# FORECASTING CLIMATE AND LAND USE CHANGE IMPACTS ON ECOSYSTEM SERVICES IN HAWAIʻI THROUGH INTEGRATION OF HYDROLOGICAL AND PARTICIPATORY MODELS

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# Abstract

Water is critical for supporting life, and fundamental for provisioning, regulating, and cultural ecosystem services that support human wellbeing. However, freshwater resources are projected to become scarcer in Hawaiʻi due to a growing human population, a changing climate, and altered land use and land cover. Therefore, to meet future needs, society needs to manage water more effectively using an interdisciplinary ecosystem services-based approach that accounts for physical, social, and ecological interactions. In order to support holistic management of freshwater ecosystem services in Hawaiʻi, I developed a modeling tool that can integrate physical and ecological processes and social systems. First, I identified appropriate hydrological models to estimate the hydrologic attributes (quantity, quality, location, and timing) that underpin delivery of multiple freshwater ecosystem services. Due to Hawaiʻi's unique hydrogeological conditions, many standard models cannot accurately quantify hydrologic processes, and thus cannot estimate hydrologic attributes or evaluate ecosystem services. I identified a suite of potential models, developed a set of criteria that I used to select candidate models for estimating freshwater ecosystem services in Hawaiʻi, and evaluated performance for the most promising models. In addition, I created a decision tree for model selection that decision-makers and researchers interested in modeling freshwater ecosystem services can use. Second, I coupled a hydrological model (AnnAGNPS) with a participatory model (using Fuzzy Cognitive Mapping) in a wetland ecosystem on Kauaʻi to translate hydrological model outputs into ecological benefits for three wetland birds: Hawaiian Stilt or Aeʻo (*Himantopus mexicanus knudseni*), Hawaiian Coot or ʻAlae keʻokeʻo (*Fulica alai*), and Hawaiian Moorhen or ʻAlae ʻUla (*Gallinula galeata sandvicensis*). Model coupling suggested that a decline in precipitation would reduce abundance of all three bird species. Results suggest that managers should focus on water depth, food availability, and disease in order to manage abundance. Finally, I used the coupled hydrological-participatory model approach to predict the management and policy outcomes of environmental scenarios for different stakeholder groups who hold diverse values for freshwater ecosystem services. Results revealed stakeholders' agreement on key environmental stressors, as well as their differing views on restoring streamflow, which largely corresponded to their values for ecosystem services (agricultural production versus conservation). This study identified and used models in a coupled framework to simulate environmental changes, and inform enhanced management of freshwater ecosystem services in Hawaiʻi. The resulting decision support framework is easily adaptable for different ecosystems and islands.

# Introduction

Water is life.
(Ola i ka wai)

- Kapuaʻala Sproat, 2009

Water is fundamental to life on Earth, yet its condition continues to deteriorate globally, threatening nature and humans alike. The importance of nature for clean water, and the importance of water for human wellbeing, is encapsulated in the concept of freshwater ecosystem goods and services. Increasingly, water managers have turned to ecosystem goods and services, the direct and indirect benefits people obtain from nature, as an organizing paradigm that helps integrate natural and human systems (Maynard *et al.*, 2015; Scott *et al.*, 2014). The goal is to ensure that social-ecological systems are managed to sustain water needs of the both nature and humans for human well-being and environmental sustainability (Niasse & Cherlet, 2015; Ringler *et al.*, 2013).

There is a growing need for tools to inform decision makers on ecosystem services provisioning and response to management, particularly for water-related services (Vigerstol & Aukema, 2011). This dissertation focuses on developing tools to quantify and predict freshwater-related ecosystems services in Hawaiʻi. Hawaii's unique geology, geographic isolation, and economic and cultural connection to water require customized tools for guiding water resources management. My dissertation focuses on pairing ecohydrological models with participatory models to integrate the natural and human systems.

This introductory chapter is structured as follows. I begin by providing some background on ecohydrology for those not familiar with the connections between ecology and hydrology. I briefly discuss the literature on freshwater ecosystem services before discussing the status, trends and management of water resources in Hawaiʻi. My introductory chapter is followed by three technical chapters, and a summary chapter.

## ***Background/Literature Review***

### *Ecohydrology*

There is a growing literature on ecohydrology for managing the water-related ecosystems for the sustainable use by societies. Ecohydrology is defined as (Nuttle, 2002, p. 1),

> the sub-discipline shared by the ecological and hydrologic sciences that is concerned with the effects of hydrological processes on the distribution, structure, and function of ecosystems, and on the effects of biotic processes on elements of the water cycle.

The United Nations Educational, Scientific and Cultural Organization (UNESCO) first coined the term ecohydrology in its 5th IHP (International Hydrological Programme, 1996-2001) to highlight concerning human impacts on ecosystems (Harper *et al.*, 2008). The study of ecohydrology emphasizes the hydrologic mechanisms that control ecologic patterns and processes to preserve, enhance or restore terrestrial ecosystem's ability to provide goods and services (Harper *et al.*, 2008; Nuttle, 2002). Representing climate-soil-vegetation dynamics, the ecohydrological processes encompasses from the root–soil–rock interface at the pore scale to the vegetation–atmosphere boundary at global scales (Moore *et al.*, 2015; Rodriguez-Iturbe, 2000).

The focus of ecohydrology involves studying hydrological factors driving the terrestrial ecosystems and ecological factors controlling water fluxes (Krysanova & Arnold, 2008). The fundamental theory of ecohydrology is based on soil moisture balance because it describes how much rainfall evapotranspires, infiltrates, and become runoff. In addition, ecohydrology considers complex biogeochemical, hydrological, and ecological processes and interactions at extensive temporal and spatial scales (Krysanova & Arnold, 2008; Rodriguez-Iturbe, 2000). Here are some examples of these processes. For a thriving ecosystem, water needs of the vegetation are closely related soil because, for example, trees can extract water from deep soil layers, and grasses depend on shallow soil moisture. Retention of solutes in soil moisture is controlled by its residence time in the soil (Rodriguez-Iturbe, 2000). For nutrient cycling, plant nutrient uptake depends on soil moisture because moisture effect the carbon sequestration via photosynthesis as well as nitrogen mineralization to enable nitrogen available for plant growth (Chapin III *et al.*, 2011). Biomass production such as in savanna biome depends on soil moisture availability in the nitrogen and phosphorous cycles, which then control the carbon cycle (Scholes & Walker, 2004).

Terrestrial ecosystems control hydrological functions governing water quantity, quality, timing and location of freshwater flows (Brauman, 2015; Brauman *et al.*, 2007). Changes in forest cover directly threaten water resources. Deforestation increases streamflow (Bowling *et al.*, 2000; Hornbeck *et al.*, 1997) and stream temperature (Beschta & Taylor, 1988). Moreover, forest conversion affects streamflow as indicated by the conversion of young pine trees from mature deciduous forest, causing an annual streamflow reduction by 20% because of more interception and evaporation, especially at leaf emergence (Swank & Douglass, 1974). In addition, changes in land use and land cover effect climate because forests with higher canopy height and greater density are also more aerodynamically rougher than short vegetation, absorbing more heat and maintaining lower surface temperature (Grace *et al.*, 1989; Wilson *et al.*, 1987). In addition, spatially heterogeneous vegetation (a mixture of crops, trees, and grass prairie) and soil moisture can influence atmospheric boundary layer structure and generate mesoscale atmospheric circulation with more vigorous and extensive precipitation than homogeneous vegetation (i.e., grass) alone (Avissar *et al.*, 2004; Giorgi & Avissar, 1997; Roy & Avissar, 2002). Therefore, changes from spatially heterogeneous native forests to homogeneous invasive forests influence freshwater resources. For example, alien to Chile, *Pinus radiata* and Eucalyptus caused water supply decrease during the summer (Oyarzún & Huber, 1999).

### *Freshwater Ecosystem Services (FES)*

Freshwater ecosystem goods and services, i.e., the benefits freshwater systems provide to humans, are the product of ecohydrologic functions, processes and structures (e.g., transpiration, filtration) on hydrologic attributes (e.g., flow quantity and quality) (Brauman, 2015). These goods and services can satisfy human needs directly (i.e., via provisioning, regulating, and cultural services) or indirectly (i.e., via supporting services) (De Groot *et al*., 2002; Haines-Young & Potschin, 2013). A few benefits generated by the hydrological cycle include: drinking water, fish, flood regulation, and erosion regulation (Capon & Bunn, 2015; Coates *et al*., 2013). Some of these benefits are known as goods (i.e., tangible material items such as freshwater, fish), while others are services (i.e., ongoing processes such as water purification and flood mitigation) (Costanza *et al*., 1998); for ease, I follow the general practice of referring to ecosystems goods and services simply as ecosystem services. Therefore, freshwater ecosystem goods and services become freshwater ecosystem services, or FES.

### *Water Resources in Hawai'i*

#### Status and Trends

The quantity and quality of water resources in volcanic islands such as Hawai'i are critical for freshwater goods and services, including drinking and agricultural water, fish, flood regulation, climate regulation, erosion regulation, spiritual and inspirational benefits, soil formation, and nutrient cycling (Brauman, 2015; Brauman *et al*., 2007; Capon & Bunn, 2015; MEA, 2005). Surface water is significantly important economically, ecologically, culturally, and aesthetically in Hawai'i (Oki, 2003). It supplies more than 50% of irrigation water in the Hawaiian islands (Oki, 2003). In addition, the people of Hawaii derive numerous benefits from streams springs, and wetlands fed by groundwater discharges (Lau & Mink, 2006). These include important cultural harvest of limu (seaweed), cultivation of kalo, and preservation of fishponds (Canoeplants, 2015; Hlawati, 2001). Groundwater provides 99.7% (1.6 x $10^6$ $m^3$/day in 2010) of Hawaii's needs including drinking water, irrigation, and domestic uses (USGS NWIS, 2015). According to the state's Commission on Water Resources Management, water demand is projected to be 1.6 x $10^6$ $m^3$/d in 2030, approximately 34% increase more than in 2010 (CWRM, 2008).

The quantity and quality of freshwater resources across the state of Hawai'i are diminishing. Specifically, nearly a century-long trend of declining stream base flows and groundwater levels (Figure 1) across the state (Bassiouni & Oki, 2012) implies lower groundwater recharge and storage (Bassiouni & Oki, 2012; Oki, 2004). Similarly, there are freshwater quality issues in many places across the state. The annual cost of stream impairment has increased from $21 million in 1998 to $42 million in 2006 (Figure 2), showcasing the declining quality of inland water resources (HDOH, 2014). While no study has compiled a statewide freshwater quality trend, a few reports on chloride concentrations point to widespread issues. Groundwater chloride, indicative of salination, has been rising since 1977 across monitored wells on Maui reaching higher than threshold levels (250 milligrams per liter or mg/L) for potable water set by EPA; they reached from ~55 to >400 mg/L between 1977 and 1995 (Wallsgrove & Penn, 2012).

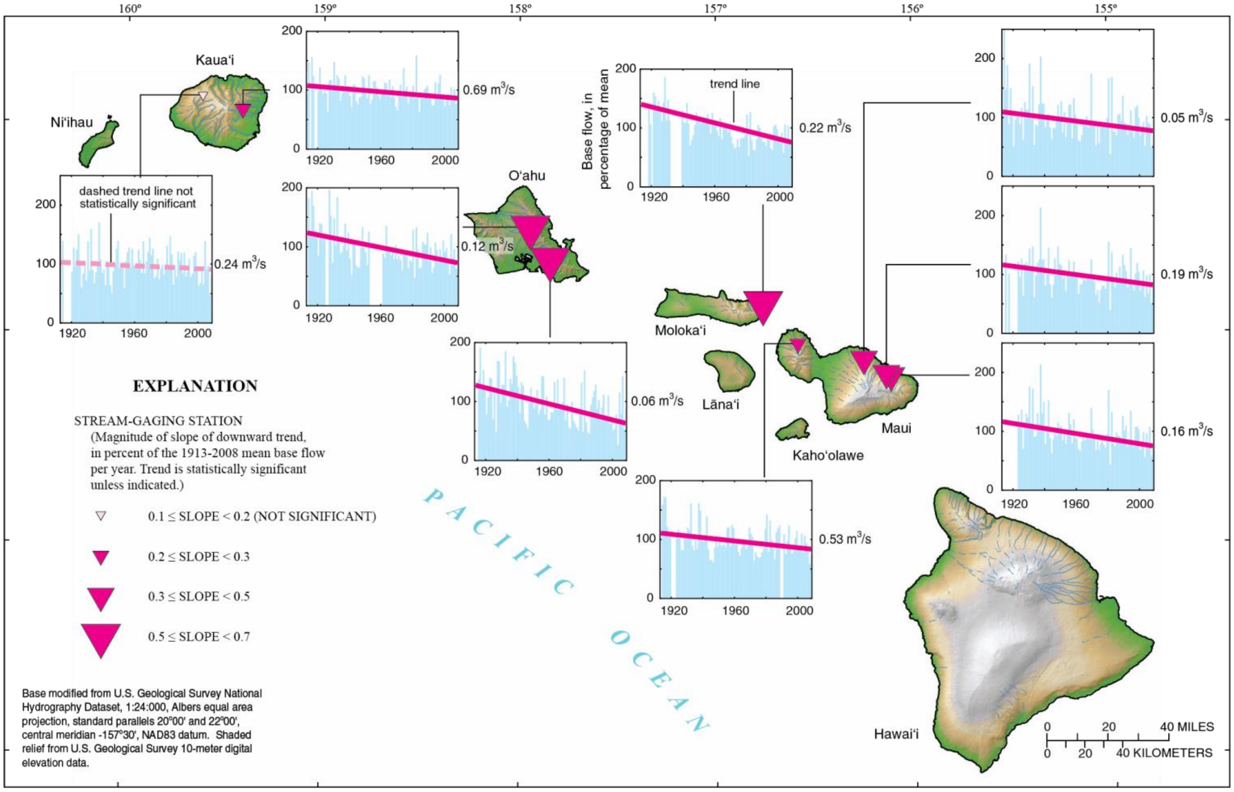

*Figure 1.   Stream base flow trend in the State of Hawai‘i from 1913 to 2008* (Bassiouni & Oki, *2012; Oki, 2004). Reproduced with permission by the author.*

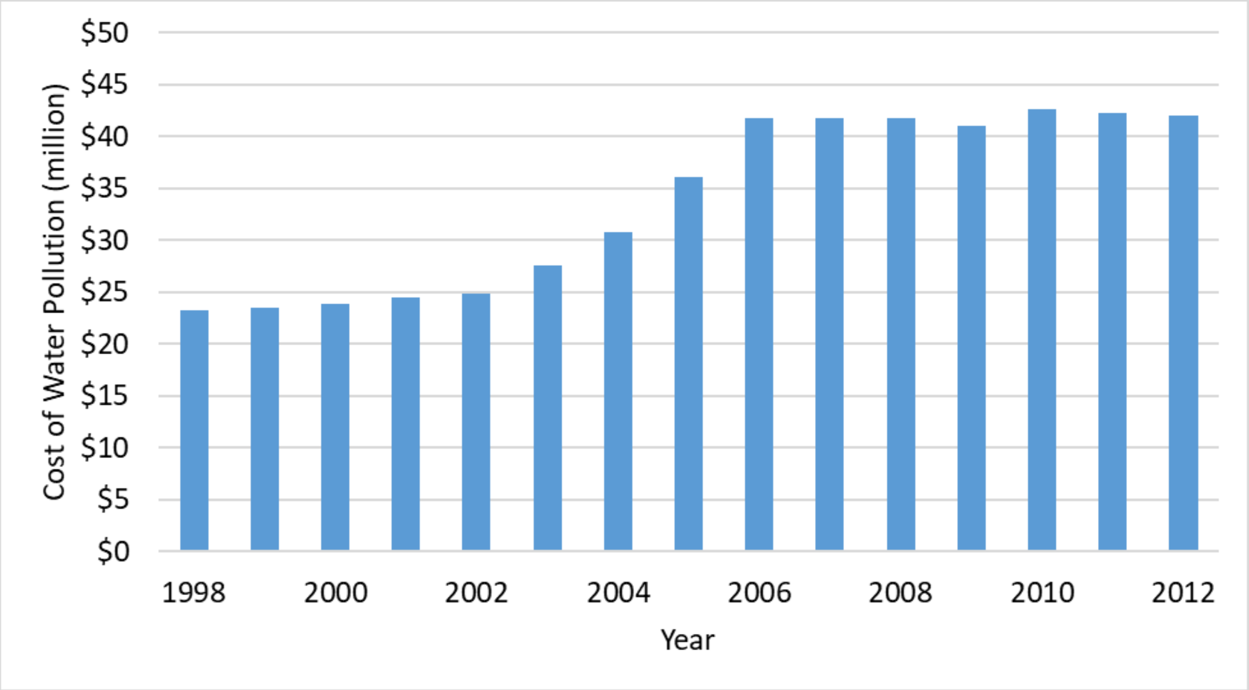

*Figure 2. Water quality trend analysis on the annual cost of water pollution from impaired streams in Hawai'i (HDOH, 2014, p. 94).*

In the future, Hawaii's water resource will be increasingly impacted by climate change. Hawai'i has already experienced changes in temperature and precipitation, and trends are expected to persist or even worsen. Hawaii's temperature increased over the past ~100 years, with a significant uptick in the rate of change over the past 30 years (i.e., 0.043°C decade$^{-1}$ for 1919–2006 and 0.163°C decade$^{-1}$ for 1975–2006), and increased warming at higher elevations (Giambelluca *et al.*, 2008; Safeeq & Fares, 2012). Future warming is projected to be 4°–5°F (2.2°–2.8°C) by 2085 (Keener *et al.*, 2013).

Rainfall amounts and patterns across Hawai'i will also continue to change, although there is some debate about the specifics. Observed rainfall and streamflow data indicated diminishing annual mean precipitation from 1951 to 2000 across the islands (Diaz *et al.*, 2005; Oki, 2004). An analysis of annual rainfall data from 1920 to 2009 (using source data from (Frazier *et al.*, 2015)) showed ~1.1% decline at a decadal scale for seven major Hawaiian islands excluding Ni'ihau. Kaua'i, O'ahu, Maui, and Hawai'i declined at 0.8%, 0.6%, 1.7% and 1.1% respectively, while Moloka'i, Lana'i, and Kaho'olawe increased at 0.8%, 3.5%, and 1.7%, respectively. Studies found longer statewide droughts (Chu *et al.*, 2010) and fewer orographic precipitation on windward coasts (Garza *et al.*, 2012).

Most studies agreed on a continuing, clear downward trend on overall rainfall amount as the climate warms. A debate surrounds spatial and temporal patterns of precipitation, however, with the differences largely driven by the methods used to downscale climate prediction models. One study reported that Hawai'i and Maui will become wetter, while Kaua'i and O'ahu will be slightly drier (Keener *et al.*, 2013). A statistical downscaling method indicated that precipitation will decrease 5%–10% in the wet-season and increase 5% during the dry season (Elison Timm *et al.*, 2015). Dynamical downscaling models suggested summer will be wetter and winter drier (Lauer *et al.*, 2013). There is also some disagreement about the frequency and trends of high intensity rainfall events. Elison Timm *et al.* (2011) reported decreasing high intensity rain events as well as increasing low intensity events across the state, but Chen & Chu (2014) found increasing high intensity rainfall on the island of Hawaiʻi.

Local rainfall amounts and patterns are also influenced by local climate variation factors such as El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Lau & Mink, 2006). Rainfall and direct runoff is strongly related to ENSO (Oki, 2003), with drier than normal winter months commonly following ENSO events (Chu, 1995). Moreover, ENSO is inversely (negatively) correlated with PDO (Mantua *et al.*, 1997).

In addition to climate, land use and land cover changes in Hawaiʻi impact freshwater quantity (Brauman *et al.*, 2014). Alterations in land use and land cover are caused directly by extraction (i.e., via surface water diversion ditches) and urban development (Fortini *et al.*, 2013), indirectly by invasive species (Fortini *et al.*, 2013) and climate change (Sakai *et al.*, 2002; Wagner *et al.*, 1999; Wood *et al.*, 2007). From 1926 to 2004, groundwater recharge decreased approximately 44 percent (2.6 to 1.5 x $10^6$ $m^3/d$) in central and west Maui due to a decline in agricultural irrigation (from 3.4 to 3.0 x $10^6$ $m^3/d$), and an increase in urban land use, accompanied by rainfall reduction (Engott & Vana, 2007). Compared to agricultural crops or bare land, forests store substantially more water (Wood, 1977). Accordingly, native montane forests functions as groundwater recharge areas, and they are protected as conservation land use districts. However, spread of thirsty alien species, such as strawberry guava, translates to increased water use by alien species (Kagawa *et al.*, 2009).

