ecological impacts for a number of different development-wastewater scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Recharge mm/year (MGD/MLD)</th>
<th>Optimized sustainable yield (MGD/MLD)</th>
<th>Spring discharge (MGD/MLD)</th>
<th>Replacement cost (million SUS/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate demand</td>
<td>High demand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current land cover</td>
<td>201/761</td>
<td>152/575</td>
<td>57/116</td>
<td>0</td>
</tr>
<tr>
<td>RCP 8.5 mid-century rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current land cover</td>
<td>170/644</td>
<td>127/481</td>
<td>62/235</td>
<td>35</td>
</tr>
<tr>
<td>1: Corridor development, high forest protection</td>
<td>168/636</td>
<td>125/473</td>
<td>63/238</td>
<td>41</td>
</tr>
<tr>
<td>2: Corridor development, targeted forest protection</td>
<td>161/609</td>
<td>116/439</td>
<td>64/242</td>
<td>71</td>
</tr>
<tr>
<td>3: Corridor development, no forest protection</td>
<td>158/598</td>
<td>113/428</td>
<td>54/204</td>
<td>81</td>
</tr>
<tr>
<td>4: Sprawl development, high forest protection</td>
<td>167/632</td>
<td>121/458</td>
<td>63/238</td>
<td>54</td>
</tr>
<tr>
<td>5: Sprawl development, targeted forest protection</td>
<td>439 (160)</td>
<td>115</td>
<td>62/235</td>
<td>74</td>
</tr>
<tr>
<td>6: Sprawl development, no forest protection</td>
<td>432 (157)</td>
<td>113</td>
<td>54/204</td>
<td>81</td>
</tr>
</tbody>
</table>

*Table 1 Scenario Results:* Sustainable yield, spring discharge, and replacement costs (under two demand growth assumptions) of land cover scenarios.
**Outputs:** *Pearl Harbor Aquifer:* Estimates of future groundwater replacement costs and sustainable yield for a number of different land use and climate scenarios. Maps showing optimized pumping across Pearl Harbor for a range of spring discharge constraints. Tradeoff curve depicting the relationship between spring discharge and optimal withdrawal rates.

**West Hawai'i Aquifers:** Net present values of integrated watershed-aquifer-nearshore management for strategies that include protection of existing native forest, removal of invasive species, or both. Maps illustrating priority areas for watershed protection (see Activity 2.3.3). Maps of N concentrations for different assumptions above cesspool conversion and future urban development (see Activity 2.2.6).

**Publications and Papers:**


**Outcomes:** The groundwater optimization work in Pearl Harbor can directly influence water and watershed management in these areas. Incorporating our results into water resource planning will benefit the community and environment through avoidance of over-pumping, reduction of future costs to water users, as well as protection of valued groundwater dependent ecosystems and native forests.

The watershed conservation and net present value analyses from the Kona area can also influence water and watershed management. Targeted investments in forest protection and restoration will benefit important forested ecosystems while simultaneously supporting continued groundwater use into the future. The net present value analysis suggests that such investments, when made in conjunction with an optimal pumping plan, make sense from a cost perspective. Results from the KBA modeling of development-wastewater impacts on groundwater quality may help to expedite the state-mandated conversion of existing cesspools. This would result in cleaner ground and coastal waters, which is important for both human health and groundwater-dependent ecosystems.

**Activity 2.3.3:** Spatial analysis of watershed investments. (Bremer, Burnett, Wada)

**Results:** We produced priority investment maps based on which areas would result in the greatest avoided loss of recharge or increase in recharge in the case of reforestation. The highest priority areas (80th percentile of benefits) for native forest protection were estimated to prevent the loss of over 49,600 m$^3$ of recharge per ha over 50 years (Figure 47) and were primarily located in low to mid-elevation mesic forest areas at highest risk of invasion by invasive canopy species as well as in high elevation, cloud forest areas at high risk of conversion to non-native grassland or bare ground. We also found that forest restoration is projected to increase recharge by over 88,900 m$^3$ per hectare over 50 years in the highest priority areas with substantial fog interception but that decreases in recharge occur in areas with low fog interception (Figure 48).
Outputs: Priority investment maps for forest protection to identify areas with the greatest avoided loss of recharge (Figure 47).

Priority investment maps for reforestation to identify areas with the greatest potential recharge gains (Figure 48).

R package to simulate landcover spread and the associated changes in water yield and recharge (or any other landcover-dependent spatial regressions). The package is still in development but is currently available for download from GitHub (https://github.com/natedemaagd/LandCover)

Publications and Papers:


Outcomes:
The Hawai‘i Department of Water Supply plans to use the results from activity 2.3.3 to make decisions regarding size, scope, and location of future watershed conservation. Such targeted investments will benefit important forested ecosystems while simultaneously supporting...
continued groundwater use into the future.

**Objective 2.4.** Community Engagement.

**Activity 2.4.1: Agency Outreach**

‘Ike Wai researchers are using early results to address specific concerns of water management stakeholders. The modeling team manually calibrated the KBA model using reported head levels (obtained from the Commission on Water Resource Management (CWRM) Section 2.2.6) as well as measured salinity, nitrate+nitrite (further referred to as N), and phosphate (further referred to as P) compiled by ‘Ike Wai (Figure 33). Two preliminary water management scenarios were completed using the calibrated KBA model, where the baseline results were set as the starting conditions for the scenario runs.

**2.3.2 Management Scenarios:** The set of wells used in the Pearl Harbor pumping optimization model by Elshall in Year 3 was refined to include integration of a spring constraint and incorporation of land use and climate scenarios (see activity 2.2.8). The results show the spatial distribution of maximum SY with all springs restored to pre-industrial levels, indicating a major tradeoff between pumping and spring protection. Results from this analysis can inform decision-making around location and magnitude of groundwater withdrawals in the Pearl Harbor aquifer.

**Outcomes:** The major agency outreach conducted in Year 5 was through the stakeholder workshop held on February 20, 2020, in partnership with the University of Hawai‘i Water Resources Research Center. The purpose of that workshop was to share emerging results of the project and refine analyses. See Activity 2.4.6 for details of the event as well as additional stakeholder engagement activities.

**Activity 2.4.2-2.4.4:** These activities were combined with Activities 2.4.5 - 2.4.6.

**Activity 2.4.5: Negotiate, document, and manage landowner agreements.**

No new landowner agreements were established in Year 5. The focus this year has been to finalize data collection on existing landowner agreements and analyze data already collected. Travel restrictions due to the pandemic further limited field activity. Final geophysical field data was collected at the end of 2020 on the Dole lands surveying the Schofield Dam area.

**Activity 2.4.6: Develop Strategic Community Partnerships.**

On February 20, 2020, in partnership with the University of Hawai‘i Water Resources Research Center, a stakeholder workshop was conducted to share ‘Ike Wai project results and research capabilities with the broader community, including a number of state and local agencies, partnerships, and non-profit organizations. Approximately 40 non-‘Ike Wai members participated. ‘Ike Wai members also put together a symposium at the Hawai‘i Conservation Conference (Sep 1-3, 2020), titled “Water, ecosystems and people - insights from the ‘Ike Wai project on the Pu‘ulōa (Pearl Harbor) and Hualālai aquifers”. Findings from several of the research teams were shared with a diverse group of scientists, policymakers, conservation practitioners, educators, students, and community members (over 70 non-‘Ike Wai members participated virtually).

Most recently, a virtual meeting was arranged on December 3, 2020 to share research findings with and receive feedback from QLT stakeholders, who have been very supportive of ‘Ike Wai research efforts in the areas of geophysical surveying, well sampling, precipitation collection, and buoy deployment. We received positive feedback and interest in potential future collaborations. We plan to arrange similar virtual small-group meetings with other key stakeholders over the coming months.
Activity 2.4.7 (Previously 3.4.2): Conduct general education and disseminate information

Results: Project information, current results and student opportunities continue to be disseminated through the Hawaii EPSCoR website (www.hawaii.edu/epscor) and various social media channels that include Instagram, Twitter and LinkedIn. Facebook fans have increased to include 13 counties and 57 cities. There were more than 14,500 impressions on Twitter, a 700% increase from the previous year. Additionally, communication between EPSCoR jurisdictions was increased through establishing and participating in national EPSCoR communications meetings and a national EPSCoR LinkedIn group.

Project team members participated in two community engagement events, the Kona Science Cafe on November 19, 2020 and a meeting with Queen Lili‘uokalani Trust on December 3, 2020 with a total of 50 participants to share project results.