Both climate change and land use and land cover change affect water quality in Hawaii. Unusual climatic conditions, for example droughts, sea-level rise, and intense storms (Keener *et al.*, 2012), can pollute freshwater resources through salt-water intrusion, and flash flood-induced sediment discharges. Feral ungulates have reduced herbaceous land cover, and thereby exacerbated erosion especially in steep slopes, causing increases in suspended solids and nutrients in streamflow (Polyakov *et al.*, 2007). Increased urbanization also reduced sediment-retaining land cover, increasing erosion potential (Nearing *et al.*, 2005), and increased impermeable surfaces that transport pollutant-laden runoff to nearby streams and coasts (Booth *et al.*, 2002). In addition to sediment and sediment-bound nutrients, Hawaiian waterways and groundwater are threatened by nutrients and other pollutants. The now-fallow agricultural fields continue to release nutrients into the surface waterbodies (WMP-WC, 2015), multiple golf courses that transect Hawaii's landscapes release nutrients from fertilizers and pesticides (Oki, 2003) and inadequate sewage treatment pollute groundwater and coastal waters (Dailer *et al.*, 2010).

### Management of Water Resources in Hawaiʻi

The people of Hawaiʻi have emphasized the importance of water literally and figuratively through their water resources management practices and laws (Sproat & Higuchi, 2015). Historically, pre-European contact (i.e., before 1778), water resources were managed by one or more king-appointed stewards (aka *Konohiki*) in land tenure units called ahupuaʻa (Kaneshiro *et al.*, 2005; Nakuina, 2007). Streams (*kahawai*) were at the heart of an ahupuaʻa, and were regulated strictly so that there was enough flow downstream (Nakuina, 2007). However, the traditional Hawaiian water resources management system eroded over time due to a shift in governance, land tenure system, economy, agriculture,  and land use (Kaneshiro *et al.*, 2005).

Current law and policy of water in Hawaiʻi are grounded in Article XI, sections 1 and 7 of the Hawaiʻi Constitution, which form the basis for protection, conservation, regulation and use policies of water resources. The Constitution is further reinforced by State Water Code (Hawaiʻi Revised Statutes, Chapter 174) for various items, including the water rights of the descendants of native Hawaiians, water use reporting and regulation, water quality, instream flow standards, wells, and stream diversion works. These constitutional and state provisions as well as Hawaiʻi common law (originating in the Hawaiian monarchy) form the Public Trust Doctrine to entrust the state to manage water resources sustainably, accounting for changing needs and conditions. In addition, in the context of water management, the Precautionary Principle states that preventative measures must be put in place against environmental degradation (Wallsgrove & Penn, 2012), demanding public agencies' action and reprimanding inaction even under scientific uncertainty (e.g., water commission's decisions in the *Waīahole I* water diversion case).

In addition, the Hawaiʻi Constitution and Water Code support certain water rights in Hawaiʻi such as environmental, appurtenant, riparian, correlative, and traditional and customary Native Hawaiian rights. Environmental rights ensure that each person has access to a clean and healthful environment with implication for meeting individual water needs. Appurtenant rights are water rights attached to a specific piece of property; riparian rights are water rights of land adjacent to a stream; correlative rights pertain to the land to its underlying groundwater. Traditional and customary water rights protect the rights of native Hawaiian home lands for current and future water needs (Miike, 2004; Sproat & Higuchi, 2015).

Following these directives and rights, several mechanisms have been put in place, including the Hawaiʻi Water Plan, instream flow standards, designated water management areas, and use permits. The State Water Code exercises appurtenant rights in designated water management areas (CWRM, 2008). Instream flow standards are set for each stream to regulate the amount of flowing water (with natural variability) according to its conditions in 1988 and 1989. These standards are specified to protect freshwater flora and fauna, instream and non-instream uses (CWRM, 2008; Miike, 2004). The Water Code delegates the designation of water management areas where the water resources are threatened by existing and proposed uses (Miike, 2004; Wallsgrove & Penn, 2012). Water use permits are required for consumption of surface and groundwater in water management areas (except domestic users and water catchment systems), stream modifications and drilling wells thoroughout the state. Groundwater sources are managed by maintaining sustainable yields, modeled water limits by US Geological Survey, without impairing their utility or quality (Sproat & Higuchi, 2015).

Based on State Water Code (including native Hawaiian water rights) and the common law, current water resources are managed by different government agencies (CWRM, 2008):

- Water quantity by Commission on Water Resources Management (CWRM);
- Water quality by Department of Health (DOH);
- State water projects by Department of Land and Natural Resources (DLNR);
- Agricultural water use and development by Department of Agriculture (DOA);
- Water use and development by respective county.

While these agencies interacted with each other in producing the State Water Plan, a deficit in agency cooperation in management, for example between management of water quantity (by CWRM) and quality (DOH), precludes an effective integrated approach. Clearly, the domains of each agency have impacts on the others: a change in water quantity affects and alters water quality: sediments discolor nearshore water during and after storms; low flow stream water quality is dependent on groundwater discharge; heavy storms flood manholes, sewer system and pollutes urban environment causing beach closures; agricultural runoff increases pollutant concentrations in water courses; built regions affect peak, timing and location of storm flows and accompanying contaminants. Hence, water quantity and quality should be treated as one entity and managed using a coherent and coordinated approach. The importance of a systems perspective has been acknowledged by many agencies, including the US EPA (USEPA, 2015), whose Office of Water wrote:

> … [We] are still working with laws and regulations that treat land, air, water and living resources as separate entities instead of as interrelated systems. This regulatory pattern makes comprehensive solutions and their implementation problematic, and complicates protection of ecosystems and habitat.

In addition, there are multiple competing water users (i.e., domestic, municipal, and industrial, commercial, and agriculture users) with diverse and conflicting interests. There have been disputes of neighboring users over water systems including: extracting excess water, changing the water course, and reduced streamflow due to groundwater pumping (CWRM, 2008). For example, in the Waiahole ditch dispute, there was a reallocation of 0.1 x $10^6$ $m^3$/d surplus water between the developers of leeward and central O‘ahu, and farmers and conservationists of windward O‘ahu. The urban developers were hoping to gain huge profits from discounted water (Gopalakrishnan *et al.*, 1996). Moreover, in the *Reppun v. Board of Water Supply* (1983) case, Honolulu Board of Water Supply’s ground water pumping was found to be decreasing the flow of Waihe‘e stream for downstream fields (MacKenzie, 2015). Furthermore, improvements in current management and enforcement of water resources are necessary for proper water use. In Hawai‘i, the use of water for plantations was approved by the courts according to the Riparian

Doctrine and the Prior Appropriation Doctrine (Gopalakrishnan *et al.*, 1996). Prior Appropriation Doctrine stipulates that sustained use of water for the original use is necessary for continued allocation. Therefore, when sugar and pineapple production stopped, the associated water right should have been lost, and the owners should have ceased the stream diversions. However, this did not happen (Gopalakrishnan *et al.*, 1996).

Clearly, improvements in current management and enforcement of water resources are necessary to protect valuable FES. Many of the issues related to water resources are the result of decisions regarding water taken without a systems perspective, which would explicitly acknowledge the interconnected nature of the water cycle and human users.

### *Integrated Management of Water*

There is a broad literature on integrative frameworks for water resources management. According to Global Water Partnership, Integrated Water Resources Management (IWRM) is defined as (van Beek & Arriens, 2014, p. 23),

> a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

The theory underpinning an integrated approach originated in the 1980s when water professionals started to recognize water as a multi-disciplinary issue (Biswas, 2004). In 1992, The Dublin Principles conceptualized the first IWRM theory, stating that “freshwater is a finite and vulnerable resource, essential to life, development and the environment”, and therefore not only policy makers but also users, planners should be involved in water resources management using a participatory approach (GWP, 2000; Hassing *et al.*, 2009). The Global Water Partnership reinforced the integrated theory in 2000 (see Figure 3) by pointing out that coordinated management of water resources and related vital ecosystems could maximize human wellbeing sustainably (van Beek & Arriens, 2014). However, a disconnect between theory and practice hindered real-world integration (Niasse & Cherlet, 2015).

In 2005, the Millennium Ecosystem Assessment (MEA) introduced the theory of FES stating that fresh water can be more valuable and supportive of human well-being if society considers and responds to ecosystem water requirements (MEA, 2005). In other words, MEA acknowledged the relationship between ecohydrology and ecosystem services (Chopra *et al.*, 2005). Still, there was no particular framework for practical integration. In 2011, International Institute for Sustainable Development (IISD) and United Nations Environmental Programme - Danish Hydraulic Institute’s (UNEP-DHI) Center for Water and Environment developed a framework (see Figure 3) with an ecosystem approach in integrated water resources management. The framework used the ecosystem service concept to inventory ecosystem services, benefits, values and trends, and prioritize management outcomes on the resulting inventory for sustainable development (Roy *et al.*, 2011). Martin-Ortega *et al.* (2015, p. 8) defines an Ecosystem Services approach to Integrated Water Resources Management (ES-IWRM) as,

> [The] ecosystem services-based approach is a way of understanding the complex relationship between nature and humans to support decision-making, with the aim of reversing the declining status of ecosystems and ensuring the sustainable use/management/conservation of resources.

While IWRM recognizes competing human uses (Niasse & Cherlet, 2015), it favors anthropogenic water demand in practice. By contrast, the ES-IWRM additionally recognizes water needs of the multiple natural ecosystems (UNESCO, 2009) and their interactions (Niasse & Cherlet, 2015). ES-IWRM can encourage adequate attention on the water needs of the natural ecosystem (i.e., 75% of total freshwater use) for the maintenance of overall ecosystem health (Falkenmark & Rockström, 2004), which then sustain and enhance the derived goods and services (GWP, 2000). It also promotes biodiversity benefits and increased resilience to extreme climate events (Roy *et al.*, 2011), and broadens the constituency in support of conservation (Ingram *et al.*, 2012) through common language (Kumar *et al.*, 2013).

Improving upon IWRM, the ES-IWRM implements a system perspective in an integrated manner (rather than sectoral) in managing water resources. It involves assessing ecosystem service flows in a freshwater system, thereby integrating ecological and social systems (Roy *et al.*, 2011). The ecological system part of the ES-IWRM emphasizes the interactions and interdependence of ecosystems (Niasse & Cherlet, 2015) through their functions of freshwater flow/transfers, and biogeochemical cycles involving organisms (i.e., plants and animals) and abiotic components (i.e., water, atmosphere, soil, parent material). Moreover, depending on the management goal, the ecological spatial (watershed, island, national or international) and temporal scales (photosynthesis to geologic cycle) will vary. Next, to promote collaboration among stakeholders (Biswas, 2004) and overcome traditional siloed views, social systems in the ES-IWRM identify existing common information as well as knowledge gaps, and build bridges across competing freshwater users (Maynard *et al.*, 2015; Roy *et al.*, 2011). Broad consideration of stakeholders helps protect any undervalued ecosystem services (Myers *et al.*, 1997) and avoids improper management, waste and degradation (Jones-Walters & Mulder, 2009). For example, current water prices may not reflect the negative effects of groundwater depletion, or the positive effects of surface water flows (e.g., spiritual enrichment and recreation).

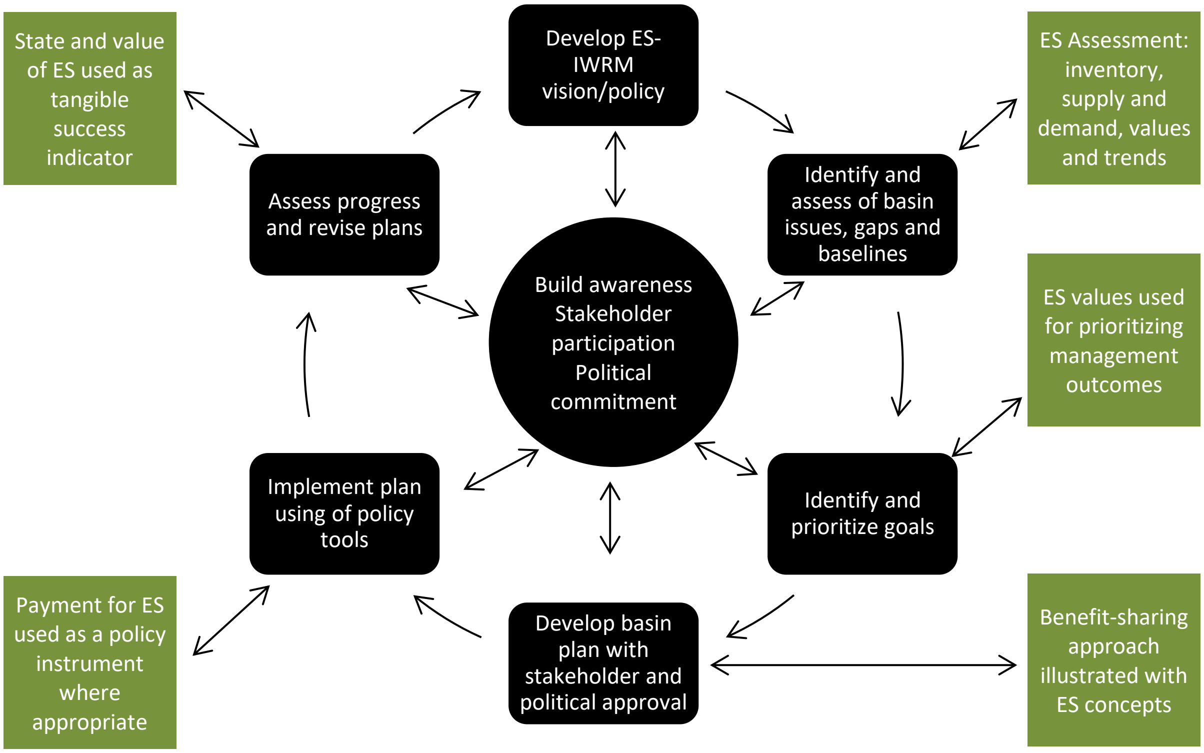

*Figure 3. Ecosystem Services-based Integrated Water Resources Management (ES-IWRM) Framework (modified from Roy et al. 2011 showing planning cycle with ecosystem services (in the square boxes) to promote awareness of water needs of ecosystem, its interactions with humans, and multiple ecosystem services. The framework also uses ecosystem services and values in the evaluation of policy tool as well as evaluation of the planning cycle.*

To quantify the effectiveness of ES-IWRM practices, UN Water carried out a global survey with over 130 UN member countries in 2012. Findings showed that since 1992, 80% of countries have adopted integrated approaches with significant nationwide infrastructure, policy, law and ecosystem improvements for socio-economic benefits (UN Water, 2012). Once adopted, continued appropriate levels of coordination were found to be essential to alleviate increases in associated risks and competition for water resources (UN Water, 2012). Several cases point to the benefits of ES-IWRM. Using ES-IWRM highlighted how the natural flow of the Senegal River provides benefits such as culturally important *waalo* agriculture, control of invasive species and related disease vectors, groundwater recharge, and forest maintenance (Niasse & Cherlet, 2015). In another case along the Komadugu River, environmental impacts from Tiga and Challawa Dams were remedied using the ES-IWRM approach to facilitate stakeholder consensus from six Nigerian riparian states related to downstream floodplain services, and wetland restoration (Barchiesi *et al.*, 2011). Although benefits were not substantially higher than costs of reducing stream diversion in Murray-Darling Basin, Australia, the ES-IWRM approaches were found to be helpful in not only decision-making but also cost-benefit analysis for forming policy (Crossman *et al.*, 2015). Next, in a case in South East Queensland, the ES-IWRM participatory framework improved collaboration across sectors, organizations and disciplines while trying to develop and application of ES-IWRM to mitigate flood damages (Maynard *et al.*, 2011). The framework provided a social narrative of the consequences of demands on nature's ability to provide goods and services (Maynard *et al.*, 2015).

On the other hand, there are still uncertainties and challenges in operationalizing the ES-IWRM. During nationwide FES assessment in England, researchers realized that there were no hydrological models to fully quantify the effect of changes and regime shifts in ecosystems on human wellbeing (Maltby *et al.*, 2011). Furthermore, a systemic ES-IWRM approach, for example in the European Water Framework Directive (Kallis & Butler, 2001), to support transdisciplinary decision-making involving policy makers, scientists, and stakeholders in an engaging, deliberative socio-ecological context can be hard due to technocratic language (Blackstock *et al.*, 2015). Further, as seen in implementation of the European Water Framework Directive, it can be expensive to provide additional labor and expertise for monitoring, reporting, quantifying and valuing ecosystem goods and services over common water resources metrics such as streamflow, sediments and nutrients (Blackstock *et al.*, 2015; Johnston & Duke, 2010).

### *Modeling for ES-IWRM*

The ES-IWRM approach requires the assessment of ecosystem services (Figure 3) either quantitatively or qualitatively. The first method of modeling FES a quantitative approach that employs biophysical models coupled with economic models to measure FES in terms of biophysical or economic metrics, for example, gallons of freshwater, salinity concentrations, marketed value of fish catch, etc. (Crossman *et al.*, 2015). On the other hand, participatory models (i.e., causal diagrams, concept mapping, mental models, etc.) assess FES qualitatively using knowledge elicitation models with or without empirical observations, and can better capture non-biophysical traditional ecological values and benefits. The third hybrid method uses biophysical modeling to capture ecosystem services and a participatory model for assessing non-biophysical ecological benefits (Janssen, 1992; Maynard *et al.*, 2011). Each of these models is described in more detail below.

Quantitative FES assessment involves using hydrological models to simulate the climate-soil-vegetation relationship (Rodriguez-Iturbe, 2000). Biophysical components of the hydrological models consider ecohydrological processes to examine the effects of abiotic hydrological processes on ecosystem structure and function, as well as the converse, i.e., effects of biotic processes on the hydrologic cycle (Nuttle, 2005). Models range from simple (e.g., InVEST (Tallis *et al.*, 2013)) to complex (e.g., KINEROS (Woolhiser *et al.*, 1990)), based on aspects such as: the number of hydrologic processes, the number of input parameters, physical or non-physical basis, predictive power, model use, temporal and spatial scale, static or dynamic states, technique of solution (Numerical or Analytical, and deterministic or probabilistic), and model structure (lumped or distributed) (PBA & NHC, 2008; Singh & Woolhiser, 2002; USEPA, 1997). While complex models are usually physically based models with extensive input requirements, simple ones tend to be qualitative and less data-intensive. Physically-based models require empirical data, and they maintain physics of the processes (e.g., laws of conservation of mass, momentum or energy) (Scharffenberg *et al.*, 2010). Generally, simple models also have little predictive power and are designed for qualitative or semi-quantitative assessments (USEPA, 1997).

Qualitative assessment of FES involves participatory modeling using methods derived from decision theory. These methods are used to define ecosystems qualitatively and build ecological models based on a knowledge (expert and/or empirical) elicitation approach (Griffiths *et al.*, 2007; James *et al.*, 2010; Mac Nally, 2007; O'Leary *et al.*, 2009; O'Neill *et al.*, 2008). Expert knowledge can handle imprecise data, facilitate informed and cost-effective decision-making (Kuhnert *et al.*, 2010), and also resolve the problem of data scarcity in defining water-related ecosystems. These decision-science models take several forms, including Bayesian analysis models (Varis, 1997), Structural Equations Models (Jöreskog, 1976), System Dynamics Models (Forrester, 1970), Agent-Based Modeling (Yang *et al.*, 2011), and Fuzzy Cognitive Mapping (Kosko, 1986). Bayesian analysis models describe uncertainty to make statistical inference on environmental and resource management problems (Voinov & Bousquet, 2010). Next, structural equation modeling (SEM) is a statistical exploratory tool with optimizing parameter estimation procedures for causal relationships (Jöreskog, 1976) between water and its environment. Moreover, Agent-based Modeling (ABM) aids in identifying the decision-makers, the interactions among themselves and their environment. Finally, a Fuzzy Cognitive Mapping (FCM) consists of concepts with connecting causal relationships in water-related ecosystems, focusing on feedbacks.

### *Research Needs/Rationale*

In Hawai‘i, water quality and quantity declines are threatening FES critical for human wellbeing. These declines point to wholly inadequate management of water resources, one that is fragmented across agencies and dimensions (i.e., quantity and quality), and myopic about the many values of water.

Fortunately, alternative, integrative management frameworks exist that incorporate insights from ecohydrology about the linkages between the biological and hydrologic systems, and FES, which highlight the relationships between the biophysical and human systems. One such approach is ES-IWRM, which has been successfully applied around the globe. In Hawai‘i, the CWRM explicitly acknowledges that a coordination framework for an integrated watershed basis is vital to the lasting success and propagation of watershed protection and conservation efforts, and overcoming the existing jurisdictional and regulatory issues inherent in the government for water initiatives (CWRM, 2008).

The ES-IWRM could help solve the problems from Hawaii's fragmented management system, and encourage incentives and resources for preserving healthy and sustainable ecosystem services while systematically handling drivers of ecosystem alteration (Roy *et al.*, 2011). However, modeling tools do not yet exist that can robustly predict ES outcomes of planning and management in the face of rapid change in Hawai‘i. Hawaii's systems are atypical – steep, volcanic geology stumps most off-the-shelf hydrological models, and values for FES are deeply rooted in cultural norms that defy quantification. This necessitates custom models that integrate the biophysical and human systems in novel and creative ways.

Therefore, there is an urgent need to develop tools for Hawaiʻi. My research seeks to develop a modeling tool that evaluates hydrologic ecosystem services to inform an ecosystem services-based approach for water resources management. The modeling tool aims to integrate biophysical (land cover, habitat, water quality and quantity) and social systems (ecosystem goods and services), providing decision support for integrated water resource management. Based on global experience and theory, I believe that such integrated ecosystem services-based modeling can lead to better water resource management decisions and outcomes.

***Dissertation Overview***

The goal of my research is accomplished in three studies: (Study 1) describe, select, and evaluate FES models for use in Hawaiʻi; (Study 2) develop and apply a hydro-ecological modeling tool to predict ecological benefit; and (Study 3) apply a hydro-social modeling tool to predict social values (Figure 4).

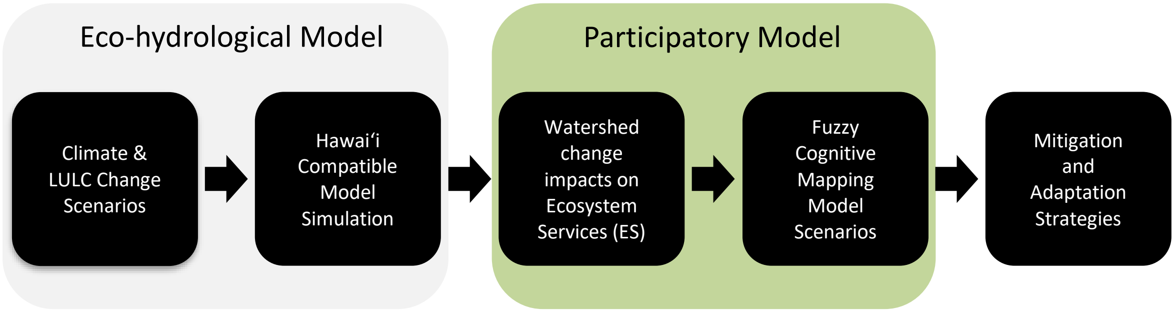

*Figure 4. Dissertation plan. Study One involves choosing Hawaiʻi-compatible eco-hydrological model(s), and Study Two and Three couple eco-hydrological models with the participatory to suggest mitigation and adaptation strategies.*

The first study identifies hydrological models that fit Hawaii’s ecosystems and decision needs through a rigorous modeling selection process and performance evaluation. I identify the processes critical to FES delivery, select a suite of models (potentially) applicable to Hawaiʻi that quantify processes critical to FES either directly or via post-processing, develop and use a set of criteria to select candidate models, and evaluate candidate model performance in selected leeward and windward watersheds. I assess existing hydrological (both surface and groundwater) model capabilities using specific Hawaiʻi ecosystem services-dependent criteria.

Using one of the evaluated hydrological models from the first study, the second study couples biophysical and expert-opinion-based participatory models (see Figure 4) to predict ecological impacts of climate change on federally-protected endangered species. Specifically, I develop a decision support approach to improve the understanding of climate change impacts on the habitat, life history functions, and abundance of endangered bird species. My approach couples a regional watershed simulation model (AnnAGNPS) under IPCC-defined scenarios and an expert knowledge-based model of bird ecology, which uses Fuzzy Cognitive Mapping (FCM). To test the approach, I use data for the Hawaiian Stilt, Hawaiian Coot, Hawaiian Moorhen populations and habitat (Hanalei watershed, Kauaʻi) as a case study.

Finally, in the third study, I expand the coupled biophysical-participatory model approach to compare and predict the behavior and/or policy responses of different stakeholder groups who hold diverse values for FES (e.g., water resource managers, conservationists and cultural practitioners) under different climate and land use change scenarios. Applying the method to a case study of Maui, the approach identifies freshwater ecosystem goods and services that are important to local people, relevant for management decisions, and ecologically essential for habitat conservation. Coupling an ecohydrological model (SWAT) with the social-ecological system models generated by various stakeholder groups predicts how biophysical changes (land use, precipitation, water withdrawals) alter outcomes for stakeholder-identified FES. This approach highlights the perceived impacts of policies affecting the hydrological system, e.g. water allocation or land management, for different stakeholder groups. This understanding could help improve management decisions, while reducing conflict and increasing equity.

## Study 1- Selecting Appropriate Hydrological Model to Evaluate Freshwater Ecosystem Services in Hawai‘i

### *Abstract*

A water resources management approach focused on managing freshwater resources at a broader scale, with an emphasis on the benefits water provides to humans (i.e., drinking water, flood control, tourism, etc.), could result in management that delivers higher benefits at lower cost. Such an ecosystem services-based approach involves understanding how hydrologic attributes (i.e., quantity, quality, location, and timing) change over time and management action. However, due to unique hydrogeological conditions in montane volcanic islands, many hydrological models cannot accurately quantify hydrologic processes (e.g., evapotranspiration), and therefore cannot estimate attributes nor associated freshwater ecosystem services (FES). To find models useful for estimating hydrological attributes in volcanic islands, I applied a set of fourteen criteria – both technical (e.g., input data requirement, complexity, ease of use, etc.) and practical (e.g., mixed land use modeling, spatial and temporal resolution of outputs, etc.) – to assess the potential of 37 surface water and 32 groundwater models. A further selection of specific models for each of the target FES involved evaluating each model for a given category (e.g., surface water quality models) based on its underlying hydrological processes and minimum characteristics. Underlying hydrological processes for all FES under consideration included quantity of evapotranspiration and streamflow; water provisioning requires groundwater recharge; cultural FES further requires timing and location of runoff routing; flood regulation requires flood forecasting with a specified lead time. Necessary processes and functions were also identified for modeling retention or export of sediment and nutrients. Further to these scientifically defensible and locally appropriate hydrological functions, minimum characteristics of a model for a volcanic island are data availability, model outputs directly or indirectly representing FES under consideration, mixed land use modeling, and the support for diverse soil, slope and climate. As an example to demonstrate the usefulness of the selection process for appropriate models to estimate the same FES in watersheds that are quite different, I created an evaluation matrix for provisioning FES based on surface water models subdivided into broad functional groups. The matrix helped me to choose OpenNSPECT and SWAT for Kalihi and Kahakuloa watersheds respectively. FES under consideration and available input data in the test watersheds required two different models in two different temporal resolutions. The models performed satisfactorily with 98.07% of observed annual streamflow in Kalihi (0.18 $m^3/s$) and 96.86% of observed daily streamflow in Kahakuloa. SWAT captured both daily peak and low flows with $R^2$ higher than 0.8, and RSR less than 25% for most years. Therefore, the two models provided accurate estimates of freshwater availability which is key to provisioning FES and cultural FES like native land use/cover and native species. In conclusion, the screening and evaluation process demonstrated here can help identify what particular hydrological models are appropriate for estimating target FES under different watershed and technical circumstances.

## *Introduction*

Water is essential for human well-being for many reasons. For instance, in Hawaiʻi, groundwater provides 99.7% of Hawaii's domestic water and 63% of all freshwater uses (USGS NWIS, 2015). Further, surface water supplies more than 50% of irrigation water to the islands, and it is significantly important economically (CM, 2012), ecologically (WMP-WC, 2012), culturally (Sproat & Higuchi, 2015), and aesthetically (Oki, 2003). However, freshwater resources are becoming scarcer, and they need to be managed for human well-being and environmental sustainability (Ringler *et al.*, 2013) in terms of efficient and equitable allocation (Gregersen, 2007).

Water resources managers are increasingly adopting an ecosystem services-based approach that explicitly recognizes the critical role of natural systems in providing so-called Freshwater Ecosystem Services (FES) (Capon & Bunn, 2015; UN Water, 2012). FES reflect the direct benefits people receive from freshwater resources (e.g., extracting fish from streams, withdrawing drinking water from aquifers, recreating at a wetland, and pumping irrigation water from streams), as well as indirect water-related services (e.g., erosion control, spiritual enhancement, and nutrient cycling) (Brauman, 2015; Brauman *et al.*, 2007; Capon & Bunn, 2015; MEA, 2005).

Watershed management has been aided by computerized watershed models capable of simulating the long-term effects of watershed processes and management activities on water quantity and quality (Moriasi *et al.*, 2007). However, existing models are not compatible with volcanic montane ecosystems, such as those in Hawaiʻi and Fiji. These islands have unique hydrogeological (Lau & Mink, 2006; White & Falkland, 2010) and ecological conditions that do not conform to the model assumptions including spatially and temporally variable climate, diverse precipitation patterns (Giambelluca *et al.*, 2013; Terry & Raj, 2002), and complex hydrogeology (Lau & Mink, 2006).

Climate in volcanic islands is spatially and temporally variable. Therefore, models designed mainly for homogeneous topography and climate may not be suitable for island topography with substantial slope gradients and varied microclimate. Also, models that run on daily time-steps may not be ideal for dry, leeward watersheds where only annual meteorological data is available.

Spatial climate variation in volcanic islands such as Hawaiʻi and Fiji stem from three major factors related to their geographical position: the Hadley cell, the high mountains, and influences from El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Lau & Mink, 2006; Terry & Raj, 2002). Hadley cell is the expansion and uplift of equatorial hot air and subsidence of cool, dense subtropical air. The cell causes moisture-rich trade winds (Chapin III *et al.*, 2011). The islands with high mountains obstruct moisture-abundant trade wind. As moist air ascends windward mountain slopes, rain falls, creating wetter climates on north and northeast (windward) watersheds and drier climates on southwest (leeward) watersheds in Hawaiʻi due to northeast trade winds (Sanderson, 1993). Similarly, Fiji has wet southeastern watersheds and dry northwestern watersheds due to southeast trade winds (Terry & Raj, 2002). Also, orographic lifting of moist air results in frequent rainfall near the peaks of all except the tallest mountains (Giambelluca *et al.*, 1986). Loss of moisture on windward watersheds leads to relatively drier leeward watersheds (Johnson *et al.*, 2014). As a result, streams in the windward watersheds are perennial while ephemeral streams with flashy floods dominate the leeward watersheds. Furthermore, centers of ENSO and PDO are close to the Hawaiian Islands, and their warm (cold) cycles have influences on Hawaiian rainfall (Chu & Chen, 2005). During ENSO, trade wind weakens and Hawaiʻi experiences flash floods from severe storms as well as droughts (PEAC, 2017; UH-SGC, 2014). Similarly, low rainfalls accompany warm PDO phase (Chu & Chen, 2005). Furthermore, Fiji experienced ENSO-related droughts in 1978, 1983, 1987, 1992 and 1997-98. In the west of the island, particularly dry years are characterized by very low stream base flows (Terry & Raj, 2002).

In addition to spatial variation, seasonal differences can have pronounced effects on precipitation. In Hawaiʻi, the wet season (October through April) has cooler temperatures and less persistent trade winds (Johnson *et al.*, 2014), quite different from the dry season (May through September). Diverse precipitation pattern makes it hard to choose an appropriate hydrological model. For example, Mt. Waiʻaleʻale on the island of Kauaʻi has a mean annual precipitation of 11,267 mm (443.5 in.) while a town 25 km (15 miles) west of the mountain, Kekaha, receives only 543 mm (21.3 in.) (Lau & Mink, 2006). In addition to rainfall, certain areas in Hawaiʻi have fog or cloud water interception at elevation between ~ 600m (2,000 ft.) and 2500m (8,200 ft.) [2500m – mid of range 2400m (Giambelluca & Nullet, 1991) to 2600m (Giambelluca *et al.*, 2011)] (DeLay & Giambelluca, 2011). Though values vary from island to island, fog interception on the windward slopes of West Maui Mountain was estimated at 20% of rainfall (Engott & Vana, 2007). Giambelluca *et al.* (2011) reported fog interception to be 32% of the total precipitation on the windward side of Haleakala Mountain, but 15% on the leeward on the leeward side.

Besides climate, many currently available models fail to characterize Hawaii's aquifers with various hydrogeochemical properties satisfactorily for the dispersion process in fractured (El-Kadi & Moncur, 2006) and porous basalts (Lau & Mink, 2006). While complex models without enough appropriate input data are not useful, assumptions in simple groundwater models that aquifers are homogenous fail to capture this complexity. Aquifers in volcanic permeable basalt rock are the major groundwater systems in Hawaiʻi (El-Kadi & Moncur, 2006). These rock systems have various formations with high anisotropy and heterogeneous hydraulic conductivity, affecting the speed of groundwater flows. Freshwater lenses occur in a variety of geologic settings including a basal aquifer and a dike-impounded caprock aquifer. Basal water can be confined or unconfined between nearly horizontal low permeable rock formations. On the other hand, dike-impounded aquifer forms within nearly vertical, low porous, dense rock slabs at high elevation away from the ocean. Dike-impounded aquifers are of high-quality freshwater lenses (El-Kadi & Moncur, 2006; Lau & Mink, 2006).

Past efforts have modeled surface water and groundwater. For instance, Polyakov *et al.* (2007) used AnnAGNPS for the Hanalei watershed in Kauai to focus on water quality. AnnAGNPS performed well at monthly time steps ($R^2 = 0.9$), though daily model outputs were less accurate ($R^2 = 0.55$) (Polyakov *et al.*, 2007). Further, MIKE SHE was used to predict flash floods in Mānoa-Palolo watershed on Oʻahu (Sahoo *et al.*, 2006). Unavailability of spatially variable data led to under-prediction of flash floods, especially for significant storm events (Sahoo *et al.*, 2006). In addition, Izuka (2011) used MODFLOW, MT3DMS, and SEAWAT to study flow and transport of contaminated roadside runoff via dry wells affecting groundwater quality. Other groundwater estimates around the state of Hawaiʻi included: recharge using water-budget model in Maui (Johnson *et al.*, 2014); and irrigation, drought and withdrawal on groundwater levels using SHARP in Lihue, Kauai (Izuka *et al.*, 2005). Past modeling exercises provide some insights into the freshwater system. However, similar studies using the ecosystem services-based approach could provide better recognition of water needs of the nature (Niasse & Cherlet, 2015), raise awareness of the multiple ecosystem services (UNESCO, 2009), promote biodiversity and increase resilience to extreme climate events (Roy *et al.*, 2011), and broaden the constituency in support of conservation (Ingram *et al.*, 2012).

Managing watersheds on volcanic islands using an ecosystem services-based approach requires models that can directly estimate FES, or produce biophysical outputs that can then be converted to FES in post-processing. While there is some past modeling of Hawaiian watersheds, to date no one has set out to evaluate a broad array of candidate models as to their ability to estimate multiple FES. Models simulating FES need to represent underlying vital processes and quantify flows accurately to predict FES delivery and potential trade-offs of alternative management scenarios. Moreover, managers need to understand the relative strengths, weaknesses, and uncertainties of watershed models under local hydrogeological and ecological conditions to make good decisions. Accordingly, I sought to answer three research questions. First, what processes underpin freshwater ecosystem services? Second, what are the minimum characteristics of a Hawaiʻi-compatible ecosystem service model? Third, what models are appropriate for what freshwater ecosystem services management decisions? To answer these questions, I identified hydrologic models that fit conditions common to volcanic islands accurately to model key processes that describe FES. I developed model assessment criteria specific to Hawaiʻi for FES models, evaluated existing models against these criteria, and populated a matrix for model comparison and selection. I then assessed performance and sensitivity of candidate models in two watersheds.

### ***Methods***

To answer the research questions, I used a series of methodological steps: a review of current models based on literature, model selection based on criteria, model simulation and evaluation on the selected few. The detailed process included:

1. Compile a list of hydrological models including:

   a. An initial list of all appropriate models based on **literature review** following methods outlined in Bagstad *et al.* (2012);
   b. A long list (reduced initial list) of models that can potentially quantify, model or map **freshwater ecosystem services or processes** following Bagstad *et al.* (2013).
2. Compile model selection **criteria** from published literature, with a focus on freshwater ecosystem service quantification (PBA & NHC, 2008);
3. Identify **a short list** of models based on the criteria;
4. Develop an **evaluation matrix** detailing the hydrological characteristics underpinning freshwater ecosystem goods and services, as well as associated technical aspects of the short list models to aid in candidate model selection;
5. **Evaluate** performance and sensitivity of two candidate models.

*Step1: Model List Compilation*

The initial list of models was compiled using model reviews (Gaber *et al.*, 2009; USEPA, 1992, 1997, 2002), model inventories from the Community Surface Dynamics Modeling System (CSDMS, 2014) and the Integrated Groundwater Modeling Center (IGWMC, 2014)), and suggestions from local experts. The models were from different agencies such as US EPA, USDA, USGS, USACE, and NOAA, as well as commercial companies such as Aquaveo and Systech Water Resources, Inc. I identified tools that assess, quantify, model or map FES or processes (Bagstad *et al.*, 2013). While many FES exist, only hydrologic models with process functions to simulate surface water runoff, groundwater recharge, and sediment and nutrient retention/export were included. Among the models, tools for conservation planning or optimization were given priority. But, I excluded one-time applications that were not easily modifiable for new locations (Maes *et al.*, 2011; Schröter *et al.*, 2005) and tools that are intended for single landscape types. Also, I removed tools that produce outputs incapable of informing change analyses (e.g., American Forest's CITYgreen (Longcore *et al.*, 2004)) and tools that are developed for mapping online explicitly. Models designed for operating systems older than Windows XP or which are no longer widely-used were removed. Finally, I excluded explicit ecosystem service valuation tools with no hydrological simulation capability and developed the long list of models.

Besides the models in the initial list, there is a group of models I excluded known as receiving models (for example, WASP (Goldstein, 2001)) because they emphasized on the response of a waterbody to pollutant loadings, flows and ambient conditions (USEPA, 1997). Instead, my collection included loading models that focus on predicting water quantity and pollutant loads and their movement under various environmental and management conditions.

*Step 2: Model Selection Criteria Compilation*

Criteria were compiled using published literature (mostly for technical aspects of models) using PBA & NHC (2008) and Gaber *et al.* (2009). Then, I added a few more criteria to consider hydrogeological and climate conditions of Hawai‘i, as well as possible FES available from Hawaiian watersheds. The criteria to capture FES included 14 required capabilities common to all simple and complex models (Westervelt, 2001), as well as four and five additional criteria for simple and complex model respectively (Table 1). Some of the criteria common to both models are based on complexity, ease of use, input data availability and required output availability (PBA & NHC, 2008).