Results published by Attias et. al in Science Advances were disseminated to a local, national and international audience estimated at more than 254 million through web, TV and print. Notable features include the New York Times, Science Node and the Honolulu Star-Advertiser. Twenty-

Table 2: List of current access agreements.

<table>
<thead>
<tr>
<th>Landowner</th>
<th>Entity Type</th>
<th>Status</th>
<th>Agreement Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawaii Island</td>
<td>State</td>
<td>Application Approved</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Division of Forestry and Wildlife Management</td>
<td>State</td>
<td>Application Approved</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Division of Forestry and Wildlife Pu‘u Wai’a Wai’a Sanctuary</td>
<td>State</td>
<td>Agreement Executed 2/1/18</td>
<td>Well Sampling</td>
</tr>
<tr>
<td>Hawaii Water Supply (WIS)</td>
<td>County</td>
<td>Agreement Executed 2/1/18</td>
<td>Well Sampling</td>
</tr>
<tr>
<td>Kamehameha Schools (KS)</td>
<td>Private</td>
<td>Access Granted</td>
<td>Geophysical Surveying, Well Sampling, Precipitation Collector, Buoy deployment</td>
</tr>
<tr>
<td>Kapaopala (Chun residence)</td>
<td>Private</td>
<td>Agreement Made</td>
<td>Geophysical Surveying, Precipitation Collector</td>
</tr>
<tr>
<td>Khoole Bay</td>
<td>Private</td>
<td>Access Granted</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Kohala Ki</td>
<td>Private</td>
<td>Access Granted</td>
<td>Geophysical Surveying, Well Sampling, Precipitation Collector, Buoy deployment</td>
</tr>
<tr>
<td>Napu‘u Water Services Private Access granted</td>
<td>Private</td>
<td>Access Granted</td>
<td>Well Sampling at Pii Waa Waa Ranch</td>
</tr>
<tr>
<td>NOAA Earth System Research Laboratory, Global Monitoring Division</td>
<td>Federal</td>
<td>Application Approved</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Natural Energy Laboratory of Hawaii Authority (NELHA)</td>
<td>State</td>
<td>Agreement Executed 8/17/17</td>
<td>Earthquake Storage, Space Rental for Well Sampling, Buoy Deployment, and Precipitation Collector</td>
</tr>
<tr>
<td>Office of Mauna Kea Management</td>
<td>State</td>
<td>Access Granted</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Palamanui</td>
<td>Private</td>
<td>Access Granted</td>
<td>Precipitation Collector</td>
</tr>
<tr>
<td>Palani Ranch</td>
<td>Private</td>
<td>Agreement Executed 6/30/17</td>
<td>Geophysical Surveying, Well Sampling, Precipitation Collector</td>
</tr>
<tr>
<td>Queen Lili‘uokalani Trust (QL T) Private</td>
<td>Private</td>
<td>Agreement Executed 8/9/17</td>
<td>Geophysical Surveying, Well Sampling, Precipitation Collector, Buoy deployment</td>
</tr>
<tr>
<td>O‘ahu</td>
<td>State</td>
<td>Approved by Board 10/9/19; Awaiting Permit</td>
<td>Geophysical Surveying</td>
</tr>
<tr>
<td>Agricultural Development Corp. (Hawaii Dept. of Agriculture)</td>
<td>Private</td>
<td>Access Granted 9/13/19</td>
<td>Geophysical Surveying</td>
</tr>
<tr>
<td>Dole Fruit Company</td>
<td>Private</td>
<td>Access Granted 9/13/19</td>
<td>Geophysical Surveying</td>
</tr>
<tr>
<td>Kamananui Ranch</td>
<td>Private</td>
<td>Access Granted 9/13/19</td>
<td>Geophysical Surveying</td>
</tr>
<tr>
<td>Kamehameha Schools (KS)</td>
<td>Private</td>
<td>Application being processed by KS</td>
<td>Geophysical Surveying, Well Sampling</td>
</tr>
</tbody>
</table>
one news articles and two video news releases about Hawai‘i EPSCoR were published by University of Hawai‘i News in 2020 with Attias’ work featured in the top 20 stories of the year. Work from Hawai‘i EPSCoR was featured on local TV news station Hawaii News Now:


Outputs:
- UH grad student earns Department of Defense fellowship
- UH Hilo, UH Mānoa team wins national award for coral reef virtual reality app
- UH Hilo 3D prints prototype medical equipment
- CTAHR alum awarded for outstanding miconia invasion study
- #ScienceMarchesOn showcases research, innovation during COVID-19
- Data science talent at UH Mānoa, UH Hilo showcased virtually
- Collaborative coral study compares old, new scientific techniques
- UH Maui College STEM education video featured in NSF showcase
- Hurricane Lane brought fire and rain to Hawai‘i
- Hawai‘i’s water security focus of UH student research
- Study predicts costly water issues if action not taken
- UH provides indigenous perspectives on AI guidance
- Citizen scientists expand data collection for UH Hilo researchers
- Cutting edge LAVA gets $5M AI upgrade
- Student work featured at international computer graphics conference
- UHERO wins national award for website
- AI student research conducted while adhering to COVID-19 protocols
- UH Hilo Marine Science student wins best oral presentation at Hawai‘i Conservation Conference
- New tech video a collaboration of animation and science
- Good environmental policy requires understanding people
- Team of UH-Hilo students, faculty publish work on coral health and disease
- Offshore submarine freshwater discovery raises hopes for islands worldwide

**Goal 3:** Establish an integrated set of pathways to train and develop a diverse cohort of students, postdoctoral and faculty researchers at UHH and UHM to address Hawai‘i’s challenges.

**Objective 3.1:** ‘Ike Wai Undergraduate Scholars Program: Undergraduate research and professional development.

**Activity 3.1.1:** Undergraduate Research. (Bruno, Pelayo, UHH Faculty)

**Results:** During the reporting period, the ‘Ike Wai Undergraduate Scholars program was restructured and relaunched as the ‘Ike Wai Internship program. Previously, the program paired undergraduates at Kapi‘olani Community College (KCC), UH Mānoa and UHH with faculty advisors, where they pursued closely mentored undergraduate research projects that were largely academic in nature. Although this research training provided excellent preparation for graduate school, it lacked direct workplace relevance.

During the reporting period, we transformed this program into a workforce development program. Instead of pairing students with professors, we now place students in internships at federal, state and local government agencies. All students are mentored by an agency representative, and many students are also being supported by a UH faculty mentor. Here is a list of participating agencies:
• Board of Water Supply (Hydrology/geology division)
• Board of Water Supply (Communications division) Hawaii Department of Health
• Division of Aquatic Resources (DAR), of the Department of Land and Natural Resources (DLNR) - Oahu
• Division of Aquatic Resources (DAR), of the Department of Land and Natural Resources (DLNR) - Hawaii Island
• Hawaii Volcano Observatory
• National Park Service - Haleakalā
• Natural Energy Laboratory of Hawaii (NELHA)
• NOAA - Pacific Island Fisheries Science Center (PIFSC)
• NOAA - Papahānaumokuākea Marine National Monument
• USGS

Fifteen students and recent graduates are interning at these federal, state and local government agencies on the islands of Oahu, Hawaii and Maui. This includes 12 students funded by ‘Ike Wai and 3 with leveraged funding. In addition to these 15, two more internship positions have been established and will be filled in early 2021.

During the reporting period, 4 ‘Ike Wai-supported interns were offered jobs with federal agencies. A NOAA intern joined the Department of Defense as a Data Scientist. A Haleakalā National Park intern accepted a position as Biological Science Technician with the National Park Service, and will start in January 2021. Two Board of Water Supply (BWS) interns received employment offers. The intern with BWS communications division joined DLNR as a Climate Change Communications Specialist. The intern with BWS hydrology-geology division received employment offers from two federal agencies: NOAA (via JIMAR) and USGS. This employment success clearly shows that the training the students are receiving through the ‘Ike Wai Internship Program is valuable and relevant. Of these 4 students, all are women of color, including 2 Native Hawaiian and Pacific Islanders.

During the reporting period, two Scholars earned authorship on peer-reviewed publications on ‘Ike Wai research. Cherryle Heu co-authored an Oceanography publication which was published June 2020, mentored by ‘Ike Wai faculty Bruno and Weyenberg. Honour Booth is first author of a manuscript on stable isotope analysis of precipitation that is pending publication, mentored by ‘Ike Wai faculty Lautze and ‘Ike Wai graduate student Tachera. Both students are women of color.