*Table 1. Model selection criteria.*

| | **Common for both simple and complex models** |
|---|---|
| **1** | Data requirements |
| **2** | Management practice under consideration for freshwater ecosystem service evaluation |
| **3** | Linkage to GIS |
| **4** | Graphical user interface for pre-processing (e.g., Windows-based input data editors) |
| **5** | Post-processing tools (e.g., printing tables and graphs directly from the model software |
| **6** | Well-defined user documentation |
| **7** | Widespread use and acceptability of model (e.g., used nationally for TMDL modeling) |
| **8** | Model availability (public domain vs. proprietary, software cost, etc.) |
| **9** | Requirements for user modeling experience |
| **10** | Level of user effort (e.g., few required parameters) |
| | **Common for both simple and complex models** |
| **11** | Scientifically defensible results |
| **12** | Model maintenance (e.g., software update and calibration update based on newly available data, etc.) |
| **13** | Possible use of the watershed model by other Hawaiian cities and counties |
| **14** | Presence of technical support |
| | **Simple model capabilities** |
| **1** | Continuous event modeling (i.e., hourly or event) |
| **2** | Mixed land use modeling |
| **3** | Ability to simulate sediment erosion and deposition |
| **4** | Ability to simulate nutrient and chemical pollutants (e.g., nitrogen, phosphorus, etc.) |
| | **Complex model capabilities** |
| **1** | Type of ecosystem goods and services |
| **2** | Resolution of outputs (space, time) |
| **3** | Type of management questions to be addressed (or issues to be resolved) |
| **4** | Interpretability and type of results (absolute or relative values) |
| **5** | Automated or manual process (ecological inputs to ecosystem services) |

*Step 3: Short List of Models Selection*

Using these criteria, I screened the long list to identify a short list for further analysis. Individual models from the long list were considered against the items on the criteria to produce the short list. Depending on the modeling requirements, short list would change for each freshwater ecosystem service, modeler’s expertise, and required output resolution under consideration.

Therefore, for case study simulations in this study, I created a project-specific short list of models for simulation of streamflow, sediment, and nutrients. Accordingly, I removed groundwater models, wetland models, and flood forecasting models from my short list. Since I was looking for free models for the case study, I removed commercial products. Also, I gave selection preference to models previously used in Hawaiʻi.

*Step 4: Model Evaluation Matrix*

Further analysis of the the shortlisted models was summarized in a matrix. They were rated according to data availability and model complexity (High, Medium, Low). Model complexity was related to model simulation capabilities, from simple to complex processes (Shoemaker *et al.*, 2005; USEPA, 1997). Different management goals would require different levels of complexity (i.e., simple output trends to complex, spatially- and temporally- explicit gridded model results). Low model complexity was defined as a simplified representation of hydrologic processes with significant limitations, medium complexity as a moderate level of analysis with some constraints, and high complexity as detailed simulation of hydrologic processes (Shoemaker *et al.*, 2005).

The matrix was developed to assess whether freshwater ecosystem goods and services were outputs or could be estimated post-process with the model outputs (see Table 5). Specifically, the analysis involved evaluating if the models could sufficiently simulate hydrological processes underpinning freshwater ecosystem goods or services in Hawaiʻi. The assessment included whether specific process equations embedded in models were compatible with Hawaiian conditions. In Appendix 1A, I summarized critical hydrological processes important for modeling ecosystem services, and the relevant process equations. Then, in the following analysis, I reviewed how each model handles hydrological processes, with particular attention to systems in or like Hawaiʻi.

Step 4a: Analysis of Hydrological Processes

Evapotranspiration

In Hawaiʻi, evapotranspiration (ET) is crucial because it makes up a significant portion of precipitation (or available soil moisture). Generally, annual ET is from less than 50 mm at the dry mountaintops to approximately 1,700 mm in sunny, irrigated regions. In leeward watersheds, ET increases with increasing mean annual rainfall, makai to mauka. In natural ecosystems, maximum ET occurs in areas with 1000 to 2000 mm/year mean annual rainfall. In non-native systems, this estimate can be affected by invasive species such as strawberry guava (*Psidium cattleianum*) that have relatively high ET (Giambelluca *et al.*, 2008). ET approximation is fundamental for hydrological and ecological modeling and assessment of water resources, and their responses to climate and land cover change in Hawaiʻi (Giambelluca *et al.*, 2014).

Based on previous modeling exercises, the Priestley-Taylor ET model was less satisfactory than other ET models at elevation 3400m at the Mauna Loa Observatory (Lau & Mink, 2006). Above and within the trade wind inversion layer, Priestley-Taylor and Penman-Monteith gave predictions closer to measured values (Giambelluca & Nullet, 1992). Below the inversion layer, Priestley-Taylor model was adequate (Lau & Mink, 2006). Potential ET from Penman-Monteith was found to be better for the whole island. In addition, Penman-Monteith is better because it accounts for thermodynamic, aerodynamic and biological processes (Bonan, 2008).

### Streamflow

For surface runoff (or overland flow), the unit hydrograph model does not consider physically based hydrologic processes (Feldman, 2000). Infiltration methods require climate variables at sub-daily (e.g., hourly) data, which are not readily available (Philip *et al.*, 2008). Therefore, SCS curve number method is more appropriate for most of the hydrological modeling in Hawaiʻi, except irrigation-specific application.

Subsurface flow using the kinematic wave storage-discharge equation (Sloan & Moore, 1984) is well-tested and -accepted, as in WEPP and SWAT models by USDA. This type of flow is usually observed in steep hillslopes with highly permeable soils and significant organic litter (Sloan & Moore, 1984), such as conservation zones of Hawaiian watersheds.

### Routing Runoff (Provisioning or Cultural Ecosystem Service)

Timing and location of streamflow (or flood wave) are simulated using either hydrologic or hydraulic routing. Runoff routing balances inflow, outflow and storage volumes. For example, diffusion and kinematic models are widely used in engineering applications. SWAT uses variable storage routing, while both SWAT and HEC-HMS use kinematic wave model.

### Hydrological Flood Forecasting (Regulating Ecosystem Service)

Hydrological considerations in flood forecasting include prediction of the relationships in upstream and downstream water levels (for example, for a flood-risk site). In the United States of America, a lead time of between 2 and 48 hours would generally be considered a short-term forecast, between 2 and ten days a medium-term forecast, while a long-term forecast would be one for which the lead time exceeds ten days (WMO, 2011).

### Groundwater Recharge

The baseflow method assumes that baseflow is the same as the groundwater recharge. However, it is not valid for Hawaiʻi where a significant portion of groundwater become submarine groundwater discharge, not at the watershed outlet. The baseflow method also assumes that watershed boundary coincides with groundwater divide. Next, using point estimates of water-table fluctuation is not appropriate either because it overlooks the lag time between infiltration and recharge. Finally, soil water budget approach is promising because it does not assume watershed boundary coincides with groundwater divide (Izuka *et al.*, 2010).

### Sediment Retention/Export

There are several sediment export processes and equations/models available. USLE uses rainfall as the factor driving soil erosivity, but MUSLE uses the runoff volume to simulate erosion and sediment yield. MUSLE is said to provide better prediction accuracy, elimination of delivery ratio process, and the possibility of sediment yield from a single storm.

### Nutrient Retention/Export

Nitrogen and phosphorus processes follow their respective cycles (Neitsch *et al.*, 2011) or mass balance approach (Sharp *et al.*, 2014). Though mass balance approach is faster, following processes according to the nitrogen and phosphorus seems to be a more realistic approach.

### Step 4b: Analysis of Capability to Capture Spatial and Temporal Variability

To consider spatial variability in Hawaiʻi, the distributed models might serve the purpose better than lumped models. For instance, SWAT modeling of freshwater quantity and quality in Study Three proved that the use of distributed model was crucial for the highly variable topography of Maui. SWAT is a semi-distributed model and used subbasins as well as smaller units, hydrologic response units.

Initial model runs using SWAT with large subbasins that flowed from mauka to makai across the island of Maui did not produce results close enough to observed data. Therefore, I divided the island into 12 sectors and 2976 (initially 261) subbasins, resulting in more agreement between simulated and observed water budget components. A model's capability to handle temporal variation must coincide with available observed data. Windward sides of islands sometimes have sufficient measured daily streamflow, sediment, and nutrients for detailed models with daily time-step simulations. On the other hand, leeward regions may not have measured daily observations for fine temporal model runs. If the model is simulated at fine temporal time step (i.e., daily or monthly) using interpolated input data, the final output should be reported at coarser (annual or annual average) time steps.

### *Step 5: Performance Evaluation of  Two Candidate Models*

While the screening process using the evaluation matrix points to candidate models for each service and condition, only actual simulation of the model in a chosen site can prove its validity, where the model performs well and produces outcomes to reflect observed local data accurately. Performance of a model and its sensitivity to Hawaiian watersheds are essential in model selection. Therefore, understanding of model evaluation and its sensitivity in a local watershed is essential for water resources managers (Westervelt, 2001). Model evaluation informs water resources managers if the use of the model outcome is appropriate for informing management decisions despite its uncertainties (Gaber *et al.*, 2009). The degree of uncertainty of a model is evaluated by 1) model corroboration to determine the agreement between model's output and reality; 2) sensitivity analysis to assess the effect of input values or assumptions on outputs; and 3) uncertainty analysis to investigate the behavior of a model imposed by the lack of real data or parameters (Gaber *et al.*, 2009; USEPA, 2013).

Model evaluation involved visual and statistical corroboration between computed and measured flows. For visual evaluation, I used a time series plot of simulated and observed flows (Moriasi *et al.*, 2007) to identify model bias (ASCE, 1993) as well as differences in timing and magnitude of peaks and lows. Further, statistical metrics included Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR) for continuous/daily event models (Moriasi *et al.*, 2007).

The NSE measures the fit of observed data variance against modeled data variance over the 1:1 line (Nash & Sutcliffe, 1970), and can be computed as follows (Moriasi *et al.*, 2007; Safeeq & Fares, 2011):

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{1}$$

Where $O_i$, $S_i$, and $\bar{O}$ are the measured, simulated and mean of measured values, respectively. N is the total number of data points in the simulation.

In addition, model accuracy can be measured through PBIAS, the average tendency of simulated values being larger or smaller than the observations (Boyle *et al.*, 2000). An optimal PBIAS value is 0.0. Positive values point to model underestimation bias, but negative values mean overestimation bias (Gupta *et al.*, 1999). PBIAS is calculated as:

$$PBIAS(\%) = \frac{100\sum_{i=1}^{N}(O_i - S_i)}{\sum_{i=1}^{N} O_i} \tag{2}$$

Residual variance is estimated by root means square error (RMSE). According to Boyle et al. (2000), RMSE gives small error variance but produces large model bias. Also, model evaluation requires standard deviation as a dimensionless statistic (Legates & McCabe, 1999; Moriasi *et al.*, 2007). RSR can be computed as:

$$RSR \ = \frac{\sqrt{\sum_{i=1}^{N}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}} \tag{3}$$

For each statistic, satisfactory simulation has the following statistics: NSE > 0.50 and RSR < 0.70; and PBIAS ±25% for streamflow, ±55% for sediment, and ±70% for N and P.

On the other hand, single-event simulation models require a different evaluative statistics (ASCE, 1993; Green & Stephenson, 1986) with Sp as the simulated peak flow rate and Op as the observed peak flow rate.

$$Simple\ percent\ error\ in\ peak\ (PEP), PEP = \frac{S_p - O_p}{O_p} * 100 \tag{4}$$

After selecting a model and obtaining all the inputs (Table 2), it was time to test its performance and validity to capture the freshwater ecosystem goods and services. I simulated the two top-ranked candidate models, OpenNSPECT and SWAT. The selection of these two models resulted from the model evaluation matrix, including which processes needed to be captured for estimating desired FES, and technical considerations. I ran each model in one watershed on either O‘ahu or Maui to test the validity of the candidate models and prove that the proposed model selection approach works. Study site simulations were to test the model performance given the desired outcome (FES, annual vs. daily streamflow), input data availability (annual vs. daily meteorological data) and needs, temporal resolution, and model complexity. In other words, desired outputs in terms of FES differed, and temporal resolution of FES required different models. In addition, model usage depended upon available input data, which were different for the watersheds. Furthermore, OpenNSPECT have different input data needs than SWAT. Consequently, OpenNSPECT could not produce daily streamflow for the watershed in Maui, and therefore I could not run OpenNSPECT in Maui. On the other hand, SWAT needed daily meteorological data, and it would not run in the O‘ahu watershed because I did not have daily data for the O‘ahu watershed. However, both models satisfied the technical and practical requirements to simulate FES of interest as indicated by the following proof of concept.

### Study Sites

The study sites, Kalihi and Kahakuloa, were chosen for performance testing (Figure 5). These watersheds were selected because they: 1) have streamflow data; 2) are on the windward or leeward side of the island; 3) have a variety of land use/cover, and 4) have no known diversion of streamflow upstream of the USGS stream gauges. Kalihi watershed is on the leeward side of O‘ahu, and Kahakuloa watershed is on the windward side of Maui (Oki *et al.*, 2010). Kalihi watershed has characteristics including annual average rainfall from 990mm to 3060mm (Giambelluca *et al.*, 2013); elevation from 16m to 829m (USGS-NED, 2013); and nineteen land use/covers including cultivated land, forests (evergreen and deciduous), urban, and wetland (NOAA-CCAP, 2011). On the other hand, Kahakuloa watershed has fairly different characteristics: annual average rainfall from 1500mm to 5000mm (Longman *et al.*, 2017); elevation from 105m to 1367m (NOAA-CSC, 2014); and seven land use/cover classes including forests (alien and native), urban, and wetland Pacific RISA, NOAA (Brewington *et al.*, 2016).

Kalihi and Kahakuloa watersheds, selected for performance testing, provide cultural aspect of freshwater ecosystem service by supporting native land use/cover and native species. Both watersheds have native species including ‘Ōpae (*Atyoida bisulcata*), Blackline Hawaiian damselfly (*Megalagrion nigrohamatum nigrolineatum*), Oceanic Hawaiian damselfly (*Megalagrion oceanicum*), Newcomb's Snail (*Erinna newcombi*), ‘O‘opu nākea (*Awaous guamensis*) (Higashi & Lapp, 2008). Accordingly, Kahakuloa stream, supporting natural habitat, was classified as potential heritage stream in 1998.

*Table 2. Model inputs, calibration data and sources for OpenNSPECT and SWAT models.*

| Model Inputs | Source |
|---|---|
| **OpenNSPECT** | |
| **Digital elevation model** | National Elevation Dataset (USGS-NED, 2013) |
| **Soil** | Soil Survey Geographic Database (USDA NRCS, 2014b) |
| **Land cover** | C-CAP 2011 (NOAA-CCAP, 2011) |
| **Rainfall, temperature** | Rainfall Atlas of Hawai‘i (Giambelluca *et al.*, 2013) |
| **Observed streamflow data** | USGS (USGS NWIS, 2016) |
| **SWAT** | |
| **Digital elevation model** | NOAA Coastal Services Center (NOAA-CSC, 2014) |
| **Soil** | Soil Survey Geographic Database (USDA NRCS, 2014b) |
| **Land cover** | Pacific RISA, NOAA (Brewington *et al.*, 2016) |
| **Rainfall, temperature (minimum and maximum)** | Rainfall Atlas of Hawai‘i (Longman *et al.*, 2017) |
| **Relative humidity, solar radiation, wind speed** | IPRC, UH Manoa (Zhang *et al.*, 2016a) |
| **Observed streamflow data** | USGS (USGS NWIS, 2016) |
| **Published actual evapotranspiration** | Evapotranspiration of Hawai‘i, UH Geography (Giambelluca *et al.*, 2014) |
| **Published direct runoff** | USGS (Johnson *et al.*, 2014) |
| **Observed sediment and nutrients** | USGS (USGS NWIS, 2016) |

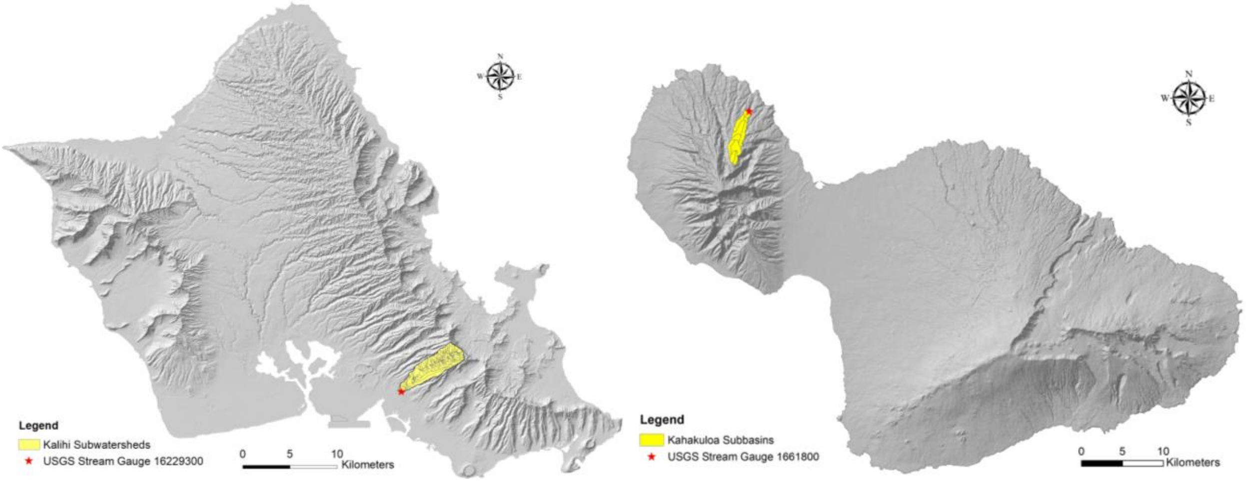

*Figure 5. Case study sites Kalihi, O‘ahu (left) and Kahakuloa, Maui (right) for OpenNSPECT and SWAT models.*

### *Results*

The initial model list (Appendix 1A) contained 90 surface water models and 86 groundwater models. Initial screening rules outlined in Step 1 reduced the initial list to a long list that included 37 surface water (Table 3) and 32 groundwater models (Table 4). All these models have the potential for use in the volcanic islands depending the FES under consideration.

### *Long List*

*Table 3. Long List of Surface Water Models.*

| **Surface Water, Water Quality or Groundwater Recharge** | | **Surface Water or Groundwater Recharge** | | **Urban Watershed** | | **Wetland** | |
|---|---|---|---|---|---|---|---|
| **1** | AnnAGNPS | 12 | GSSHA | 25 | SWMM | 34 | DRAINMOD |
| **2** | SWAT | 13 | INFIL3.0 | 26 | PCSWMM | 35 | SLAMM |
| **3** | OpenNSPECT | 14 | CRT | 27 | XP-SWMM | **Ecosystem Service Modeling Suite** | |
| **4** | KINEROS2 | 15 | HydroTrend | 28 | FLDWAV | 36 | ARIES |
| | STORM | 16 | HSPF | 29 | PRMS | 37 | Envision |
| **6** | WARMF | 17 | PIHM | 30 | HyDroDSS | | |
| **7** | WMS | 18 | Groundwater Toolbox | **Flood Forecasting** | | | |
| **8** | LWWM | 19 | VIC | 31 | NSS | | |
| **9** | MIKE SHE | 20 | tRIBS | 32 | PeakFQ | | |
| **10** | TopoFlow | 21 | HEC-HMS | 33 | WATFLOOD | | |
| **11** | InVEST NDR,<br>InVEST SDR | 22 | CREST | | | | |
| | | 23 | MODHMS | | | | |
| | | 24 | Vflo | | | | |

*Table 4. Long List of Groundwater Models.*

| Flow and Transport | | Flow | | Transport | |
|---|---|---|---|---|---|
| **1** | BIOF&T | 15 | SHARP | 23 | SUTRA |
| **2** | GMS | 16 | FEFLOW | 24 | SEAWAT |
| **3** | MODFLOW and related programs | 17 | MicroFEM | 25 | AT123D |
| **4** | GROUNDWATER VISTAS | 18 | MODFE | 26 | HST3D |
| **5** | HYDRUS2D/3D | 19 | GSFLOW | 27 | Hydrogeochem2 |
| **6** | MOC and MOC3D | 20 | MODFLOW-NWT | 28 | MT3DMS |
| **7** | MOCDENSE | 21 | MODFLOW-OWHM | 29 | PATH3D |
| **8** | MODFLOWT | 22 | SWB | 30 | PESTAN |
| **9** | PhreFlow | | | 31 | BIOMOC |
| **10** | SWIFT | | | 32 | R-UNSAT |
| **11** | SWMS_2D | | | | |
| **12** | VS2DI | | | | |
| **13** | PHAST | | | | |
| **14** | TopoDrive and ParticleFlow | | | | |

*Short List*

Using the 23 criteria to capture FES (Table 1) and as an example for case study simulations in this study, the long list was further reduced into the short list of models including AnnAGNPS, DHSVM, OpenNSPECT, InVEST, SWAT, HSPF, and tRIBS. I created a project-specific short list of models for simulation of streamflow, sediment, and nutrients. Therefore, depending on the modeling requirements, the short list would change for each freshwater ecosystem service, modeler's expertise, and required output resolution under consideration. In other words, another modeler could select a few groundwater models from the long list to estimate the flow and transport of nutrients, and create a short list and an accompanying evaluation matrix (similar to the following one below) to finalize the selection.