Three alumni of last year’s ‘Ike Wai undergraduate Scholars program are currently in graduate school. At UH Manoa, Melanie Keliipuleole and Honour Booth are pursuing Masters degrees in Marine Biology and Chemistry, respectively. At UH Hilo, Kainalu Steward is pursuing a Masters in Tropical Conservation Botany & Environmental Science (TCBES). Two are women and all three are minorities, including two Native Hawaiians.

At UHH, the ‘Ike Wai Scholars program continues to provide academic-year research opportunities for five undergraduate students. These scholars are mentored by UHH faculty Weyenberg and Hong, with 2 and 3 scholars, respectively. Hong’s projects focus on the use of Natural Language Processing to analyze old Hawaiian newspapers for impacts of historical events and analyzing sound file of phone calls of bank customers. The use of NLP fits naturally with the newly-developed curricular emphases within Hong’s department (College of Business and Economics at UHH). Weyenberg’s projects span two separate fields: the first continues the use of statistical techniques to analyze coral cover, and the second focuses on principal component analysis and other dimension reduction techniques.
Activity 3.1.2: Undergraduate Professional Development (PD). (Bruno, Jacobs, Cleveland)

Results: A wide range of undergraduate professional development (PD) was offered during the reporting period including: field work opportunities; applying to scholarships and undergraduate research opportunities; applying to the NSF Graduate Research Fellowship program and a variety of workshops on Hawaiian culture that highlight the integration between Hawaiian culture and Western science. Although virtually all of the in-person local and national conferences that students were planning on attending were cancelled due to COVID, many offered virtual alternatives, including Geological Society of America (GSA), American Geophysical Union (AGU) and the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS).

Objective 3.2: Summer Bridge Programs: Attract early undergraduates to 'Ike Wai-related STEM fields by developing and implementing summer bridge programs.

Activity 3.2.1: O'ahu Summer Bridge for rising sophomores. (Bruno)

Results: The O'ahu Summer Bridge program is an annual (May) field-based collaboration between the Kapi'olani Community College (KCC) Native Hawaiian Advancement Office and UH Mānoa based on 'Ike Wai research. It forms a key part of the pathway through which we recruit KCC students into undergraduate 'Ike Wai programs and SOEST majors. The Oahu Summer Bridge program utilizes a near-peer mentoring system, where alumni from the previous year's program (many of whom are 'Ike Wai undergraduate interns) serve as teaching assistants and role models for STEM success. During the reporting period, we revised the 2019 content to develop a 2020 program that seamlessly integrated: Hawaiian culture and community; geology, hydrology, and environmental science; and exploration of college STEM majors and careers. We also recruited a teaching team that included 5 peer mentors, 'Ike Wai graduate students and faculty and Native Hawaiian cultural specialists. Unfortunately, the May 2020 program was cancelled due to COVID. The O'ahu Summer Bridge program is on track to be offered during May 2021, and it will be offered virtually if an in-person workshop is not possible.

Activity 3.2.2: Hilo Summer Bridge for rising freshmen and sophomores. (Pelayo, UH Hilo faculty)

The UHH bridge efforts fully transitioned to a research focus for upper-division undergraduates. Thus, the UHH Summer Bridge program completely transitioned to a summer research experience entitled the 'Ike Wai Data Science Summer Research Program. In previous years, the summer efforts included a combination of both lower-division student coursework in introductory courses and this upper-division research effort. This full pivot to research reflects the larger pool of Data Science undergraduate students and faculty research capacity.

Faculty members Burns and Hong ran concurrent Hilo Data Science Research programs in the summer of 2020, which included ten students in a marine biology-focused project and six students with text analytics focus. The marine biology project, led by Burns and in collaboration with NOAA, had students examine coral patches between two time points to assess which reef characteristics lead to coral patches ‘winning’ or ‘losing’ over time. Students gained skills in photogrammetry, geospatial data processing, univariate and multivariate statistical analyses and writing. The UHH Data Science infrastructure enabled the work to be completed remotely due to covid by using the CyberCANOE system. The results of this work will be submitted for publication with all students as co-authors in 2021. The text analytics component, led by Hong, used natural language processing techniques to understand Historical Hawaiian texts, such as old Hawaiian newspapers. Students collated information about important events and topics related to water usage in Hawaii using advanced text analysis techniques. The project has a high potential impact by creating new methods for historical research of the Hawaiian language.
Publications:


Objective 3.3: Individualized Professional Development: Create and implement individualized professional development plans for graduate students and postdocs, and Mentoring Cascade.

Activity 3.3.1: Individualized Development Plan (IDP) for graduate students and postdocs. (Bruno, Eason)

Results: Training sessions are held each term for all incoming ‘Ike Wai graduate students and postdocs on how to create an effective IDP (no new trainees participating in the program during this reporting period). All graduate scholars and postdocs are required to complete an IDP within 60 days of hire. As of December 2020, all continuing graduate students and postdocs had completed IDPs, for a running total of 23 graduate students and postdocs with IDPs over the course of the project. A key outcome of this self-assessment of job-related skills/experience and career goals is enhanced awareness of the additional skills and experience needed to obtain their professional goals. A manuscript on the ‘Ike Wai IDP program was published in summer 2020 (see Activity 3.7).

Based on the success of the IDP pilot study (Eason et al., 2020), we are now focusing on expanding IDP use outside of the project. We have developed an improved set of IDP forms and guidelines which are now publicly available for use in STEM programs around campus. After numerous meetings with department chairs and information sessions with interested units to introduce faculty to IDPs and their use, several units are on track to implement IDPs in Fall or Spring 2021.

Publications and Papers:


Activity 3.3.2: Mentoring Cascade. (Bruno, Eason)

Results: All ‘Ike Wai graduate students and postdocs participated in the mentoring cascade as mentees. All nine active (plus 14 previous) graduate students and postdocs have selected PD mentors from a list of ‘Ike Wai faculty and staff members outside their research group/field. New mentors and mentees are trained on the IDP process (only one new pairing in 2020). In addition to the ongoing IDP presentations and outreach efforts (see Activity 3.3.1), we plan to hold a final in-house mentoring workshop in spring 2021.

In response to a site visit recommendation, the ‘Ike Wai mentoring cascade was expanded to include faculty as mentees. New, untenured investigators can now request a senior, tenured faculty mentor from within or outside the ‘Ike Wai project team. All nine young faculty were contacted by the Education Director during Fall 2019 with an invitation to be paired with a mentor, which six faculty accepted. The other three new faculty were already paired with one or more mentors through their department and did not feel the need for additional mentoring at this time.

Objective 3.4: Cohorted Professional Development: Develop and implement a series of education and training workshops for ‘Ike Wai Graduate Students, Postdocs, Faculty and Staff.

Activity 3.4.1: Cohorted Professional Development (PD) Training. (Bruno, Eason)
**Results:** During the reporting period, we offered nine workshops to ‘Ike Wai Graduate Students, postdocs, faculty and staff. COVID-19 has required various adjustments in content and/or delivery, and all workshops and activities are now held online. In some instances, this made it easier to open opportunities to a larger population and include participants from outside the project. In response to site visit recommendations and to better address the project’s cultural components/needs, we have focused more heavily on cultural trainings. External facilitators Ku‘ulei Kanahele and Ulu Keali‘ikanaka‘olehaililani from the Edith Kanaka‘ole Foundation conducted a 3-hour workshop on Papakū Makawalu (Oct 2020), a Hawaiian worldview of the physical, intellectual, and spiritual foundations from which life cycles emerge. An additional All-Hands meeting was dedicated to training in cultural values and community engagement. This team-taught workshop drew from various cultural and community resources, including Hawaiian-language newspapers and the Kulana Noi‘i, which are ethical guidelines for conducting research in Hawaii in partnership with communities.

We’ve also incorporated cultural topics into our professional development activities for graduate students and postdocs, including integrating data from the Hawaiian-language newspaper translations with the project’s scientific data and results, and developing a Hawaiian language guide with common Hawaiian words, phrases, and place names relevant to the project. This language guide has been incorporated into the project’s Community Engagement Packet for internal use.

Additional in-house workshops and professional development activities in 2020 included two workshops on applying for fellowships (one general, and one specifically for applying to the NSF Graduate Research Fellowship Program), career-planning workshops (e.g., Virtual Panel on Non-Academic Careers, Preparing for the Academic Job Search), and a mini-session on evidence-based goal-setting practices.

**Objective 3.5: Data Science: Establish two academic programs at UH Hilo in Data Science, a certificate and a BA in data analytics.**

**Activity 3.5.1:** Initiate Strategic Faculty Hires in Data Science. (Pelayo)

**Results:** The four UH Hilo Data Science hires were completed in Years 1-4, and thus no additional faculty hires were completed during Year 5. The four hired faculty continue to work on data science educational efforts within the university and provide research opportunities for undergraduate and graduate students.

**Activity 3.5.2:** Develop a Data Science Pathway. (Pelayo, UH Hilo faculty)

The UHH Data Science Team prepared a successful Authorization to Plan (ATP) document for the data science major, resulting in the UH Hilo administration formally providing authorization to proceed with developing the Data Science Major in Spring 2020. Burns, Weyenberg, Mandel, and Hong were also approved to make use of the new DATA alpha for their upper and lower division courses that form part of the data science program. The team developed an outline for the major, consulting with faculty in numerous departments across UHH to develop several interdisciplinary concentrations for the degree. The degree program was slated to be submitted for approval in 2020; however, it was delayed until 2021 (with guidance from the UH Hilo administration) due to inability to fill necessary faculty positions due to hiring freezes associated with Covid19.

New courses that were proposed and approved during Year 5 include QBA 367 (Applied Business Analytics) and a Business Analytics certificate, which includes this new course along with other QBA and DATA courses previously approved. This new program and course will be available to students in Fall 2021. For an additional year, Pelayo, who formally left UHH in 2019, continues.
to advise these curricular efforts and manage much of the programmatic aspects of the grant.

Publications and Papers:


Magel JMT, Burns JHR, Gates RD, Baum JK (2019) Effects of bleaching-associated mass coral mortality on reef structural complexity across a gradient of local disturbance. Scientific Reports. 9(1) 2512: DOI: 10.1038/s41598-018-37713-1


Objective 3.6: Business and Community: Connect 'Ike Wai to business and community.

Activity 3.6.1: Engage with Stakeholders. (Bruno, Pelayo, Chun)

Results: The 'Ike Wai Community Engagement Packet (created during a previous reporting period) contains a primer on the 'Ike Wai project, maps of study sites and Hawaiian translations, and the Kulana No'i, which are ethical research standards rooted in the Hawaiian culture. This must-read resource continues to drive our stakeholder engagement, and workshops are regularly scheduled during 'Ike Wai all-hands meetings to ensure that all project members’ skills are kept up-to-date. The most recent workshop was offered on 6/18/20, as one of the cultural trainings
recommended by the Year 4 site visit team.

As noted above under Objective 3.1, during this reporting period the Undergraduate Scholars program was transformed into the 'Ike Wai Internship program. The academic research experiences were replaced by internships with government agencies. Seventeen internships were established. Fifteen of these positions have been filled and two are scheduled to be filled in January 2021.

During the reporting period, we developed and are currently administering an employer survey to better understand Hawaii’s anticipated geoscience workforce development needs in the coming decade (2021-2030), so we can prepare students to meet these needs. Surveys have been distributed to federal, state and local governmental agencies and private businesses related to geoscience. To date, over 30 agencies have responded. Encouragingly, following this survey, several government agencies and private businesses (such as environmental consulting companies) sent us position advertisements and requested our help in identifying appropriate candidates, which we did.

Objective 3.7: Educational Research

Activity 3.7.1: Geoscience Educational Research. (Bruno, Eason)

Results: At the onset of the five-year 'Ike Wai project, five geoscience education research publications were proposed. Three were published during previous reporting periods. The remaining two publications (listed below) were published during the current reporting period. All five publications were first-authored by current or former members of the 'Ike Wai geoscience education research team (Böttjer-Wilson, Bruno, Eason, Engels). Numerous former team members continued to co-author publications after they left 'Ike Wai, attesting to the success of this EPSCoR grant in establishing robust, continuing collaborations.

Publications and Papers:


IV. Solicitation-Specific Project Elements

A. Workforce Development: Workforce development efforts during the reporting period have focused on research and professional development training for undergraduates (Objectives 3.1-3.2), graduate students and postdocs (Objectives 3.3-3.4) and faculty/staff (Objectives 3.4-3.5). The goals, objectives and activities associated with these workforce development programs are detailed immediately above in Section III. A key part of faculty-level workforce development is establishing and filling new tenure-track positions at UH Mānoa and UH Hilo to build capacity in water science and data science, respectively. This brings new expertise into the UH system, enabling the creation of new undergraduate and graduate training programs and ultimately resulting in the development of a diverse, local workforce equipped to tackle pressing challenges such as ensuring Hawai’i’s future water security. All tenure-track faculty positions were completed in previous years of the project.
**B. Diversity:** Broadening participation is integral to the ‘Ike Wai research and education missions. We set ambitious demographic targets (both in terms of gender equity and ethnicity). For undergraduates, our goals are 75% women and 50% underrepresented minorities (URM), including 25% Native Hawaiians and Pacific Islanders (NHPI). On O‘ahu and Hilo, out of 35 total participants, 69% of undergraduate students were women, with 37% identifying as URM, and 20% of students identifying as NHPI. Our undergraduate cohort fell short of our targets for Year 5, as we were not able to offer the O‘ahu Summer Bridge in 2020 as we did in previous years, which historically had found success in broadening participation with a well-established partnership with the Kapi‘olani Community College Native Hawaiian Advancement Office.

For graduate students and post-doctoral researchers, our targets were 50% women and 25% URM. Our current graduate/postdoc cohort were 44% female and 33% URM. No new hires were made in Year 5 of the project and the current cohort was comprised of students that were hired in previous reporting periods. These hires were broadly advertised through local and national minority-serving organizations, including UH Native Hawaiian Student Services, Institute of Broadening Participation, Society for Advancement of Chicanos and Native Americans in Science (SACNAS), the American Indian Science and Engineering Society (AISES) and the NSF Science and Technology education and diversity listserv. Our commitment to diversity is reflected in our core values and the demographic makeup of the leadership team, which is 40% female and 30% URM. We are actively mentoring and supporting women faculty, in addition, we support the dissemination and advancement of Native Hawaiian cultural insights and traditional/historical knowledge both within and beyond the ‘Ike Wai project.

<table>
<thead>
<tr>
<th>Project Role</th>
<th>Total Participants</th>
<th>% Female</th>
<th>% URM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faculty participant (or equivalent)</td>
<td>19</td>
<td>37%</td>
<td>5%</td>
</tr>
<tr>
<td>Technical support staff</td>
<td>13</td>
<td>38%</td>
<td>2%</td>
</tr>
<tr>
<td>Non-technical support staff</td>
<td>2</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Post docs</td>
<td>2</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>Graduate students</td>
<td>8</td>
<td>38%</td>
<td>38%</td>
</tr>
<tr>
<td>Undergraduate students</td>
<td>35</td>
<td>69%</td>
<td>37%</td>
</tr>
<tr>
<td>Leadership Team</td>
<td>10</td>
<td>40%</td>
<td>30%</td>
</tr>
<tr>
<td>Combined</td>
<td>89</td>
<td>52%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Table 3: Project broadening participation breakdown

Indian Science and Engineering Society (AISES) and the NSF Science and Technology education and diversity listserv. Our commitment to diversity is reflected in our core values and the demographic makeup of the leadership team, which is 40% female and 30% URM. We are actively mentoring and supporting women faculty, in addition, we support the dissemination and advancement of Native Hawaiian cultural insights and traditional/historical knowledge both within and beyond the ‘Ike Wai project.