*Evaluation Matrix*

Using the criteria set out in Step 2 and the hydrological process analysis in Step 4 now summarized as ecosystem services and output, I developed a model evaluation matrix (Table 5) and applied it to the models on the short list for method illustration.

The matrix indicates model capabilities that are necessary for FES modeling. Hydrological processes and equations (Appendix 1A and Step 4a) are used to determine FES modeling capacity of each model. Freshwater purification via infiltration has to do with model considering percolation through the soil matrix using ecohydrologic functions, processes, and structures. Climate regulation (via carbon sequestration) capacity of a model is signaled by the tree biomass production process. Flood regulation or retention service provision by a model is marked by surface runoff difference from different land uses/covers. Erosion or nutrient regulation or retention service provision by a model is signaled by sediment or nutrient modeling process.

Considering these FES and underlying processes, all models, except InVEST, can simulate surface water efficiently using appropriate water budget component calculations. InVEST uses Budyko curve to calculate ET, which is not suitable for Hawaiʻi. Therefore, I noted surface water output from InVEST as "No."

Simulation in windward or leeward aspects depends on the input and calibration data availability. Windward watersheds might require more detailed input and calibration data (e.g., daily) than leeward watersheds. Regions with insufficient data could still be simulated using a detail-oriented model based on interpolated/extrapolated data but with reduced accuracy in results.

The final decision of compatibility depends on the combination of all the capabilities for each model. VBL for a model means that it is possible to run it in both windward and leeward watersheds, but its performance might vary according to the island because of the differences in physical and ecological properties (i.e., rainfall, slope, vegetation, etc.)

*Table 5. Model evaluation matrix example. H = High, M = Medium, L = Low, Y = Yes, N = No, W = Watershed and/or Subwatershed, HRU = Hydrologic Response Unit, VBL = Varies by Location*

| **Model Capabilities** | **Model** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **AnnAGNPS** | **DHSVM** | **OpenNSPECT** | **InVEST Water Yield** | **SWAT** | **HSPF** | **tRIBS** |
| **Type** | Lump | Grid | Grid | Grid | Lump | Lump | Grid |
| **Linkage to GIS** | Y | Y | Y | Y | Y | Y | Y |
| | | | | **Input** | | | |
| **Data Requirement** | H | H | L | M | M | H | H |
| **Pre-processing Tool** | Y | N | Y | N | Y | Y | N |
| **Pre-processing Difficulty** | H | M | L | L | M | H | M |
| **Level of User Expertise Requirement** | H | H | L | L | H | M | H |
| **Complexity** | H | M | L | L | H | M | H |
| | | | | **Freshwater Ecosystem Services** | | | |
| **Purification via Infiltration** | Y | Y | N | N | Y | Y | Y |
| **Climate Regulation** | N | N | N | N | N | N | N |

| **Model Capabilities** | **Model** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **AnnAGNPS** | **DHSVM** | **OpenNSPECT** | **InVEST Water Yield** | **SWAT** | **HSPF** | **tRIBS** |
| **Flood Regulation** | N | N | N | N | N | N | N |
| **Erosion Regulation** | Y | N | Y | Y | Y | Y | N |
| **Nutrient Retention** | Y | Y | Y | N | Y | Y | Y |
| | | | **Output** | | | | |
| **Surface Water** | Y | Y | Y | N | Y | Y | Y |
| **Groundwater Recharge** | N | N | N | N | N | Y | N |
| **Sediment** | Y | Y | Y | Y | Y | Y | Y |
| **Nutrients** | Y | N | Y | Y | Y | N | N |
| **Land Use Change** | Y | Y | Y | Y | Y | Y | Y |
| **Climate Change** | Y | Y | Y | Y | Y | Y | Y |
| | | | **Scale** | | | | |
| **Spatial** | W | Grid | Grid | W | HRU | W | Grid |
| **Temporal** | D | D, M, Yr | Yr | Yr | D, M, Yr | D, M, Yr | D, M, Yr |
| | | | **Background Support** | | | | |
| **Technical Support** | H | M | H | L | M | M | L |
| **Documentation** | H | H | H | H | H | H | H |
| **Widely Used/Accepted** | M | M | M | L | M | L | L |
| | | | **Windward vs. Leeward** | | | | |
| **Windward Performance** | Y | Y | Y | Y | Y | Y | Y |
| **Leeward Performance** | N | N | Y | Y | N | N | N |
| **Hawai‘i Compatible** | VBL | Y | Y | N | VBL | VBL | VBL |

*Case Study Simulations*

Based on the selection criteria and matrix, I chose two candidate models SWAT and OpenNSPECT for the case study simulations as follows. Although the models were screened systematically using several essential considerations, I believe only actual watershed modeling can confirm the models’ validity.

OpenNSPECT – Distributed Model

OpenNSPECT (Eslinger *et al.*, 2012) was used to simulate FES in Kalihi watershed on O‘ahu (Figure 6). The model used modified TR-55 curve number method for estimating average surface runoff depth. It accounted the average number of raining days per year, giving 36 days with over 1 inch of rainfall. The method computed combined curve number (0.375) by dividing the product of 307 subwatershed areas and corresponding curve numbers with total study area (1357.50 ha). In addition, based on Type I 24-hour synthetic rainfall distribution for Hawai‘i, runoff volume was computed as 5,800,000 $m^3$/year (0.184 $m^3$/s), close to stream gauge data (5,914,175 $m^3$/year or 0.188 $m^3$/s). As a single event model, OpenNSPECT had an acceptable PEP of -1.97 % which was within ±25%. In addition, OpenNSPECT was sensitive to the number of raining days Appendix 1A.

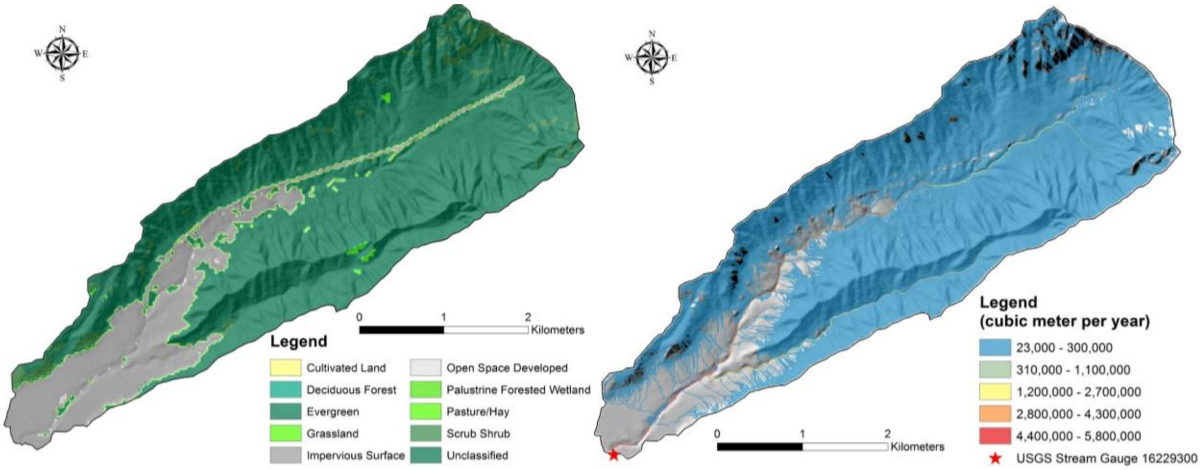

*Figure 6. Case study watershed for OpenNSPECT model in Kalihi, O‘ahu with 2005 land use/cover (left), and water runoff (bottom right).*

SWAT – Semi-Distributed Model

For finer temporal scale, simulation of more water budget components (besides surface runoff), and semi-distributed approach, I ran SWAT model in in Kahakuloa watershed (Figure 7) in Maui. The model was simulated from 1990 to 2009 for annual (and daily) time step at 1km spatial resolution.

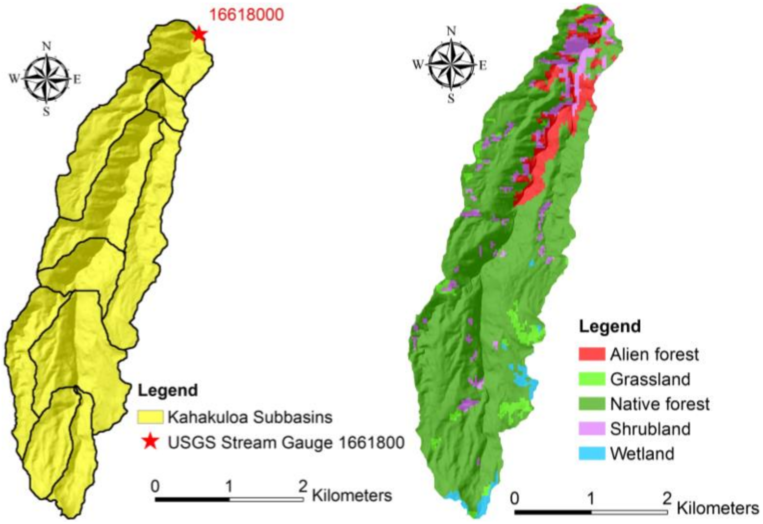

*Figure 7. Case study watershed for SWAT model in Kahakuloa with subbasins (left), and land use/cover (right).*

Daily SWAT model outputs were relatively close to observed values (Figure 8) according to the continuous event modeling statistics. It captured both peak and low flows with $R^2$ higher than 0.8, and RSR was less than 25% for most years. In addition, the model performed well with long-term annual average water budget components compared against observed data (Table 6). All the water budget components were within 10% of the observed values, mainly from 2000 to 2009. Both calibration and validation simulations had $R^2$ greater than 0.8, NSE greater than 0.5, and RSR was less than 25%.

For sensitivity analysis, SWAT model outputs were first divided into two sets (i.e., ten years each) for calibration and validation. Then, using statistics explained in Step 5, I compared annual average values (Table 6) in the Kahalua watershed. Both calibration and validation had good statistics, including NSE, PBIAS, and RSR. The results from the validation are also illustrated using daily streamflow and 95% uncertainty bands around it (Figure 8). On the other hand, sensitive parameters for the SWAT model were given in Appendix 1A.

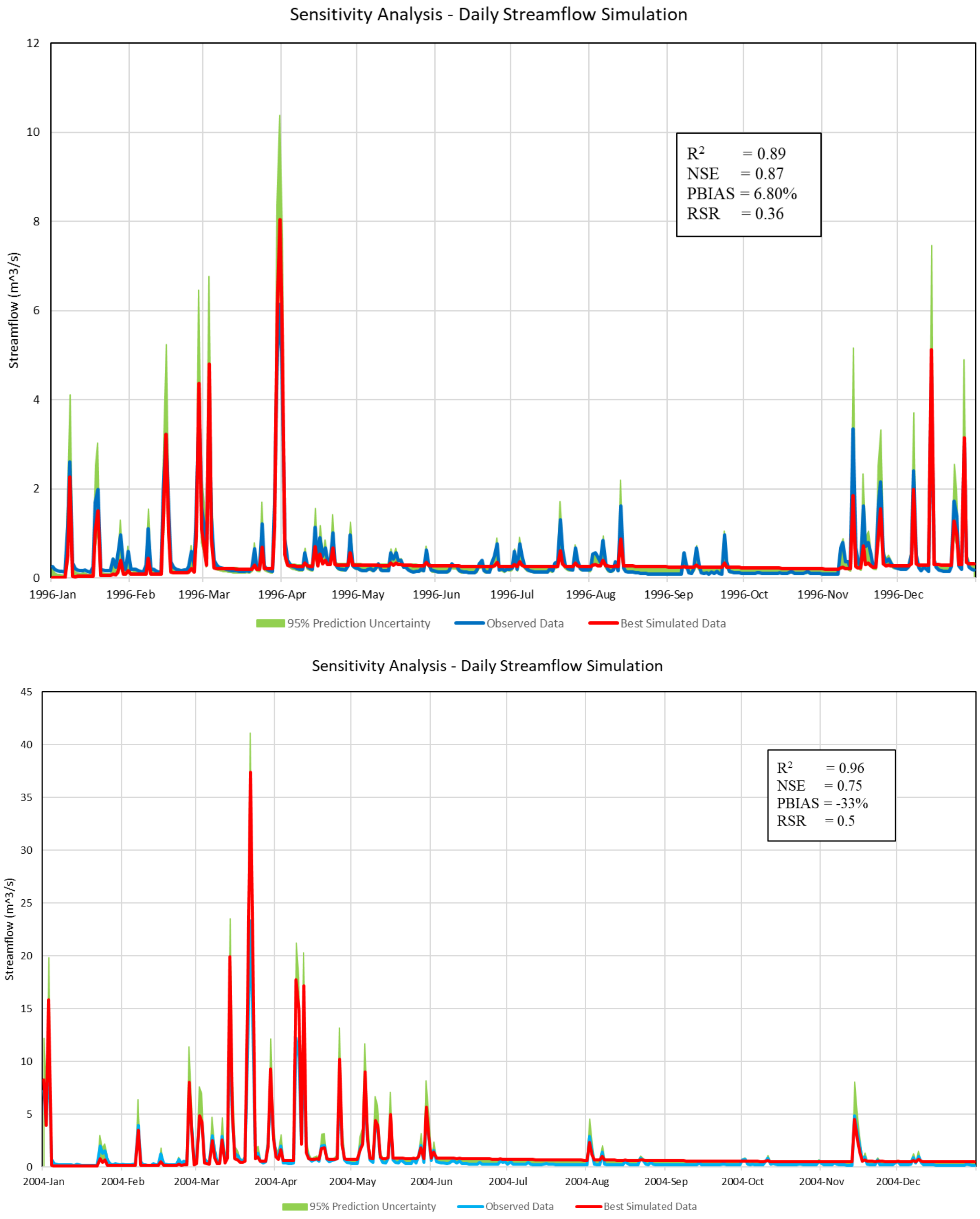

*Figure 8. SWAT model simulation results at daily streamflow comparison for calibration year 1994 (top) and validation year 2004 (bottom) with panels showing continuous event modeling statistics: $R^2$, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR).*

*Table 6. SWAT model output for annual water budget components used for calibration and validation.*

| | Calibration (1990-1999) | Validation (2000-2009) |
|---|---|---|
| **Surface Runoff (%)** | 92.97 | 108.45 |
| **Streamflow (%)** | 93.3 | 100.41 |
| **Evapotranspiration (%)** | 96.5 | 92.38 |
| **$R^2$** | 0.81 | 0.97 |
| **Nash-Sutcliffe efficiency (NSE)** | 0.52 | 0.72 |
| **Percent Bias (PBIAS)** | 6.7 | -0.41 |
| **RSR** | 0.69 | 0.53 |

Satisfactory performance at different temporal steps (annual for OpenNSPECT and daily for SWAT) proved the validity of the two candidate models. Water resources simulations for Kalihi and Kahakuloa watersheds could provide information to determine water needs of native land use/cover and native species, supporting provisional and cultural ecosystem services. SWAT model was applicable at daily time step for management of these freshwater ecosystem services.

In Kalihi and Kahakuloa watersheds, water quantity and its changes under future environmental and human impacts can be properly quantified using OpenNSPECT and SWAT. Modeling results could inform if there was sufficient freshwater resources to support cultural FES by preserving native native species including ‘Ōpae (*Atyoida bisulcata*), Blackline Hawaiian damselfly (*Megalagrion nigrohamatum nigrolineatum*), Oceanic Hawaiian damselfly (*Megalagrion oceanicum*), Newcomb's Snail (*Erinna newcombi*), ‘O‘opu nākea (*Awaous guamensis*) (Higashi & Lapp, 2008). Additional ecological assessment is necessary. However, managers could use this information to make decisions to justify usage and allocation of financial and labor resources for preservation of streamflow in the study watersheds.

### *Discussion*

This study set out to answer three questions: First, what processes underpin freshwater ecosystem services? Second, what are the minimum characteristics of a Hawai‘i-compatible ecosystem service model? Third, what models are appropriate for what freshwater ecosystem services management decisions? I address each of these in turn below.

When planning to manage water resources using an ecosystem services-based modeling approach, managers should start with identifying the freshwater ecosystem services of concern and the management application requirements. The choice of the right hydrological model depends on underlying hydrological processes that result in an FES. For example, evapotranspiration, overland flow, subsurface flow, and groundwater discharge are necessary for estimating provisioning ecosystem services, while routing runoff including streamflow velocity and the water surface profile is essential for estimating regulating ecosystem service such as flood control. The processes that underpin provisioning and regulating ecosystem services also affect cultural FES, such as spiritual contemplation (Brauman *et al.*, 2007). Different models do better than others at incorporating these processes.

Approximating evapotranspiration in volcanic islands is fundamental for hydrological and ecological modeling and assessment of water resources, and their response to climate and land cover changes in Hawaiʻi (Giambelluca *et al.*, 2014). The Penman-Monteith function is the most reliable approach because it accounts for thermodynamic, aerodynamic and biological processes (Bonan, 2008). Next, overland flow has effects on freshwater availability, sediment and nutrient retention, and flood regulation. SCS curve number method is appropriate for determining overland flow in most of the hydrological modeling in Hawaiʻi, except irrigation-specific application. While SCS curve number method is the underlying function, spatial configuration and water budget accounting differ. For instance, AnnAGNPS uses subwatersheds while SWAT runs on hydrologic response units that are spatial segments with homogeneous slope, soil, and land use or land cover. Further, the conservation zone of volcanic islands has subsurface flow because of steep hillslopes and highly permeable soils. Subsurface flow is best estimated using Kinematic wave storage-discharge equation (Sloan & Moore, 1984), as in WEPP and SWAT models by USDA. Subsurface flow is particularly necessary for recharging streams and spring formation essential for native aquatic species habitat and cultural FES. The return of springs and native species in East Maui in recent years is a prime example of subsurface flow and its impact on cultural FES. Quantification of subsurface flow is also required for supporting FES such as nutrient cycling and soil formation (Capon & Bunn, 2015). Also, modeling of streamflow (i.e., a combination of overland flow, subsurface flow and groundwater discharge) is required for understanding the water availability and quality for riparian vegetation and aesthetic beauty landscapes as cultural FES.

Besides the hydrological processes, the minimum characteristics of a Hawaiʻi-compatible model include diverse biophysical and technical capabilities (Table 1) that can be evaluated using an evaluation matrix like similar to the one in this study (Table 5). The criteria reinforce the fact that ecosystem service consideration is an essential factor for choosing an appropriate model to evaluate a management practice. In addition, the model capabilities in the example evaluation matrix are necessary for FES modeling.

Minimum characteristics of a model for a Hawaiian watershed are data availability, model outputs directly or indirectly representing FES under consideration, scientifically defensible and locally appropriate hydrological functions, mixed land use modeling, and the support for diverse soil, slope and climate. Data availability in a windward against a leeward watershed is an important characteristic for model selection. Windward watersheds might require more detailed input and calibration data (e.g., daily) than leeward watersheds. Watersheds with insufficient data could still be simulated using a detail-oriented model based on interpolated/extrapolated data but with reduced accuracy in outputs. On the other hand, models similar to, for example, OpenNSPECT could not be simulated for daily streamflow because the model structure is not designed to accept meteorological data with more than one time step. Further, model outputs and their hydrologic attributes (i.e., quantity, quality, timing, and duration) must represent FES of interest directly or indirectly in Hawaiʻi and other montane tropical islands. For example, the quantity, timing, and duration of streamflow from a hydrological model inform if there is adequate freshwater for provisioning FES such as irrigation or excess runoff indicating a flood. The hydrologic attributes must have scientifically defensible functions describing the hydrological processes (Step 4a) because they determine the FES modeling capacity of each model. In addition, all the processes and underlying functions of a compatible model must apply to the Hawaiian landscape to simulate surface or groundwater efficiently using appropriate water budget component calculations. For example, InVEST uses the Budyko curve to calculate ET, a method that is not suitable for Hawaiʻi. In addition to basic water budget components, an ideal model for Hawaiʻi should support mixed land use modeling and allow easy alteration of related parameters because Hawaiian landscapes usually have diverse and unique land uses and land covers. Finally, an ecosystem-service model should accommodate diverse soil, slope, and climate in Hawaiʻi because correct representation of the watershed is necessary for the correct simulation of the FES. Attentions to the spatial and temporal scales of these physical properties are essential for selecting an appropriate model.