**C. Partnerships:** We have maintained strategic partnerships with over 25 different entities, including local foundations with missions focused on island sustainability, resiliency and land stewardship, state agencies and key landowners and community forums. These partnerships provide two important benefits to the project, 1) a direct and trusted connection between our project activities and the potential benefits and impacts on the community and 2) access to land for study sites and wells and to current and legacy data important to our work. These partnerships include:

- Department of Fish and Wildlife (DOFAW) - Land owner; study site access and data sharing.
- Hawai‘i Community Foundation – There are opportunities to develop an ongoing strategic partnership with HCF for collecting existing water legacy data in the State not included in agency data and to develop a methodology for determining ROI on watershed conservation.
- Hawai‘i County Department of Water Supply (HDWS) - Well owner and operator; study site access and data sharing
- Hawai‘i Department of Health - ‘Ike Wai Internship partner
- Hawai‘i Volcanoes Observatory - ‘Ike Wai Internship partner
- Hawai‘i Water Service (HWS) - Land/well owner; study site access and data sharing.
- HI-SEAS - Land owner; study site access and data sharing.
- Honolulu Board of Water Supply - O‘ahu well access, ‘Ike Wai Internship partner
- Hualālai Resort - Land owner; study site access and data sharing.
- Huehue Ranch - Land/well owner; study site access and data sharing.
- Hui Aloha Kiholo - Study site access and data sharing
- Hui Loko - Landowner study site access and data sharing.
- Department of Hawaiian Homelands community of Kailapa, and the Richardson School of Law (University of Hawai'i): collaboration to assess water resources as part of the Māhukona aquifer system.
- Kamehameha Schools (KS) - Landowner; Study Site access.
- Ka'onohi Farms - Land owner, study site access and data sharing
- Kaʻūpūlehu Marine Advisory Council - Study site access and data sharing
- Kohnana‘iki Resort (KR) - Land/well owner; study site access and data sharing.
- Makani Golf Club (MGC) - Land/well owner; study site access and data sharing.
- Mauna Loa Observatory (MLO) - Land owner; study site access and data sharing.
- Moanalua Gardens Foundation (MGF) - Land stewardship organization
- Napu‘u Water Inc. (NW) - Land/well owner; study site access and data sharing.
- Natural Energy Lab of Hawai‘i (NELHA) - Land/well owner; study site access and data sharing.
- The Nature Conservancy - Land owner; study site access and data sharing
- Office of Mauna Kea Management (OMKM) - Land owner; study site access and data sharing.
- Palani Ranch (PaR) - Landowner; study site access and data sharing.
- Papahānaumokuākea Marine National Monument - ‘Ike Wai Internship partner
- Pu‘u Wa‘awa’a Ranch (PWR) - Land/well owner; study site access and data sharing.
- Queen Lili‘uokalani Trust (QLT) - Land/well owner; study site access and data sharing.
- Stormwater Quality Branch of the Department of Facility Maintenance at the City and County of Honolulu - ‘Ike Wai Internship partner
- Sumida Farms - Land owner, study site access and data sharing
- Ulupono Initiative - A private social impact investment firm who is providing additional funding to expand the scope of our agency outreach to include an assessment of the water management system in Hawai‘i.
- West Hawai‘i Landfill (WHL) - Land/well owner; study site access and data sharing.
- Mālama Pu‘uloa - community organization, now part of a graduate course exploring human-environment and water relationships in Pearl Harbor.

D. Collaborations: During the reporting period ‘Ike Wai researchers were involved in collaborations with 29 external collaborators across 15 different institutions. Collaborations include continued research, processing and publication by Eric Attias for his CSEM Marine CSEM study offshore Kailua-Kona that resulted in the identification of high resistivity deposits of low salinity water in the offshore subsurface with his colleagues from the Scripps Institution of Oceanography, University of Malaysia Terrengganu, and Frontier Geosciences, which resulted in a publication in Science Advances. Researchers from the economics team continued their work with colleagues at state agencies with the creation of maps of priority areas for watershed investments based on groundwater recharge and economic modeling by the economics team.

Researchers from the geophysics and hydrogeology team also continued their collaborations with other universities to continue processing and analyzing their results, including the application and development of machine learning algorithms to learn more about the drivers of carbon fluxes in global SGD and the analysis of the results of completed geophysical surveys and geochemical results. The Cyberinfrastructure team continue to work with colleagues from the Texas Advanced Computing Center on Project Tapis: Next Generation Software for Distributed Research. Tapis is a new platform for distributed computational experiments that leverages NSF’s investments in the Agave, Abaco and CHORDS projects. Working alongside a diverse set of domain researchers to drive real-world use cases, Tapis will be the underlying cyberinfrastructure for computational workflows and science gateways (such as the ‘Ike Wai Gateway).
E. Sustainability: Continued funding beyond the five-year duration of this award is essential for expanding the scope of our water resources research and our continued engagement with the community. During the award period, 37 competitive proposals were submitted by 'Ike Wai faculty, totaling $37,217,360 in requested funds. Of these proposals, 16 were submitted by one of the eight new 'Ike Wai tenure-track hires that were funded on this project, totaling $28,688,660 in requested funds (43% of submitted proposals, 77% of requested funds).

Eighteen new awards were made in 2020 totaling $9,544,987. Of these awards, nine were made to the new faculty, totaling $2,840,230 in requested funds arriving in 2020 (50% of awards, 30% of total awarded funds). Dr. Travis Mandel of UH Hilo was awarded $549,790 for a prestigious NSF CAREER: Accelerating Scientific Data Collection through Human-in-the-Loop Artificial Intelligence proposal to create new algorithms and interaction paradigms that enable humans and artificial intelligence systems to work together, leveraging each other’s strengths to collect better data ($104,087 awarded in the reporting period). Dr. John Burns of UH Hilo received three awards totaling $525,233 in the reporting year: the ‘Burroughs Welcome Fund: Postdoctoral Enrichment Program for Underrepresented Minorities’, an award from the Department of Interior titled ‘Evaluate Coral Reef, Marine Fish, and Benthic Monitoring Protocol in Pacific Island and South Florida Caribbean Inventory and Monitoring Networks,’ and ‘Responding to Invasive Species and Hurricane Walaka Impacts in Papahanaumokuakea (HI)’ from the National Fish & Wildlife Foundation. Dr. Jonghyun Harry Lee also received three awards, including two from Sandia National Laboratories, one titled ‘Deep Learning Applications for Physics-informed Machine Learning in Earth Sciences ($11,999)’ and the other titled ‘Realtime Forecasting of CO2 Flow and Pressure Distribution Using Scientific Machine Learning ($35,000)’. Lee was also the co-PI on an NSF Elements: ALE-AMR Framework and the PISALE Codebase award for $599,996. Dr. Leah Bremer received an award from American Forests for $98,504 titled ‘On the Path to Carbon Neutrality: A Hawai‘i Carbon Land Use Opportunity Assessment’. Dr. Nicole Lautze received an award from the Department of Energy for $15,000 to a project titled ‘Large-Scale Carbon Storage in Saline Volcanic Basins’.

Other significant awards from NSF awarded to senior personnel in 2020 include an NSF award to Dr. Barbara Bruno for $315,260 for her proposal ‘GP-GO: Ahihi Learning Ecosystem Model for Hawaii Geoscience Workforce Development’ and the NSF awards to Dr. Gwen Jacobs for her ‘Category I - Jetstream 2: Accelerating Science and Engineering On-Demand’ project ($105,000 to UH in reporting period, subaward from Indiana University) and ‘IRNC Core Improvement: SXTransPacIFIC Islands Research and Education Network’ project ($3,060,763). Dr. Jason Leigh was also the PI on two NSF awards, ‘CHS: Small: Collaborative Research: Articulate+ - A Conversational Interface for Democratizing Visual Analysis’ for $73,741 and ‘Collaborative Research: CSSI Frameworks: SAGE3: Smart Amplified Group Environment for Harnessing the Data Revolution’ for $2,249,993. Dr. Kianna Frank also received $378,651 from NSF for her REU Site: Environmental Biology for Pacific Islanders.

V. Broadening Participation

Recruitment of women and under-represented groups into ‘Ike Wai roles at the undergraduate, graduate, post-doctoral and faculty roles continues to be a goal in Year 5 of the project. As reported in Solicitation-Specific Project Elements: Diversity section of the annual report, we were striving for a participation profile for undergraduates of 75% women and 50% underrepresented minorities (URM), including 25% Native Hawaiians and Pacific Islanders (NHPI) and Graduate and Postdoctoral participants of 70% women and 25% URM. Our Year 5 undergraduate cohort comprised of 69% of undergraduate students identifying as women, with 37% identifying as URM, and 20% of students identifying as NHPI.
Our graduate students and post-doctoral researchers cohort was 44% female and 33% URM. No new hires were made in Year 5 of the project and the current cohort was comprised of students continuing in their current positions and finishing up their degrees.

The 'Ike Wai Education team does plan to offer the O'ahu Summer Bridge in 2021 as we did in previous years, which historically had found success in broadening participation with a well-established partnership with the Kapi'olani Community College Native Hawaiian Advancement Office.

VI. Expenditures and Unobligated Funds

The 'Ike Wai has been awarded $20,000,000 in the five years of the project's cooperative agreement. The remaining funds at the end of the reporting period, December 31, 2020 were $1,816,310. The projects anticipates the expenditures of salary, fringe benefits, research supplies and participant support funds for students to total $1,441,310 to the initial award end date, May 31, 2021. $375,000 is projected to remain. A no-cost extension to extend the project until May 31, 2022 was submitted to NSF to complete work impacted by the University of Hawaii and the State of Hawaii travel restrictions and in-person gathering restrictions imposed to combat the COVID-19 pandemic, including funding work to migrate data and data products to the long term accessible data archive for the project, complete the Hawai'i Climate Data Portal, to increase basic CI skills in data management, visualization and dissemination techniques for investigators, support publication costs and support communication and dissemination of project results.

VII. Special Conditions

Two Programmatic Terms & Conditions were specified in Amendment #002 (1841642) - Update to Cooperative Agreement (CA) issued September 14, 2018.

Hiring of Faculty and other Key Personnel: Because of the need to develop institutional capacity in hydro-engineering (Aim 2.2.c), the awardee will accelerate the hiring of a faculty member at UHM with computational hydrogeology expertise, with the objective of this new member being an active participant on the project by the beginning of Year 2. A schedule for the hiring search will be included in the project’s Strategic Plan and its outcome reported on in the Annual Report. NSF EPSCoR must first approve any changes.

Actions: Completed in Year 2 with the hire of Dr. Niels Grobbe

External Advisory Committee Membership: The awardee will arrange for a representative from the US Geological Survey with knowledge of this agency’s past and current hydrological modeling of Hawaiian aquifers to serve as a member of the project’s External Advisory Committee.

Actions: Completed in Year 1: Dr. Cliff Voss has served on our External Advisory Board since Year 1. In addition to attending our EAB meeting Dr. Voss is now an affiliate faculty member of the Water Resources Research Center (WRRC).

VIII. Response to Recommendations

1. External Evaluator Recommendations.

The key findings of the external evaluation in Year 5 are listed below. We concur with the key findings of the evaluators and include feedback and a response to the recommendation below.
• The ‘Ike Wai Project has generated a wealth of new data and knowledge about water in Hawai‘i, including a groundbreaking discovery about submarine groundwater in volcanic zones.

Response: We concur with this finding and note that Eric Attias’ discovery received national and international recognition and was widely distributed to the media including an article in the New York Times. This recognition underscores the importance of this discovery for both the intellectual merit and the broader impacts on new ways to sustain critical water resource for island and coastal communities.

• Evaluation data indicate ‘Ike Wai has partially addressed recommendations related to collaboration and cultural awareness included in prior external evaluation reports.

We concur with this observation and note that many of the in-person activities planned for Year 5 to support collaboration and cultural awareness were cancelled this year due to COVID-19 impacts on gathering and travel. In addition, the stay at home restrictions enacted March 2020, were a significant disruption to productivity and increased isolation for some. Team members with young families were especially challenged. For the remainder of Year 5 and into the no cost extension period the team looks forward to resuming in-person activities both cultural awareness and data skills training.

• There remain continued challenges integrating ‘Ike Wai work both in terms of leveraging cross-disciplinary expertise within the team, as well as connecting the work to community needs.

We concur with this observation and note that in Year 5 the significant challenges posed by COVID-19 as described above. In the final year and beyond we will focus on targeted community meetings and boosting collaboration opportunities through the Data Science Fellows program which connects grad students and mentors at UH Hilo with mentors and students at UH Mānoa. This mechanism has led to the emergence of new collaborations between faculty at the two institutions, as well as new multidisciplinary collaborations between data science faculty and domain scientists.

• There is mixed awareness of and access to ‘Ike Wai data and data products by water resource stakeholders in Hawai‘i.

We concur with this observation and in response to the recommendations below, we outline our plans to improve the awareness, dissemination and use of the valuable data generated by this project.

The recommendations from the external evaluation are listed below. We provide our plans and actions to address them below.

Recommendations:

Focus efforts to complete the data processing necessary for ‘Ike Wai data and data products, so that they are accessible prior to the close of the project.

• The CI team will host individual and group consulting and training sessions to review the status of current data sets and assist with the cleaning and annotation of data sets.

• Hands on training will be provided to researchers to prepare data sets for publishing to IkeWai.org and to Hydroshare, the national repository for hydrological data and models.
• The CI team will host training workshops in the use of GitHub code repository and methods to store both code and datasets associated with published manuscripts.

Scale up existing efforts to share out ‘Ike Wai data and project findings via presentations and stakeholder meetings.

• The team will submit publications and present papers on ‘Ike Wai data, tools and repositories at national meetings including PEARC21, Earthcube and AGU to raise awareness of these resources. They are to present a panel discussion at the Tropical Islands Water Conference in April 2021.

• We will enhance the usability and presentation components of Ikewai.org to highlight datasets and data products by linking them to research results and contributors.

• We will include tutorials, walkthroughs and videos highlighting available data and search tools in ikewai.org.

Implement a communication plan to share data access information with researchers, stakeholders, and community members.

• The communications team will develop a plan to improve the awareness and sharing of Ike Wai data tools. Specific actions are listed below.
  o Add images and descriptions of data on data sets and products in Ike Wai.org. Add a section introducing ikewai.org on the website landing page.
  o Disseminate research results and information on data products at the April 2021 Tropical Islands Water Conference including a press releases, social media campaign
  o Host targeted meetings with stakeholder groups to discuss results/data products and guidance on access and use.
  o Create marketing products (informational brochure/magazine/newsletter) that share results/data products to send to organizations represented at WRRC stakeholder meeting

• The communications team will also highlight various aspects of ikewai.org in newsletters and social media posts to increase awareness about specific data products and the data portal in general to researchers, stakeholders and community members.

Response to Reverse Site Visit Recommendations:

**RSV Recommendation 1:** The project would be significantly strengthened by the addition of hydrogeology expertise to integrate and complement the new and existing faculty.

Response: Completed in Year 4: Dr. Stéphanie Barde-Cabusson joined the ‘Ike Wai team in January 2019. Dr. Barde-Cabusson is a hydrogeologist with expertise in near surface geophysics (geoelectrical methods), soil temperature measurements, and field geology.

**RSV Recommendation 2:** The panel saw the activities of the project to be separated and not well integrated together. This issue is significant and could potentially put the project at risk of not achieving its goals.

Response: Completed in Year 4

• **Collaborative Research:** Collaborations between UH Hilo and UH Mānoa team members take place primarily through activities in the Hawai'i Data Science Institute. Travis Mandel
and John Burns have given seminars in 2020 and Sophia Ferreira, John Burns’ student, is a Data Science Fellow. Trista McKenzie was a Data Science Fellow in the previous year and applied her new skills towards a collaboration with Harry Lee. All four UH Hilo faculty have contributed to grant proposals in collaboration with UH Mānoa faculty. UH Hilo faculty participate in cyberinfrastructure training workshops and use Mana, our HPC resource, in both their research projects and for classroom use.

- **Curriculum Development:** UHH, UHM and Chaminade University continue their collaborative efforts to share curriculum in data science. We have established a GitHub repository for workshop and tutorial materials as well as Jupyter notebooks with exercises and curated data sets, especially those with Hawai‘i specific data. The Hawai‘i Climate Data Portal is an exemplar of an active repository of highly valuable climate data. The data workflow uses machine learning techniques to automate the QA/QC data cleaning procedures.

- **Data Science Skills Training:** The Hawai‘i Data Science Institute (HI-DSI) offers hands-on training workshops in a variety of data science and advanced cyberinfrastructure skills. For two months of 2020 we hosted meetings and seminars in person in the Data Science Institute. All activities – workshops, seminars, team meetings, were conducted via video conference – typically Zoom. UHH faculty participated in many of these activities.

**RSV Recommendation 3: Access to Field Research Sites:**

**Response:** In September 2020, we secured access to the Kamehameha Schools land in Kona. We were not able to complete field work in this area due to COVID-19 travel restrictions. However, access agreements for O‘ahu (Dole Property) and Kona are now in place for the next two years. The agreements have been transferred to WRRC and Tom Giambelluca. A comprehensive review of progress to research sites on Hawai‘i Island and O‘ahu is provided in Activity 2.4.1: Agency Outreach and Access Agreements.

**RSV Recommendation #4: The RSV panel noted the apparent disengagement of the UH Hilo activities with those of UH Mānoa.**

**Response:** As described above, the UH Hilo faculty are involved in collaborations, the Data Science Fellows program and are writing collaborative grants with UH Manoa Faculty. Both sets of faculty have collaborations with faculty colleagues at their institutions.