Considering hydrological processes and minimum characteristics for FES management decisions, water resources manager can choose the appropriate models using the long list of models (37 for surface water and 32 for groundwater) subdivided into broad management categories. The details of these models were given in the appendix (Table 1A - 2 to Table 1A - 11) to aid the model selection for FES management decisions.

Surface water models provide information on fresh water, and groundwater recharge quantities, while their accompanying water quality processes inform water purification, erosion regulation, and pollutant retention qualities. Managers could choose surface water models (Table 1A - 2, Table 1A - 3, and Table 1A - 4) to understand the freshwater availability as provision FES and pollutant retention as regulating FES under different land use and climate change scenarios. Previously, water-budget models were applied in Pearl Harbor (Giambelluca *et al.*, 1996) and Maui (Johnson *et al.*, 2014) for understanding trends in freshwater availability as changes in provisioning FES. Also, AnnAGNPS was used to understand erosion regulation of different land covers, soils and slopes in Hanalei watershed in Kauai (Polyakov *et al.*, 2007). Further, flood-forecasting models (Table 1A - 5) inform flood protection service, while wetland models (Table 1A - 5) describe flood protection and pollutant retention. For example, NSS and PeakFQ from USGS (United States Geological Survey) are possible models for predicting flood, while DRAINMOD is for wetland. NSS is a stochastic model for currently ungauged streams using regional regression equations (Ries, 2007), and it can be used for leeward watersheds of the islands for emergency planning. Finally, ecosystem service modeling suites such as ARIES and Envision (Table 1A - 7) can provide general information on the different freshwater ecosystem goods and services.

Groundwater models (Table 4) inform managers regarding groundwater quantity, quality and timing. Decision-makers can choose appropriate models based on their capabilities (Table 1A - 9 to Table 1A - 11) and processes (Appendix 1A). To determine groundwater quantity under environmental changes, managers can use flow as well as flow and transport models (Table 1A - 9 and Table 1A - 10). Groundwater estimates around the state of Hawaiʻi included: recharge using water-budget model in Maui (Johnson *et al.*, 2014); and irrigation, drought and withdrawal on groundwater levels using SHARP in Lihue, Kauai (Izuka *et al.*, 2005). For groundwater quality, transport as well as flow and transport models (Table 1A - 9 and Table 1A - 11) are useful. For instance, Izuka (2011) used MODFLOW, MT3DMS, and SEAWAT to study the flow and transport of contaminated roadside runoff via dry wells affecting groundwater quality. In addition, flow and transport models (for example, GMS package) can predict the effect of pollutants such as wastewater injection on the groundwater table and the nearshore marine environment. Transport models, for instance, PATH3D, can be used to delineate groundwater recharge capture zone, and wellhead protection zone (Zheng, 1992).

The criteria, evaluation matrix and final simulation (as done in the case study) revealed relative strengths, weaknesses, and uncertainties of the models. These efforts also revealed trade-offs between models (discussed in more detail below). The strength of a model can be because of its type such as lump, grid (aka distributed) or a hybrid such as semi-distributed. For instance, as a semi-distributed model based on subwatersheds and HRUs, the strength of SWAT is to quantify FES with more details than a lump model such as AnnAGNPS. However, detailed modeling can be a model weakness when there is lack of detailed data. For example, SWAT requires detailed spatial data and parameters to define a complex landscape. On the other hand, a simple model such as OpenNSPECT is relatively easy to use and requires fewer parameters. In addition, some model uncertainty can arise from model inputs, underlying processes, and parameterizations (Cornell *et al.*, 2012). For instance, InVEST water yield model does not have an appropriate underlying process for representing evapotranspiration in Hawaiʻi, and it would produce large uncertainty in model outputs. Therefore, managers need to understand all the advantages and disadvantages of a model to make good decisions under local hydrogeological and ecological conditions.

Besides the model qualities above, there are some other model features, such as extra modules for planning and model price. Some hydrological models have additional modules for planning and informing stakeholders. For example, WARMF has a module called *Consensus* to obtain various stakeholder positions on water quality issues, as well as communicate information for understanding the watershed and its response to management actions (Goldstein, 2001). Further, the cost of software might be an issue with using the models. However, as reported in Appendix 1A, there are many reputable models that are free of charge. In fact, many commercial products have the same core process modules as the free ones, but with a better user-friendly interface, and possibly an additional post-processor. For example, MODFLOW developed by USGS is the core module for a commercial package, GMS.

Unlike other model reviews, this study highlights the role of nature underlying hydrological processes to produce FES. US EPA had several model reviews for TMDL development, but they were for predicting pollutants for water quality planning (USEPA, 1997). Further, an evaluation of tools in San Pedro watershed in Arizona quantified and valued ecosystem services for the decision-making process. However, it used ecosystem service suites, not hydrological models suitable for thorough investigation of water budget components in a spatially and temporally variable landscape of a volcanic island (Bagstad *et al.*, 2013). In Hawaiʻi, a model review was done in 2008 for the Waikele watershed (PBA & NHC, 2008), but it did not focus on FES. Since then, there have been many advances in model development, and the Waikele report did not account for various land covers or microclimates present across Hawaiʻi. In addition, previous modeling efforts in Hawaiʻi favored the water needs for the human (Izuka, 2011; Polyakov *et al.*, 2007). This study, by contrast, emphasizes the water needs of nature. It considers freshwater resources as ecosystem services for environmental sustainability.

Finally, other island systems in the Pacific, such as Samoa, Fiji, and Nauru, could benefit from using my research approach. Similar to Hawaiʻi, these nations have competitive freshwater uses (SOPAC, 2007a, 2007b), and sources of freshwater source pollution such as sedimentation, salinization, solid waste disposal and over-pumping (SOPAC, 2007b). All three island nations are developing countries (Burns, 2002), and are expected to experience severe climate change impacts (Burns, 2001) on freshwater quality and availability (Keener *et al.*, 2012), and therefore need integrated water resources planning.

### *Trade-offs and Limitations of Different Models*

Selection of certain hydrological models over others has trade-offs. While simple models, for example, OpenNSPECT, does not require much data, they cannot provide model results with fine spatial and temporal outputs. On the other hand, the SWAT model can provide detailed information required for specific management application, but it has high data requirement and expertise.

In terms of hydrological processes, both OpenNSPECT and SWAT use the curve number method for calculating surface runoff. It is widely used for design purposes, but it does have some limitations. Curve numbers describe common conditions, and therefore simulates extreme storm events poorly. The method does not account for rainfall duration or intensity, and its accuracy reduces when runoff depth is less than 12.7 mm (Cronshey, 1986). Accordingly, OpenNSPECT modifies the method and reduces annual runoff depth by accounting the average number of raining days per year. On the other hand, the SWAT model uses a modified approach to minimize high surface runoff by considering plant evapotranspiration in the procedure. It is particularly useful for leeward Hawaiian watersheds with less land cover.

Regarding FES evaluation, while provisioning and regulating FES can be quantified via hydrological modeling, intangible supporting and cultural FES can be measured indirectly using additional means. However, these models are out of scope for this study. For example, nutrient cycling (a supporting FES) is due to the presence and activity of microorganisms or metazoa (Griebler & Avramov, 2014). Accordingly, an ecological model that defines the microbial activity would be necessary besides the hydrological model to post-process the resulting FES. Further, aesthetic appreciation and native species diversity (cultural FES) would require Hedonic models and choice modeling (Crossman *et al.*, 2015) besides a hydrological model.

For future studies, it would be beneficial to see how well a groundwater model performs in conjunction with surface water model from the suggested list. Coupled surface water and groundwater models would give better insights into the submarine groundwater discharges that largely affect nearshore marine water quality in some Hawaiian watersheds.

### ***Conclusion***

Freshwater resources management should rely on eco-hydrological modeling that explicitly recognizes the role of natural ecosystems to benefit human well-being. Accordingly, decision-makers could draw upon transformation of biophysical outputs (from hydrological simulation) to ecosystem goods and services for management applications (Guswa *et al.*, 2014).

This study systematically screened existing hydrological models to derive a list of models compatible with Hawai‘i and its unique and complex hydrogeological and ecological conditions. Which model to use to estimate FES depended primarily on the ecosystem service under consideration, namely how well the model captures the underpinning biophysical processes that are known to be important for FES generation. Other key criteria, including complexity, ease of use, and input data availability were also determined to be crucial for selection of the most appropriate model. The resulting long list of models can be used for similar island systems, and the same screening method can be readily applied to other systems. The study demonstrated the use of an evaluation matrix to select the most appropriate model for a specific ecosystem service and context; this process, too, can be extended to other sites.

## Study 2 - Predicting Local Scale Climate Change Impacts on Endangered Birds by combining Watershed Models with Expert Knowledge-based Modeling

### *Abstract*

Climate change is expected to have significant impacts on native, threatened and endangered wildlife. Understanding and modeling these impacts useful for wildlife managers, however, remain difficult due to complex climate change, and costly and high data requirements. Consequently, we proposed an easily-interpretable and data-efficient decision support approach to understand climate change impacts on the abundance of three endangered wetland birds (Hawaiian Stilt, Hawaiian Coot and Hawaiian Moorhen). We coupled a watershed model, AnnAGNPS, and ecological models using fuzzy-cognitive mapping software, Mental Modeler, in Hanalei watershed, Kauaʻi. Results suggested that increased precipitation would increase Stilt abundance, but decrease Coot and Moorhen abundance. Decreasing precipitation might have negative effects for all three species. Moreover, decision-makers should pay equal attention to controlling components (water depth, food availability and disease) with system-wide influence. Finally, besides being adaptable to similar environmental contexts, our approach captured both direct and indirect climate change impacts through ecological connectivity.

### *Problem Statement and Significance*

Current modeling frameworks lack efficient knowledge transfer between scientific communities and decision makers. Understanding and modeling climate change impacts in a manner that is useful for decision-makers remains difficult because many empirical modeling frameworks require large amounts of long-term data that can be costly to collect.

Climate change is expected to have significant impacts on native, threatened and endangered bird species, particularly in terms of habitat alteration in Kauaʻi National Wildlife Complex. Resource managers' need to adapt to local ecological change depends on transparent and tractable modeling framework. Therefore, it is essential to develop a fast and easy decision framework that will provide wildlife managers with a low cost approximate understanding of the dynamic interaction of climate change, habitat and wildlife ecology based on pooling available expert knowledge and existing data about watershed projections.

### *Background*

Though climate change will impact all ecosystems, it is of particular concern to oceanic islands. Specifically, climate change and its large scale effects on environmental factors (temperature, rainfall, sea level) and associated extreme events are likely to bring about localized changes in agricultural systems, infrastructure, water resources, human health, and economy in island nations, such as those of the Pacific Ocean (Barnett, 2005; Carter *et al.,* 2001; Easterling *et al.,* 2007). However, local scale ecological dynamic changes brought about by climate change are poorly understood (Denman *et al.*, 2007; Friedlingstein *et al.*, 2006; Sitch *et al.*, 2008), though some general trends have recently emerged (Rosenzweig *et al.*, 2007). For example, decreasing trends in precipitation and stream base flow (Chu *et al.*, 2010; Oki, 2004) may impact freshwater ecosystems and aquatic species (Oki, 2004). Decrease in stream flow (Bassiouni & Oki, 2012; Oki, 2004) may also interrupt movement of native species along streams, and prevent their return after spending the larval stage in the ocean, thus disrupting their life cycle (Keener *et al.*, 2012). Trends in available habitat for native species conditions decreases rapidly with elevation, putting species currently found on high elevations especially at risk (Eiben & Rubinoff, 2010; Keener *et al.*, 2012).

Although ecologists are beginning to synthesize the cumulative impacts of climate change to island ecosystems (Price *et al.*, 2009), information about how natural resource managers can mitigate these impacts is generally unavailable. Understanding local scale dynamics and climate change impacts in terms relevant to management priorities is therefore key if communities are expected to learn about, and collectively adapt to, undesired outcomes (Pahl-Wastl & Hare, 2004).

One approach to aid in understanding local scale dynamics is integrating expert based knowledge into the construction of ecological models (Griffiths *et al.*, 2007; Mac Nally, 2007; O'Leary *et al.*, 2009; O’Neill *et al.*, 2008). The value of using expert knowledge in model construction is that experts can help fill the gaps in many complex environmental modeling and decision-making contexts due to insufficient empirical data and highly variable predictions (Kuhnert *et al.*, 2010). Additionally, management decisions may be time sensitive, and institutions may not be able to afford to collect data for robust models. Indeed, recent studies have indicated that expert knowledge can increase the precision of formal data-driven models and facilitate informed decision-making in a cost-effective manner (Kuhnert *et al.*, 2010). Two main modeling methods that bolster traditional forms of ecological models through expert knowledge include Bayesian approaches (Marcot *et al.*, 2006) and Fuzzy-Cognitive Mapping (FCM) approaches (Adriaenssens *et al.*, 2004).

Bayesian approaches have been used to elicit expert knowledge in a range of contexts (Crome *et al.*, 1996; Denham & Mengersen, 2007; James *et al.*, 2010), and incorporated into ecological models. Bayesian ecological models include 1) key components affecting or influencing an ecological aspect, and 2) unidirectional conditional dependencies linking the components. Experts, professional scientists and/or local stakeholder (Zorrilla *et al.*, 2010), describe relevant components probabilistically related to one another based on observed data or personally-held knowledge. Such Bayesian approaches have been applied to resolve wetland degradation conflicts between stakeholders (Zorrilla *et al.*, 2010), and to determine the habitat suitability of the threatened Australian brush-tailed rock-wallaby (*Petrogale penicillata*) (O'Leary *et al.*, 2009).

Similarly, FCM approaches have also recently been employed as a way to conceptually define network relationships found in a range of ecosystem contexts characterized by high degrees of complexity with poorly understood causal linkages (Gray & Zanre, 2013). Although FCM has been applied in many social and natural science disciplines, more recently it has been applied to understanding behavior and trajectory of ecosystems scenario modeling (Ozesmi & Ozesmi, 2004). The FCM approach is typically used in individual or group settings with experts where the structure of a system is defined in terms of (1) the variables that comprise the system, (2) the causal bi-directional, including feedback, relationships between those variables, and (3) the perceived degree of influence that one variable has on another, either positively or negatively (Kosko, 1987). Contrary to Bayesian approaches, FCMs allow feedback relationships, enabling any additional variable to influence existing components (Jetter & Kok, 2014).

Given their flexibility, FCMs are useful for accounting for human impacts on ecosystems; describing instances where detailed scientific data are lacking and uncertain, but there is local expert knowledge regarding the human-nature interaction (Nyaki *et al.*, 2014). Other benefits include environmental risk assessments analyzing problems and finding solutions via comparing and contrasting knowledge and perceptions of experts from the same discipline as well as different disciplines. After construction, FCMs can be used to simulate varying system states under different policy options, or environmental or social change scenarios. In addition, FCMs have been used to promote public involvement in policy making by informing the public different management options, and enabling a community support for management decisions (Ozesmi & Ozesmi, 2004). Similar to Bayesian models, FCMs enable inclusion of cross-sectoral stakeholder expertise because knowledge of local-scale processes is especially useful for modeling building and decision-making (Henly-Shepard *et al.*, 2015). In recent years FCMs have been used to inform management actions for the Lake Erie ecosystem (Hobbs *et al.*, 2002), to understand motivation for bush meat hunting in Tanzania (Nyaki *et al.*, 2014), to understand the relationship between soil quality and farming dynamics (Halbrendt *et al.*, 2014), and to understand fisheries as a social-ecological system (Gray *et al.*, 2012).

### *Objective*

Given the need to interpret biophysical outputs in terms of an ecological impact (i.e., change in endangered bird species population), my overarching goal is to develop a modeling approach that couples biophysical models, and expert knowledge. My objective is to calibrate a watershed model and couple it with ecological aspects of wetland bird habitat using a FCM approach to facilitate management.

### *Research Questions*

I addressed three questions focused on the management of three endangered birds on the Hawaiian Island of Kauaʻi. First, what are the relationships between locally managed wildlife species, their life history characteristics and their local habitat? Next, how do these local physical and ecological systems interact and impact these managed species under different climate change scenarios? Finally, what are the strengths and weaknesses of this enable modeling approach for local wildlife management?

### ***Rationale***

Local scale ecological impacts of global climate change are highly uncertain (Denman *et al.*, 2007; Friedlingstein *et al.*, 2006; Visser *et al.*, 2000), in part due to the difficulties in down-scaling and coupling complex global processes with complex local processes (Denman *et al.*, 2007; Sitch *et al.*, 2008). As a result, current modeling approaches that make climate change scenarios relevant at the local ecological scale management priorities remain elusive. One approach to aid in understanding local scale dynamics is integrating expert based knowledge into the construction of ecological models (Griffiths *et al.*, 2007; Mac Nally, 2007; O'Leary *et al.*, 2009; O'Neill *et al.*, 2008) through FCM (Adriaenssens *et al.*, 2004). Combining empirical and expert-based conceptual models in a FCM framework allows managers to understand the local ecological impacts due to global climate change, making it relevant to the management scale. Additionally, this framework can be easily employed by wildlife managers to understand the impacts of climate change on different types of species across different ecological conditions.

### ***Methods***

To answer my research questions and test my modeling framework, I evaluated how climate change affects the habitat, life history stages, and abundance of three federally-listed endangered wetland birds: Hawaiian Stilt or Aeʻo (*Himantopus mexicanus knudseni*), Hawaiian Coot or ʻAlae keʻokeʻo (*Fulica alai*), and Hawaiian Moorhen or ʻAlae ʻUla (*Gallinula galeata sandvicensis*). These species represented three of the four managed species in a federally managed wetland in the Pacific Islands (USFW, 2011). Furthermore, the managed wetland represented a complex habitat type that is reliant on highly variable hydrological regimes. Models focused on the Hanalei watershed on the island of Kauaʻi, which houses one of the largest wetlands and National Wildlife Refuges for endangered Hawaiian wetland birds in the archipelago (Figure 9). Hanalei encompasses an area of 54.4 km$^2$ and extends from the peak of Mount Waiʻaleʻale at 1,570 m to sea level at Hanalei Bay (Polyakov *et al.*, 2007).

#### *Modeling Framework*

The modeling framework (see Figure 4) included integrating two models in a five-stage process: (1) defining climate change scenarios; (2) modeling watershed changes under climate change scenarios using a watershed model AnnAGNPS (Annualized Agriculture Non-Point Source); (3) describing relationships between watershed dynamics and bird habitat using FCM; (4) developing model scenarios by integrating the two models; and (5) using scenario results to discuss adaptation and management strategies. Using the framework, I built a Fuzzy Cognitive Mapping model (FCMM) for each of the three wetland birds (Hawaiian Stilt, Coot and Moorhen) in Kauaʻi, and estimated culturally important ecological benefit from their existence.

#### Step1: Climate Change Scenarios

To define climate change reference scenarios, I used data from the IPCC report on Emission Scenarios (IPCC SRES, 2001) including different $CO_2$ emission rates and their effect on temperature and precipitation changes for the next 100 years. The dataset involved four $CO_2$ emission rate: 330 ppm (2003-04 rate), 550 ppm, 710 ppm and 970 ppm, as well as precipitation changes (±5%, ±10% and ±20%) specific to the Hawaiian Islands based on previous work (Safeeq & Fares, 2011). In addition, the model scenarios were based on the IPCC's extreme temperature values of the "likely" range (1.1° C and 6.4° C). Safeeq and Fares (2011) previously developed 24 scenarios in Pacific Islands using these three components ($CO_2$ emission rates, temperature, and precipitation variations). However, only six (extreme and intermediate scenarios) (Table 7) of the 24 climate change scenarios were selected for this study: to reduce the complexity of all possible scenarios and represent the most climate change variations, as well as to limit the scope of the study and focus on the usage of the model coupling framework rather than on the climate change scenarios.

*Table 7. Selected extreme and intermediate IPCC climate change scenarios used in this study representing the most climate change variation.*

| **Scenarios** | **$CO_2$ Emission (ppm)** | **Temperature (°C)** | **Precipitation (%)** |
|---|---|---|---|
| **Reference** | 330 | - | - |
| **Scenario 1** | 330 | 1.1 | 0 |
| **Scenario 2** | 330 | 6.4 | 0 |
| **Scenario 3** | 330 | 0 | -20 |
| **Scenario 4** | 330 | 0 | 20 |
| **Scenario 5** | 970 | 6.4 | -20 |
| **Scenario 6** | 710 | 0 | -5.3 |

Step 2: Watershed Model – AnnAGNPS

I used empirical data for the Hanalei watershed (see Figure 9) as model input for AnnAGNPS including a digital elevation model, soil, rainfall, annual isohyets, land cover, temperature, sky cover, wind speed/direction, and evapotranspiration calculated using FAO method (Table 8). These data were organized as input files for AnnAGNPS simulation.

*Table 8. AnnAGNPS model inputs and sources.*

| **Model Inputs** | **Source** |
|---|---|
| **Digital elevation model** | USGS |
| **Soil** | Soil Data Mart, NRCS, USDA |
| **Rainfall** | NCDC (NOAA), NREM (UHM), USGS |
| **Annual rainfall isohyets** | Rainfall Atlas of Hawai'i |
| **Land cover** | NOAA, USGS |
| **Temperature, wind speed/direction, sky (cloud) cover** | NWS (NOAA) |
| **Evapotranspiration** | Calculated using FAO Method |

AnnAGNPS is a continuous simulation watershed-scale program developed by USDA ARS (United States Department of Agriculture, Agriculture Research Service) and NRCS (Natural

Resources Conservation Service). This watershed model can be used to evaluate non-point source pollution from agricultural watersheds (see Appendix 2A) in terms of erosion, fertilizer, pesticide, and irrigation application rates, point source loads and wetland management over time within the watershed (USDA NRCS, 2014a).

AnnAGNPS simulated transport of sediment and nutrients from primary sources of pollutants: feral ungulates and alien plants that increase erosion in high elevations, cesspools and septic systems in urban areas, taro ponds, water bird impoundments, and cattle grazing (HCZMP, 1996; Orazio, 2001; Polyakov *et al.*, 2007; WMPHBW, 2012).

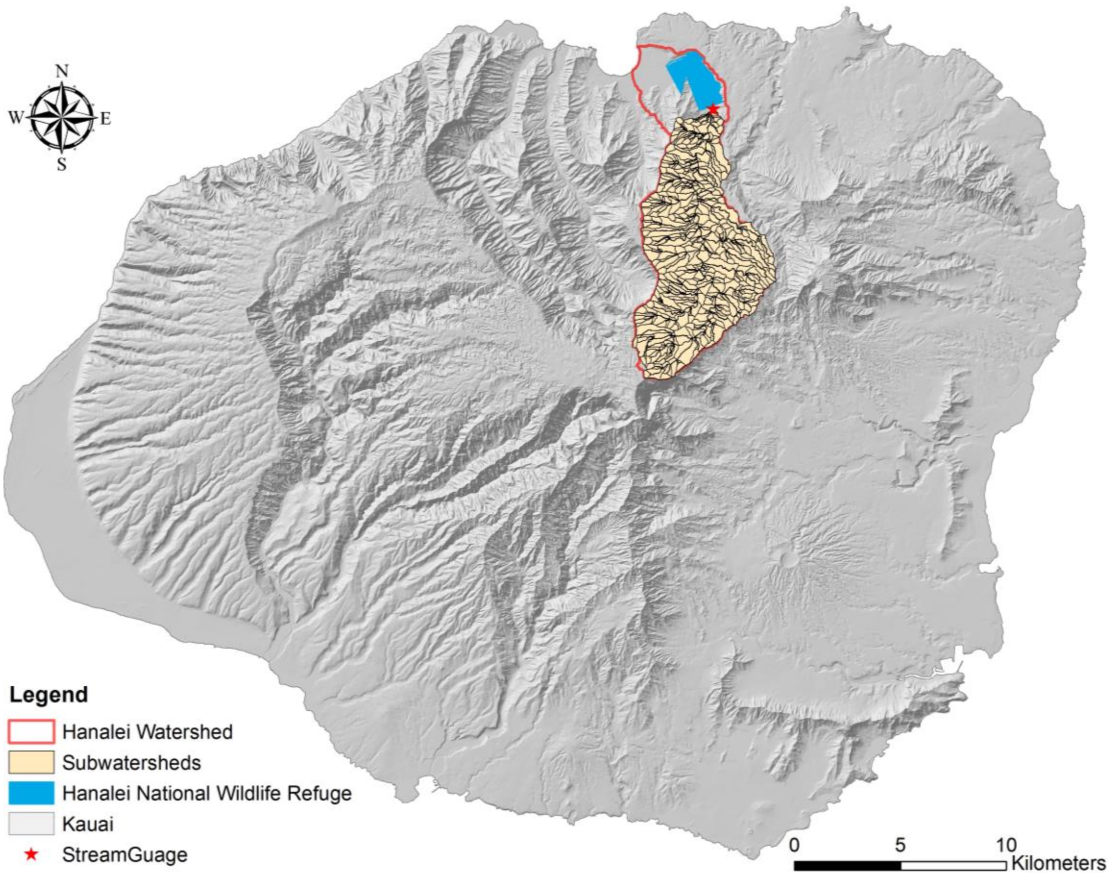

*Figure 9. Study site - Hanalei Watershed, Kauaʻi, Hawaiʻi.*

### Step 3: Watershed Change Impacts on Bird Habitat and Population

To develop ecological models based on the knowledge of local scientific experts and couple it with the climate and watershed model output, I used a FCM program called Mental Modeler (see www.mentalmodeler.org; (Gray & Zanre, 2013). First, I held a participatory modeling workshop with four local ecologists who are experts in the three bird species to construct the conceptual expert models, followed by two individual meetings with scientific experts to refine the models. One FCMM were developed for each of the three species that defined relationships between life-history with habitat variables, watershed model variables, and predator/prey interactions (Table

9). As a reference for model building, the workshop utilized relevant local wildlife management technical reports (e.g., Wetland Habitat Treatment Techniques used at Hanalei and Huleʻia National Wildlife Refuges).

*Table 9. Fuzzy Cognitive Mapping model inputs and sources.*

| Model Inputs | Source |
|---|---|
| **Life History** | Kauaʻi National Wildlife Management Guidelines, Literature Research |
| **Watershed components** | AnnAGNPS Outputs |
| **Predator/Prey** | Literature Research, Local Expert Interviews |
| **Remaining habitat components** | Literature Research, Local Expert Interviews |

Constructing an FCM within the Mental Modeler software was carried out in three steps using an approach based on Ozesmi & Ozesmi (2004). First, I defined the important system components relevant to an individual or community based on interviews of individuals and group containing local experts with experience in that particular system. In this context, these components included aspects of the ecological system related to the habitat and the outputs of the watershed model, aspects of the ecological system that were important to wildlife managers based on technical documents, and other aspects that were identified by experts as important to the birds' life-history stages. Ecological system components within FCMs were physical or environmental factors that comprised the system. In the second and third steps, I identified relationships between system components in terms of directionality of the relationship and type of relationship (i.e., positive or negative) as well as strength of relationship. Relationship directionality, a causal influence of one component on another component, was represented in the FCM as an arrow. The relationship arrows were either uni- or bi-directional. For the third step, the strength of the relationship between components may be classified qualitatively as High, Medium, or Low, defined either positively or negatively, and translated into values parametrized between +1 and -1 inclusive. Positive directional effects indicated that the component with relationship arrow origin increased the other component when activated through scenario analysis. Conversely negative relationships indicated the component with relationship arrow origin decreased the other component. Using this approach, components in the model were defined using six basic ecologically relevant categories including a) Life history requirements; b) Watershed dynamics; c) Predator/Prey relationships; g) Avian disease (i.e. botulism); h) Invasive species; and, i) Habitat.

Life history requirements

During the expert workshops, I used United States Fish and Wildlife Service (USFWS) management documents to frame the modeling activity to increase the relevance of the outputs in terms used by local refuge managers. The three wetland birds were modeled according to their life history components: breeding/nesting success, foraging success, and parenting success (USFW, 2011). These components were found to be crucial for the abundance of study wetland birds. Managers protected water sources and managed water levels to maximize nesting success, brood survival, food availability, and recruitment of wetland birds. In addition, they controlled human and predator access to wetland bird habitats during the breeding season. In my analysis, all the other components in the expert-based model were linked to these the life history components directly or indirectly.

### Watershed Dynamics

Modeled watershed components that had an impact on the vital rates of the wetland birds included temperature, precipitation, stream flow, and contaminants (nitrogen (N), phosphorus (P), organic carbon (OC)). Different climate change scenarios based on IPCC projections were translated into varying quantities of these watershed components simulated by AnnAGNPS. Quantitative watershed components were transformed into semi-quantitative FCMM components, covered later in more detail in the FCMM scenarios section using fuzzy-set theory to parameterize the watershed model output in a way that was appropriate for FCMM input. In addition, water availability component represented available water required to maintain wetland habitat needs, and above/below optimal water depth component represented adverse water levels. Moreover, direct impact from N, P, OC and sediment characterized water quality issues in the wetland habitats.

### Predator/Prey

Previous studies defined predator-prey interactions in their models since climate change may affect predator-prey dynamics  through changes in abundance, the process of predation itself (including defense against predators), and at the community level through trophic cascades or regime shifts (Bretagnolle & Hanneke, 2010; Durant  *et al.*, 2007; Visser *et al.*, 2004). Predators also have non-lethal or non-consumptive effects on their prey (Peckarsky *et al.*, 2008), such as changes in distribution, phenology, population density (Bretagnolle & Hanneke, 2010; Murdoch *et al.*, 2003), behavior morphology or physiology, and disrupted synchrony (i.e. mistimed in terms of their reproduction (Bale *et al.*, 2002; Logan *et al.*, 2006).

In my study, all the wetland birds have specific predators (VanderWerf, 2012). Predators were grouped depending on their predation level (i.e., high, medium, low) as a negative impact. Feral cats (*Felis silvestris*) were classified as a high negative impact whereas rats (*Rattus spp.*) were categorized as a medium negative impact and the rest of the predators, including feral dogs (*Canis domisticus*) as a low negative impact given their relatively lower rates of abundance. Although feral dogs can have more impacts than the rest of the predators (i.e. Black-crowned Night-Heron (*Nycticorax nycticorx hoactli*), Ruddy Turnstone (*Arenaria interpres*), Cattle Egret (*Bulbulcus ibis*), Common Mynah (*Acridotheres tristis*), Bullfrog (*Rana catesbeiana*) and fish such as Tilapia (*Oreochromis niloticus*)) (Clark, 1975; USFW, 2011), the study wetland management units are considered well protected from these threats.

### Avian Botulism

Experts also identified pathogens in the models which were expected to influence bird populations, mediated by changes in habitat conditions and warming climate. Avian botulism was a lethal disease to the wetland birds, particularly the Hawaiian Stilt and Coot (Morin, 1998), and it was a persistent issue in the study area and across the USA. For example, in January 1994 an outbreak of avian botulism type C (*Clostridium botulinum*) increased wetland bird mortality (~50 Coots out of 56, and ~2 Stilts out of 12) at ʻAimakapa Fishpond (Morin, 1996).

### Invasive Species

The effects of invasive species on bird habitat and their interaction with the wetland bird species were also included in the model. In most wetlands worldwide, the predominant vegetation is invasive (Zedler & Kercher, 2004), and it must be controlled by active management. Characteristic wetland associated plants include non-native pickleweed (*Batis maritima*) and non-native California grass (*Brachiaria mutica)* (Coleman, 1981). Several species of invasive alien plants can reduce value of wetland habitat for wetland birds, particularly California grass (USFW, 2011). Notably, the non-native plant species are closely monitored and managed in the wetland management units where the protected wetland birds are found.

### Habitat

Specific habitat requirements of each bird species differ to some degree and thus vary in how they are modeled. Hawaiian Stilts are found in edges of shallow ponds, and mud flats where water is fresh to hypersaline (up to 116 ppt recorded; (Coleman, 1981)), as well as ancient Hawaiian fishponds (Morin, 1994; Robinson *et al.*, 1999).

Hawaiian Coots breed on natural freshwater ponds, flooded taro fields, sugar cane field reservoirs, concrete-lined sewage-treatment ponds, and brackish fishponds at low elevations. Wandering coots may be found on stock tanks and mountain streams at higher elevations, nearly sterile artificial ponds on golf courses, and brackish to salt estuaries. Birds disturbed on coastal ponds may fly out to sea, but remain on calm waters within reefs (Henshaw, 1902; Perkins, 1903) and have been reported to be present on a lagoon near the watershed management unit near Lihue, Kauaʻi (Pratt & Brisbin Jr., 2002).

Hawaiian Moorhens use natural ponds, marshes, streams, springs or seeps, lagoons, grazed wet meadows, taro and lotus paddies, shrimp-aquaculture ponds, reservoirs, sedimentation basins, sewage ponds, and drainage ditches. The moorhens often nest along relatively dense emergent vegetation edges (Berger, 1972) of narrow interconnecting waterways (Chang, 1990). Though actual records lack until the 1950s, Moorhen decline from 1850s to 1950s (i.e., 57 Moorhen in 1950s) is attributed to humans (Engilis & Pratt, 1993), and the decline of rice and taro paddy cultivation in Hawaiian Islands (Bannor & Kiviat, 2002).

Among others, a major difference between Hawaiian Stilt, Coot and Moorhen is that Stilt is a carnivore whereas Hawaiian Coot and Moorhen are omnivores, creating only two different FCMMs (Figure 10, Figure 11) of the same wetland ecosystem.

Although all three endangered species are found in most bodies of freshwater, the conceptual expert models are specifically based on understanding of the managed wetland units in the refuge. These wetlands are heavily managed by the USFWS and the optimal water depths are regulated to meet the requirements at each stage in a species life cycle or season. USFWS manages 3.36 ha of early succession seasonal wetland habitat from March through September on Hanalei National Wildlife Refuge (NWR) for Hawaiian stilts.  Management scheme for Hawaiian coots and moorhens includes preparing 1.84 ha of brood rearing habitat from March through July on Hanalei NWR.

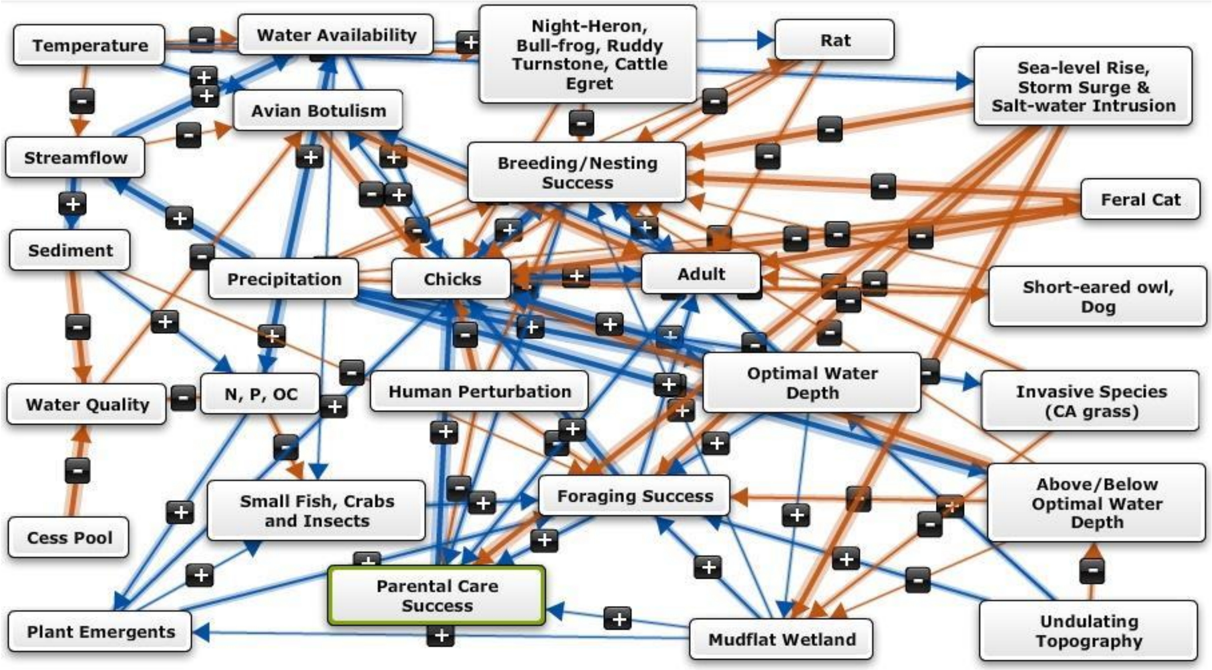

*Figure 10. Fuzzy-logic Cognitive Map of Hawaiian Stilt constructed in Mental Modeler based on expert knowledge.*

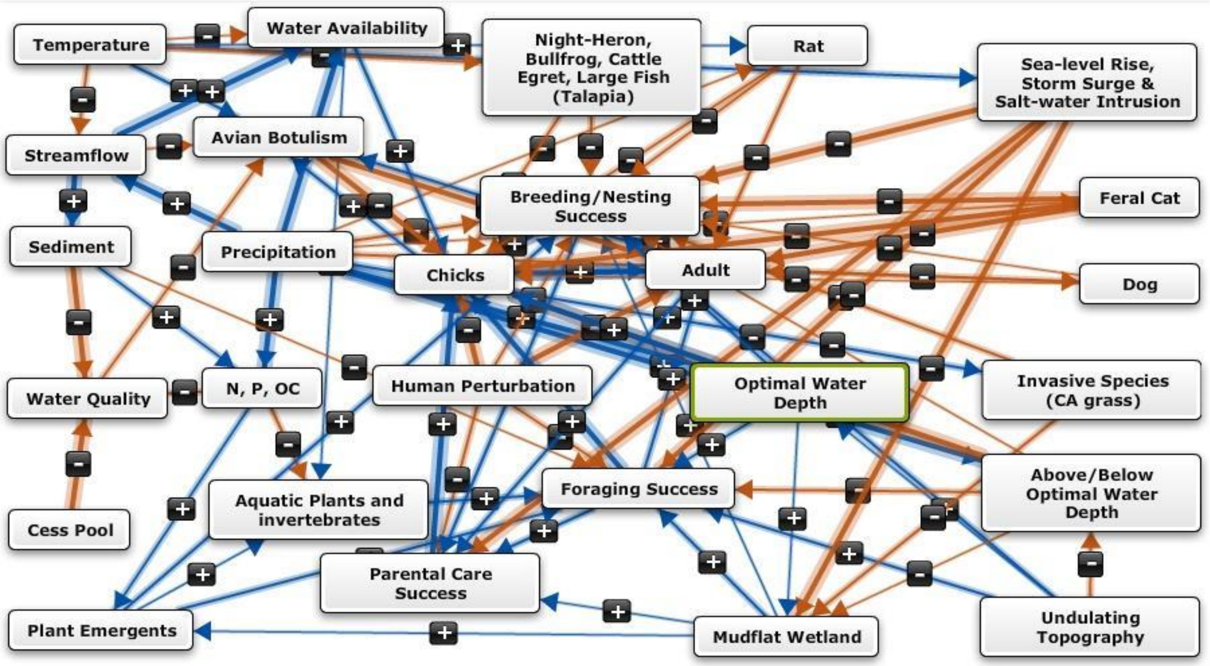

*Figure 11. Fuzzy-logic Cognitive Map of Hawaiian Coot/Moorhen constructed in Mental Modeler based on expert knowledge.*

Step 4: Fuzzy Cognitive Mapping Model Scenarios (Coupling Watershed and Expert-based Models)

The life history, watershed, predator-prey and habitat components were modeled by experts during workshops based on sharing their collective expertise and experience using the FCM GUI via the Mental Modeler software (Gray *et al.*, 2014). Three species specific models were developed with the experts and then used in conjunction with the empirically-based watershed models projections for coupled scenario analysis in FCMM Simulation (Appendix 2B).

To translate the watershed model output in a form that was appropriate to be coupled with the FCMM, first, quantitative AnnAGNPS outputs (Table 10) were converted into the qualitative appropriate levels of change (i.e., H+/-, M+/-, L+/- or N) as illustrated in Figure 12. Levels of change described the relative influence of each component on others (Lin & Lee, 1996), and were accompanied by membership weights (Glykas, 2010).