**RSV Recommendation 5. The project does not appear to be currently performing the research activities in economic modeling:**

**Response:** Completed in Year 3. The social science team has developed econometrics models and collaborated with the modeling team and the climate team to create models for predicting costs and sustainable yield and impacts of land use on aquifer recharge.

**RSV Recommendation 6. Long-term Sustainability:** The RSV panel noted that there was a lack of clarity of the long-term sustainability of the ‘Ike Wai project beyond the scope of this award.

**Response:** We have previously reported on progress towards sustainability of ‘Ike Wai educational and research programs through alliances with key campus institutes and centers. The Water Resources Research Center (WRRC) partners with Sea Grant, Institute of Sustainability and Resilience, and the Hawai‘i Data Science Institute. The Cyberinfrastructure team was awarded 2 NSF grants in 2019 Project Tapis: Next Generation Software for Distributed Research ($997k) and an MRI award ($700k) to support Mana the High Performance Computing cluster. This year we became one of the regional partners of the distributed academic cloud resource, Jetstream2. Participants have received awards to continue project activities beyond the end of
Response to NSF Year 4 Site Visit Recommendations:

**SV Recommendation 1:** Submit an updated plan for strengthen on-site hydrogeology expertise other than through partnerships and collaborations.

**Response:** Completed in Year 3. We addressed this issue by recruiting Dr. Donald Thomas and Dr. Thomas Giambelluca, both with extensive research experience to join the team.

**SV Recommendation 2:** Develop a mentoring plan for the early career faculties,

**Response:** Completed Year 4. All nine new faculty have been paired with a mentor and are meeting quarterly to discuss their plans for research and teaching and preparation for tenure. In 2020 we continued with Co-PI Turner led grant writing sessions.

**SV Recommendation 3:** Provide a plan of potential activities between UH Hilo and UH Manoa to integrate data science training with hydrological information derived from the research, include activities that could improve communication between cyber and no-cyber infrastructure teams, and identify potential collaborative efforts focusing in the sustainability of the project.

Response: Complete Year 4. As described above, the UHH faculty are involved in collaborations, the Data Science Fellows program and are writing collaborative grants with UH Mānoa Faculty. Both sets of faculty have collaborations with faculty colleagues at their institutions

**SV Recommendation 4:** Present a plan in which all faculty and staff members who participate in the ‘Ike Wai project be required to read the Community Engagement Packet and share a cultural experience.

**Response:** Completed in Year 5.

- We planned four activities in 2020 to meet this goal. One was an all-hands meeting was dedicated to a team session focused on cultural engagement. The second training was an all-hands workshop with the Edith Kanakaʻole Foundation. The workshop was held virtually for 35 ‘Ike Wai participants.

- One graduate student/postdoc meeting per semester was focused on community engagement training

- All ‘Ike Wai team members were expected to participate in a minimum of two activities of their own choosing to develop their cultural competency, engage with place, and/or engage with the community. Many of the hands-on, in person activities were cancelled due to COVID19 safety precautions. Team members participated in Aloha ʻĀina Fridays, Mānoa campus-based activities exploring the rich history of Hawaiians on that campus, prior to lockdown.

**Sustainability (also found above):**

Continued funding beyond the five-year duration of this award is essential for expanding the scope of our water resources research and our continued engagement with the community. We have made significant progress towards supporting research projects beyond the end of the funding period with support from the NSF and other agencies. Details on these awards are included below:
During the award period, 37 competitive proposals were submitted by 'Ike Wai faculty, totaling $37,217,360 in requested funds. Of these proposals, 16 were submitted by one of the eight new 'Ike Wai tenure-track hires that were funded on this project, totaling $28,688,660 in requested funds (43% of submitted proposals, 77% of requested funds).

Eighteen new awards were made in 2020 totaling $9,544,987. Of these awards, nine were made to the new faculty, totaling $2,840,230 in requested funds arriving in 2020 (50% of awards, 30% of total awarded funds).

- Dr. Travis Mandel of UH Hilo was awarded $549,790 for a prestigious NSF CAREER: Accelerating Scientific Data Collection through Human-in-the-Loop Artificial Intelligence proposal to create new algorithms and interaction paradigms that enable humans and artificial intelligence systems to work together, leveraging each other's strengths to collect better data ($104,876 awarded in the reporting period).

- Dr. John Burns of UH Hilo received three awards totaling $525,233 in the reporting year: the 'Burroughs Welcome Fund: Postdoctoral Enrichment Program for Underrepresented Minorities', an award from the Department of Interior titled 'Evaluate Coral Reef, Marine Fish, and Benthic Monitoring Protocol in Pacific Island and South Florida Caribbean Inventory and Monitoring Networks,' and 'Responding to Invasive Species and Hurricane Walaka Impacts in Papahanaumokuakea (HI)' from the National Fish & Wildlife Foundation.

- Dr. Jonghyun Harry Lee also received three awards, including two from Sandia National Laboratories, one titled 'Deep Learning Applications for Physics-informed Machine Learning in Earth Sciences ($11,999)' and the other titled 'Realtime Forecasting of CO2 Flow and Pressure Distribution Using Scientific Machine Learning ($35,000)'. Lee was also the co-PI on an NSF Elements: ALE-AMR Framework and the PISALE Codebase award for $599,996.

- Dr. Leah Bremer received an award from American Forests for $98,504 titled 'On the Path to Carbon Neutrality: A Hawai'i Carbon Land Use Opportunity Assessment'.

- Dr. Nicole Lautze received an award from the Department of Energy for $15,000 to a project titled 'Large-Scale Carbon Storage in Saline Volcanic Basins'.

Other significant awards from NSF awarded to senior personnel in 2020 include:

- Dr. Barbara Bruno received an NSF award for $315,260 for her proposal ‘GP-GO: Ahihi Learning Ecosystem Model for Hawaii Geoscience Workforce Development’

- Dr. Gwen Jacobs for her ‘Category I - Jetstream 2: Accelerating Science and Engineering On-Demand’ project ($105,000 to UH in reporting period, subaward from Indiana University) and ‘IRNC Core Improvement: SXTransPORT Pacific Islands Research and Education Network’ project ($3,060,763).

- Dr. Jason Leigh was also the PI on two NSF awards, ‘CHS: Small: Collaborative Research: Articulate+ - A Conversational Interface for Democratizing Visual Analysis’ for $73,741 and ‘Collaborative Research: CSSI Frameworks: SAGE3: Smart Amplified Group Environment for Harnessing the Data Revolution’ for $2,249,993.

- Dr. Kiana Frank also received $378,651 from NSF for her REU Site: Environmental Biology for Pacific Islanders.
## IX. Tabular/Graphic Representation of Progress to Date

### GOAL 1: Collect new hydrological and geophysical data on the two study sites to address data gaps in our understanding of subsurface structure and flow.

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity 1.1.1</td>
<td>Activity 1.1.2</td>
<td>Activity 1.1.3</td>
<td>Activity 1.1.4</td>
<td>Activity 1.1.5</td>
</tr>
<tr>
<td>Activity 1.2.1</td>
<td>Activity 1.2.2</td>
<td>Activity 1.2.3</td>
<td>Activity 1.2.4</td>
<td></td>
</tr>
<tr>
<td>Activity 1.3.1</td>
<td>Activity 1.3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### GOAL 2: Develop a new data and modeling platform for Hawaii volcanic hydrogeology, economic modeling and decision support.

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity 2.1.1</td>
<td>Activity 2.1.2</td>
<td>Activity 2.1.3</td>
<td>Activity 2.1.4</td>
<td>Activity 2.1.5</td>
</tr>
<tr>
<td>Activity 2.2.1</td>
<td>Activity 2.2.2</td>
<td>Activity 2.2.3</td>
<td>Activity 2.2.4</td>
<td>Activity 2.2.5</td>
</tr>
<tr>
<td>Activity 2.2.6</td>
<td>Activity 2.2.7</td>
<td>Activity 2.2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 2.3.1</td>
<td>Activity 2.3.2</td>
<td>Activity 2.3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 2.4.1</td>
<td>Activity 2.4.2</td>
<td>Activity 2.4.3</td>
<td>Activity 2.4.4</td>
<td>Activity 2.4.5</td>
</tr>
</tbody>
</table>

### GOAL 3: Education and Workforce Development: Establish an integrated set of pathways to train and develop a diverse cohort of students, post-doctoral and faculty researchers at UHM and UHH to address Hawaii’s water challenges.

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity 3.1.1</td>
<td>Activity 3.1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.2.1</td>
<td>Activity 3.2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.3.1</td>
<td>Activity 3.3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.4.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.5.1</td>
<td>Activity 3.5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.6.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity 3.7.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# X. Appendix A: Abbreviations and Hawaiian Language Terms

## 1. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-bay</td>
<td>Anaeho'omalu Bay</td>
</tr>
<tr>
<td>AGU</td>
<td>American Geophysical Union</td>
</tr>
<tr>
<td>AMT</td>
<td>Audio-Magnetotellurics</td>
</tr>
<tr>
<td>BWS</td>
<td>Board of Water Supply (Honolulu)</td>
</tr>
<tr>
<td>CI</td>
<td>Cyberinfrastructure</td>
</tr>
<tr>
<td>CKAN</td>
<td>Comprehensive Knowledge Archive Network</td>
</tr>
<tr>
<td>COACH</td>
<td>Committee on the Advancement of Women Chemists</td>
</tr>
<tr>
<td>CoBE</td>
<td>College of Business and Economics</td>
</tr>
<tr>
<td>COE</td>
<td>College of Engineering</td>
</tr>
<tr>
<td>CSEM</td>
<td>Controlled-source Electromagnetic</td>
</tr>
<tr>
<td>CSS</td>
<td>College of Social Sciences</td>
</tr>
<tr>
<td>CWRM</td>
<td>Commission on Water Resource Management</td>
</tr>
<tr>
<td>CWSEI</td>
<td>Carl Wieman Science Education Initiative</td>
</tr>
<tr>
<td>DLNR</td>
<td>Department of Land and Natural Resources</td>
</tr>
<tr>
<td>DOFAW</td>
<td>Department of Fish and Wildlife</td>
</tr>
<tr>
<td>DROP</td>
<td>Down-well Remote Operating Platform</td>
</tr>
<tr>
<td>EAB</td>
<td>External Advisory Board</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FWAC</td>
<td>Fresh Water Advisory Council</td>
</tr>
<tr>
<td>G&amp;G</td>
<td>Geology and Geophysics</td>
</tr>
<tr>
<td>GDE</td>
<td>Groundwater-Dependent Ecosystems</td>
</tr>
<tr>
<td>GW</td>
<td>Groundwater</td>
</tr>
<tr>
<td>HCF</td>
<td>Hawai’i Community Foundation</td>
</tr>
<tr>
<td>HDOA</td>
<td>Hawai’i Department of Agriculture</td>
</tr>
<tr>
<td>HDOH</td>
<td>Hawai’i Department of Health</td>
</tr>
<tr>
<td>HDWS</td>
<td>Hawai’i County Department of Water Supply</td>
</tr>
<tr>
<td>HFWI</td>
<td>Hawai’i Fresh Water Initiative</td>
</tr>
<tr>
<td>HIP</td>
<td>Hawai’i Institute of Geophysics &amp; Planetology</td>
</tr>
<tr>
<td>HLPC</td>
<td>Hawai’i Leeward Planning Commission</td>
</tr>
<tr>
<td>HPC</td>
<td>High Performance Computing</td>
</tr>
<tr>
<td>HSSTC</td>
<td>Hawai’i</td>
</tr>
<tr>
<td>HVO</td>
<td>Hawai’i Volcano Observatory</td>
</tr>
<tr>
<td>ICS</td>
<td>Information and Computer Sciences</td>
</tr>
<tr>
<td>IDC</td>
<td>Interagency Data Committee</td>
</tr>
<tr>
<td>IDP</td>
<td>Individual Development Plan</td>
</tr>
<tr>
<td>IHLRT</td>
<td>Institute of Hawaiian Language Research and Translation</td>
</tr>
<tr>
<td>IKE</td>
<td>Integrated Knowledge Environment</td>
</tr>
<tr>
<td>ITS</td>
<td>Information Technology Services</td>
</tr>
<tr>
<td>KBA</td>
<td>Keauhou Basal Aquifer</td>
</tr>
<tr>
<td>KCC</td>
<td>Kapi'olani Community College</td>
</tr>
<tr>
<td>KR</td>
<td>Kohnana’iki Resort</td>
</tr>
<tr>
<td>KS</td>
<td>Kamehameha Schools</td>
</tr>
<tr>
<td>LT</td>
<td>Leadership Team</td>
</tr>
<tr>
<td>MGF</td>
<td>Moanalua Gardens Foundation</td>
</tr>
<tr>
<td>MT</td>
<td>Magnetotellurics</td>
</tr>
<tr>
<td>NELHA</td>
<td>Natural Energy Laboratory of Hawai’i Authority</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>OMKM</td>
<td>Office of Mauna Kea Management</td>
</tr>
<tr>
<td>PaR</td>
<td>Palani Ranch</td>
</tr>
<tr>
<td>PBRC</td>
<td>Pacific Biomedical Research Center</td>
</tr>
<tr>
<td>PIWSC</td>
<td>Pacific Islands Water Sciences Center</td>
</tr>
<tr>
<td>PR</td>
<td>Parker Ranch</td>
</tr>
<tr>
<td>QBA</td>
<td>Quantitative Business Administration</td>
</tr>
<tr>
<td>QLT</td>
<td>Queen Lili'uokalani Trust</td>
</tr>
<tr>
<td>RHBFSF</td>
<td>Red Hill Bunker Fuel Storage Facility</td>
</tr>
<tr>
<td>S&amp;T</td>
<td>Science and Technology</td>
</tr>
<tr>
<td>SEI</td>
<td>Science Education Initiative</td>
</tr>
<tr>
<td>SG</td>
<td>UH Sea Grant</td>
</tr>
<tr>
<td>SGCI</td>
<td>Science Gateways Community Institute</td>
</tr>
<tr>
<td>SGD</td>
<td>Submarine Groundwater Discharge</td>
</tr>
<tr>
<td>SOEST</td>
<td>UH Mānoa School of Ocean and Earth Science and Technology</td>
</tr>
<tr>
<td>SST</td>
<td>Science &amp; Technology Thrusts</td>
</tr>
<tr>
<td>SY</td>
<td>Sustainable Yield</td>
</tr>
<tr>
<td>TACC</td>
<td>Texas Advanced Computing Center</td>
</tr>
<tr>
<td>UHERO</td>
<td>UH Economic Research Organization</td>
</tr>
<tr>
<td>UHH</td>
<td>University of Hawai’i Hilo</td>
</tr>
<tr>
<td>UHM</td>
<td>University of Hawai’i at Mānoa</td>
</tr>
<tr>
<td>UHS</td>
<td>University of Hawai’i System</td>
</tr>
<tr>
<td>UI</td>
<td>Ulupono Initiative</td>
</tr>
<tr>
<td>URM</td>
<td>Underrepresented Minorities</td>
</tr>
<tr>
<td>USGS</td>
<td>US Geological Survey</td>
</tr>
<tr>
<td>WFD</td>
<td>Workforce Development</td>
</tr>
<tr>
<td>WHR</td>
<td>West Hawai’i Regional</td>
</tr>
<tr>
<td>WMP</td>
<td>Water Master Plan</td>
</tr>
<tr>
<td>WR</td>
<td>Waikī‘i Ranch</td>
</tr>
<tr>
<td>WRAC</td>
<td>Water Resources Advisory Council</td>
</tr>
<tr>
<td>WRRC</td>
<td>UH-Water Resources Research Center</td>
</tr>
</tbody>
</table>
2. **Hawaiian Language Terms**

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>'āina</td>
<td>Land</td>
</tr>
<tr>
<td>‘auwai</td>
<td>Path water flow</td>
</tr>
<tr>
<td>‘Ike Wai</td>
<td>‘Ike, meaning knowledge, Wai, meaning water</td>
</tr>
<tr>
<td>kapunalu‘u</td>
<td>Spring dived for</td>
</tr>
<tr>
<td>moku</td>
<td>Large district land division</td>
</tr>
<tr>
<td>moʻolelo</td>
<td>Stories or history</td>
</tr>
<tr>
<td>‘oiwi</td>
<td>Native son</td>
</tr>
<tr>
<td>Pono</td>
<td>What is right</td>
</tr>
<tr>
<td>po‘e</td>
<td>People</td>
</tr>
<tr>
<td>Wai</td>
<td>Water</td>
</tr>
</tbody>
</table>