*Table 10. AnnAGNPS watershed model outputs for the six different climate change scenarios. All values are annual means.*

| **Scenarios** | **$CO_2$ Emission** | **Temp.** | **Precip.** | **Stream-flow** | **Sediment** | **Nitrogen** | **Phos-phorus** | **Organic Carbon** |
|---|---|---|---|---|---|---|---|---|
| | **ppm** | **(°C)** | **(%)** | **x $10^7$ ($m^3$)** | **x $10^7$ (kg)** | **x $10^6$ (kg)** | **x $10^5$ (kg)** | **x $10^1$ (kg)** |
| **Reference** | 330 | 0 | 0 | 8.83 | 1.302 | 1.016 | 3.773 | 4.661 |
| **Scenario 1** | 330 | 1.1 | 0 | 8.82 | 1.305 | 1.020 | 3.805 | 4.678 |
| **Scenario 2** | 330 | 6.4 | 0 | 8.74 | 1.304 | 1.027 | 3.902 | 4.710 |
| **Scenario 3** | 330 | 0 | -20 | 5.91 | 0.752 | 0.672 | 2.792 | 2.547 |
| **Scenario 4** | 330 | 0 | 20 | 11.93 | 1.975 | 1.413 | 4.860 | 7.351 |
| **Scenario 5** | 970 | 6.4 | -20 | 6.18 | 0.762 | 0.729 | 2.926 | 2.572 |
| **Scenario 6** | 710 | 0 | -5.3 | 8.17 | 1.161 | 0.941 | 3.552 | 4.101 |

AnnAGNPS outputs (Table 10) under the six climate change scenarios were translated into FCMM scenarios (Table 11) using fuzzy-cognitive approximation (Glykas, 2010) plotted in Figure 12. The x-axis in Figure 12 indicated the watershed components, and the y-axis represented the weights for membership function. For example, scenario 4 produced the highest precipitation, and therefore it was denoted as a high positive (H+) level of change for precipitation (see Table 11). Scenario 4 belonged to the H+ function with a membership function weight of 1, so do all the scenarios with precipitation increase from 20% to 15%. On the other hand, scenario 3 produced the least precipitation, and therefore attributed to the high negative (H-) level of change for precipitation (see Table 11). Next, watershed component values between the extremes were defined using triangular membership functions as shown in Figure 12. For instance, 14% precipitation increase would have both H+ and M+ levels of change with 0.8 and 0.2 respective weights, meaning that the scenario had 80% H+ and 20% M+ level of change.

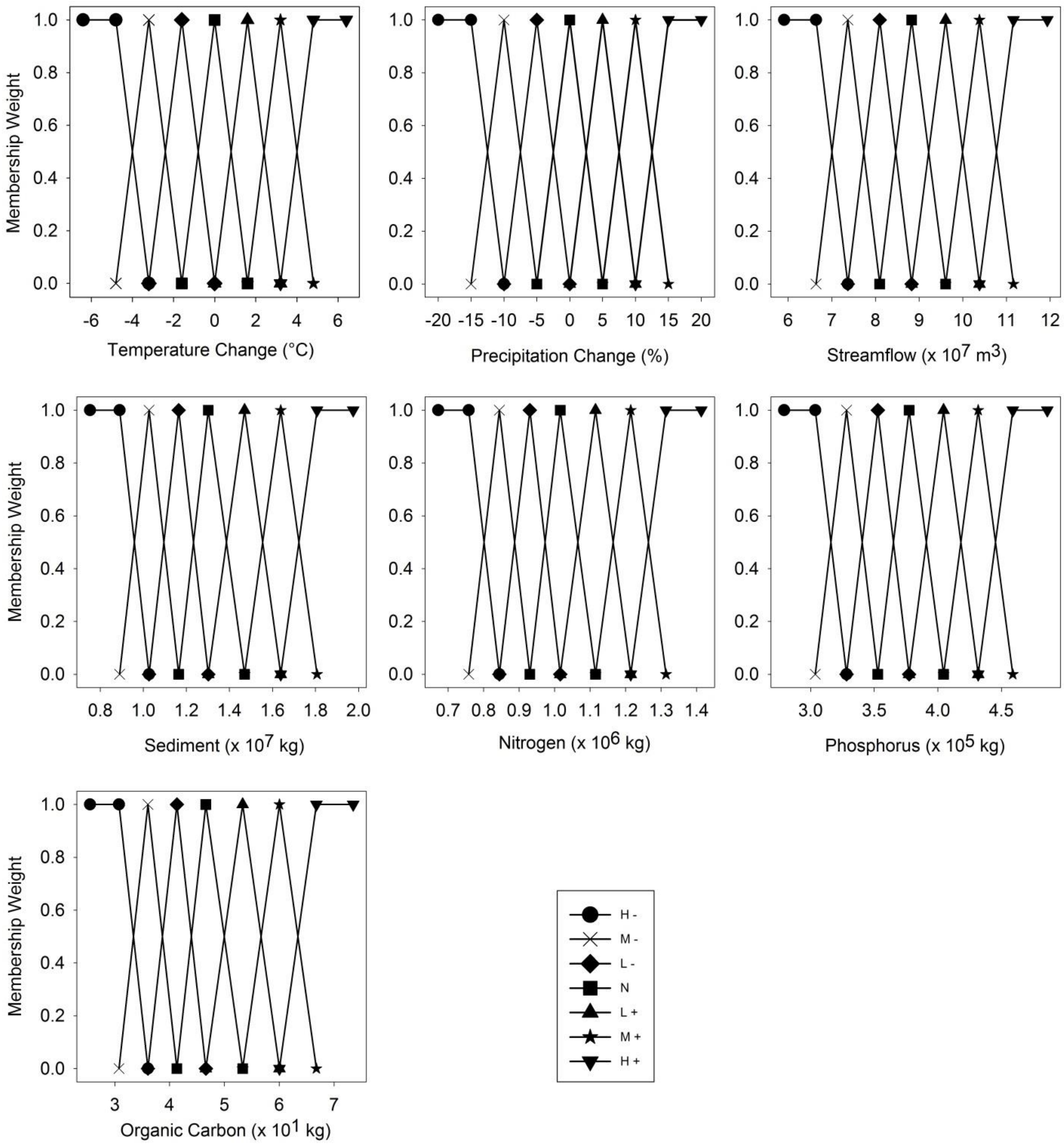

*Figure 12. Real space to fuzzy space conversion of climate change and watershed model outputs in terms of levels of change (i.e., N = No Change, H- = High Negative, M- = Medium Negative, L- = Low Negative, H+ = High Positive, M+ = Medium Positive, L+ = Low Positive. Y-axis represents weight of membership in the level of change for less extreme scenarios, representing the relative degree of membership for that level.*

*Table 11. Fuzzy interpretation of watershed model outputs (N = No Change, H- = High Negative, M- = Medium Negative, L- = Low Negative, H+ = High Positive, M+ = Medium Positive, L+ = Low Positive.*

| **IPCC Scenarios** | **Fuzzy Cognitive Mapping Scenarios** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Temp.** | **Precip.** | **Streamflow** | **Sediment** | **Nitrogen** | **Phosphorus** | **Carbon** |
| **Reference** | N | N | N | N | N | N | N |
| **Scenario 1** | L+ | N | 0.01L- & 0.99N | 0.01L- & 0.99N | 0.96N & 0.04L+ | 0.87N & 0.13L+ | 0.97N & 0.03L+ |
| **Scenario 2** | H+ | N | 0.12L- & 0.88N | 0.01L- & 0.99N | 0.86N & 0.14L | 0.53N & 0.47L+ | 0.93N & 0.07L+ |
| **Scenario 3** | N | H- | H- | H- | H- | H- | H- |
| **Scenario 4** | N | H+ | H+ | H+ | H+ | H+ | H+ |
| **Scenario 5** | H+ | H- | H- | H- | H- | H- | H- |
| **Scenario 6** | N | L- | 0.90L- & 0.10N | 0.03M- & 0.97L- | 0.89L- & 0.11N | 0.91L- & 0.09N | 0.06L- & 0.94N |

Finally, once watershed models were converted into fuzzy values, seven FCMM scenario were run on each expert-based bird model which enabled system state predictions to be calculated indicating how habitat changes and wetland bird species would be impacted under varying climate change projections. Simulations within the Mental Modeler used a logistic function (see Appendix 2B), which was a routine for FCMM scenario analysis (Jetter & Kok, 2014). Less extreme scenarios were in fact modeled using the same approach in Microsoft Excel (2010) to accommodate the accompanying weights. Fuzzy-interpreted values for scenarios were automatically adjusted during FCMM simulations and the adjusted (or modeled or stabilized) values were given for streamflow, sediment and N, P, OC. It should be clearly noted that FCMM results were relative to one another and therefore provided a system state relative change for each component.

### Step 5: Mitigation and Adaptation Strategies

"Fuzzy" modeling approach in the field of decision support for ecosystem management has gained growing interest in recent years (Jakeman & Letcher, 2003), because it is interpretable (Casillas *et al.*, 2002) and easy-to-adapt modeling (Adriaenssens *et al.*, 2004). Accordingly, this study demonstrated that FCM can be used as a tool with climate data to interpret/model things at smaller scales to inform local scale management actions, where most management actions occur to address wetland bird species' limiting factors (e.g., predation, brooding habitat availability, etc.).

### *Model Evaluation*

In my decision-support modeling framework, I evaluated FCMMs' capacities to support management (via management of certain model components), and decrease uncertainty associated with local climate change impact (via consideration of the overall ecological system). Using the adjacency matrix, evaluative FCMM structural metrics (see Appendix 2B) were calculated based on relational characteristics (Bennett *et al.*, 2013). In addition, sensitivity analysis was performed to determine the impact degree of ecological components responsible for the change in abundance of the wetland birds.

To determine FCMM characteristics and assess its quality, I computed FCMM structural metrics (see Appendix 2B) including indegree, outdegree, transmitter and receiver components, density, complexity, and hierarchy index (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004). For example, an FCMM with democratic hierarchy index would represent a system with high level of integration, dependent components, and adaptive capacity to local environmental changes (Sandell, 1996).

For the sensitivity analysis, I conducted relationship removal as well as Monte Carlo simulation that had previously been suggested for FCMM sensitivity analysis (Jetter & Kok, 2014). For relationship removal analysis, I identified sensitive relationships that were susceptible to climate change yet not directly connected to essential components using FCMMs and adjacency matrices (see Appendix 2B). A total of six relationships depicting effects of temperature on predators and that of topography on optimal water depth were chosen for the analysis. They were removed twice, all at once and one at a time (Norton, 2015), testing all possible effects (Cheng *et al.*, 1996; Ducey & Larson, 1999). Next, I employed Monte Carlo simulation of ordinary components on the wetland bird population. Random function was used to simulate 10,000 FCMM scenarios (see Appendix 2B) for each of the 16 ordinary components (i.e., components with both a non-zero indegree and outdegree) for the wetland birds.

FCMM behavior was evaluated for abundance changes before and after all the analyses to highlight the relationships most important in a system interaction for wetland bird preservation as defined by USFW wildlife management technical reports (USFW, 2011).

## ***Results***

Model results indicated that increased precipitation (scenarios 1, 2, 4) would increase adult Stilt abundance, but decrease adult Coot and Moorhen abundance (Table 12). On the other hand, reduced precipitation (scenarios 3, 5, 6) was expected to decrease abundance of all three species. Results also indicated that behaviors of each life-function in response to climate change was distinct for each species. In terms of increased water quantity, foraging success increased in general as aquatic plants and bird abundance were expected to increase with more water, except in the case of highest precipitation when flooding events are expected to displace birds. In addition, breeding/nesting success was negatively affected by status-quo (0% precipitation change) as well as increased precipitation. However, reduced rainfall had the opposite effect. Parental success was positively affected by extreme drought condition linked by increased breeding/nesting success.

*Table 12. Mental Model Output Summary ($CO_2$ = $CO_2$ emission rate, T = Temperature change (°C), P = Precipitation change (%)) for Hawaiian Stilt, Hawaiian Coot, and Hawaiian Moorhen.*

| **Scenarios ($CO_2$, T, P)** | **Popula-tion** | **Breeding/ Nesting Success** | **Foraging Success** | **Parental Care Success** | **Predator** | Prey Availability |
|---|---|---|---|---|---|---|
| | | | **Hawaiian Stilt** | | | |
| 1 (330, 1.1, 0) | + | - | + | + | - | + |
| 2 (330, 6.4, 0) | + | - | + | - | - | + |
| 3 (330, 0, -20) | - | + | + | - | + | + |
| 4 (330, 0, 20) | + | - | - | - | - | - |
| 5 (970, 6.4, -20) | - | + | + | - | + | + |
| 6 (710, 0, -5.3) | - | + | + | - | + | + |
| | | | **Hawaiian Coot and Moorhen** | | | |
| 1 (330, 1.1, 0) | + | - | + | + | - | + |
| 2 (330, 6.4, 0) | - | - | + | - | - | + |
| 3 (330, 0, -20) | - | + | + | - | + | + |
| 4 (330, 0, 20) | - | - | - | - | - | - |
| 5 (970, 6.4, -20) | - | + | + | - | + | + |
| 6 (710, 0, -5.3) | - | + | + | - | + | + |

*Hawaiian Stilt*

Both chick and adult abundance were lowest under scenario 3 (high reduction in precipitation), but highest under scenario 4 (high increase in precipitation) (Figure 13). In relative change terms, scenario 4 also led to an increase in streamflow, water contaminant variables (N, P, OC), sediment, water availability, emergent plants and a decrease in rat population. However, scenario 1 showed the most significant decrease in adults (lowest) with an increase in streamflow, water contaminant variables (N, P, OC), sediment, above/below optimal water depth, in avian botulism and a decrease in water availability, emergent plants, and in rat populations (Figure 14).

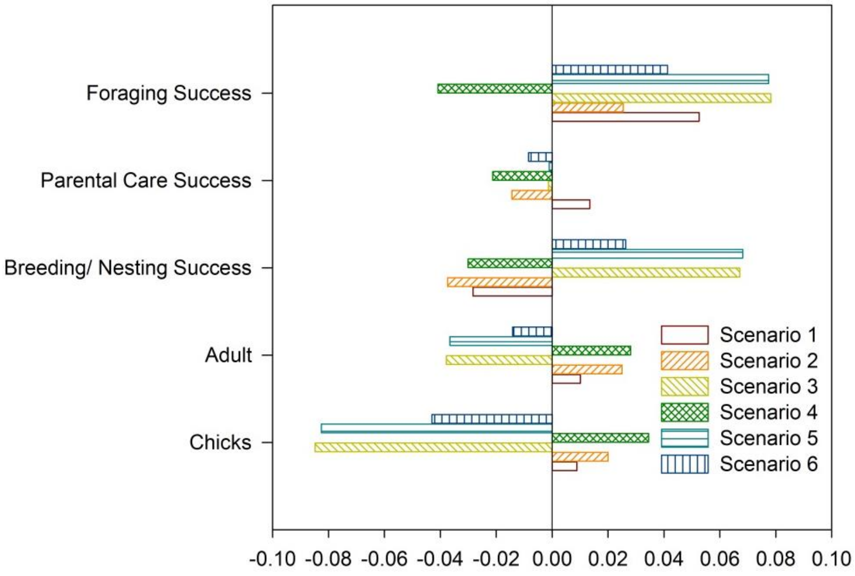

*Figure 13. Fuzzy Cognitive Mapping model scenario results for Hawaiian Stilt (life-functions and abundance).*

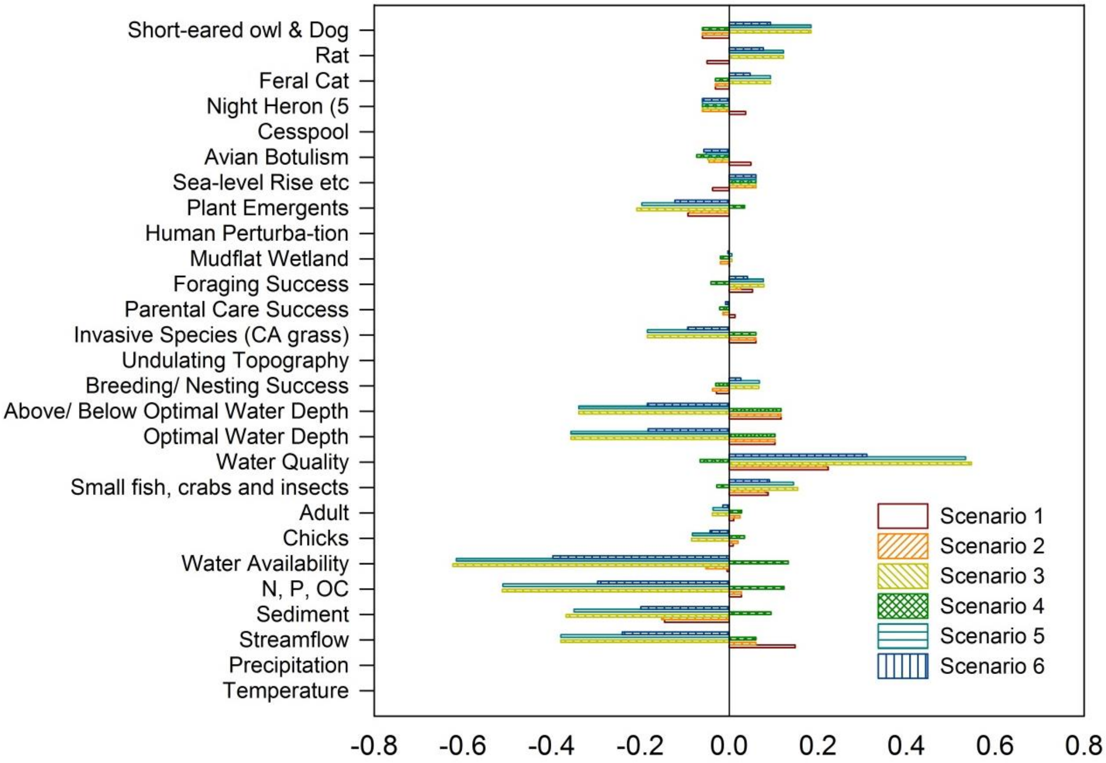

*Figure 14. Fuzzy Cognitive Mapping model scenario results for Hawaiian Stilt under the six climate change scenarios.*

*Hawaiian Coot and Moorhen*

Both chick and adult abundance were lowest under scenario 3 (high negative precipitation), but highest under scenario 1 (low positive temperature) as shown in Figure 15. Scenario 1 led to an increase in adults, streamflow, water contaminants (N, P, OC), and a decrease in sediment, water availability, emergent plants and rat populations. However, under scenario 3, there was a decrease in adults, streamflow, water contaminants (N, P, OC), sediment, water availability, above/below optimal water depth, emergent plants with an increase in avian botulism and rat population (Figure 16).

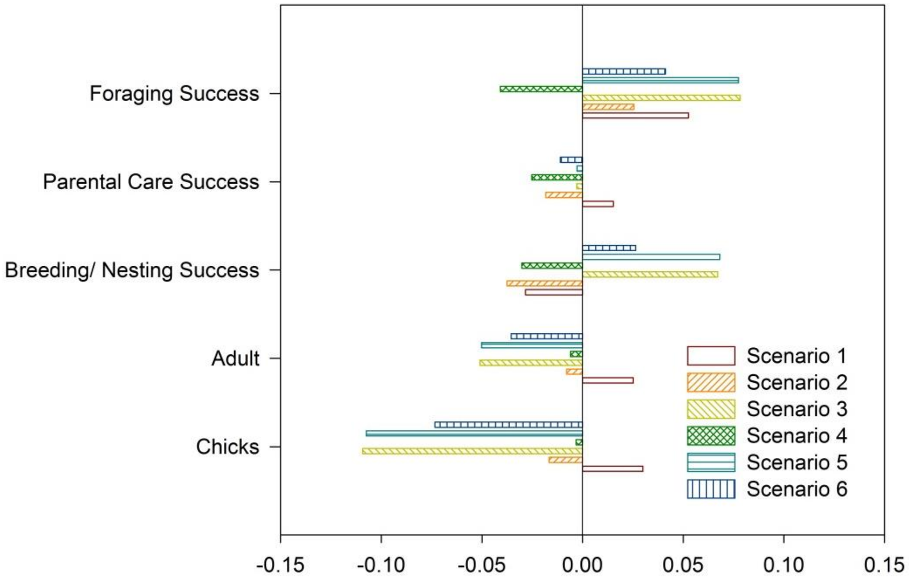

*Figure 15. Fuzzy Cognitive Mapping model scenario results for Hawaiian Coot and Moorhen (life-functions and abundance).*

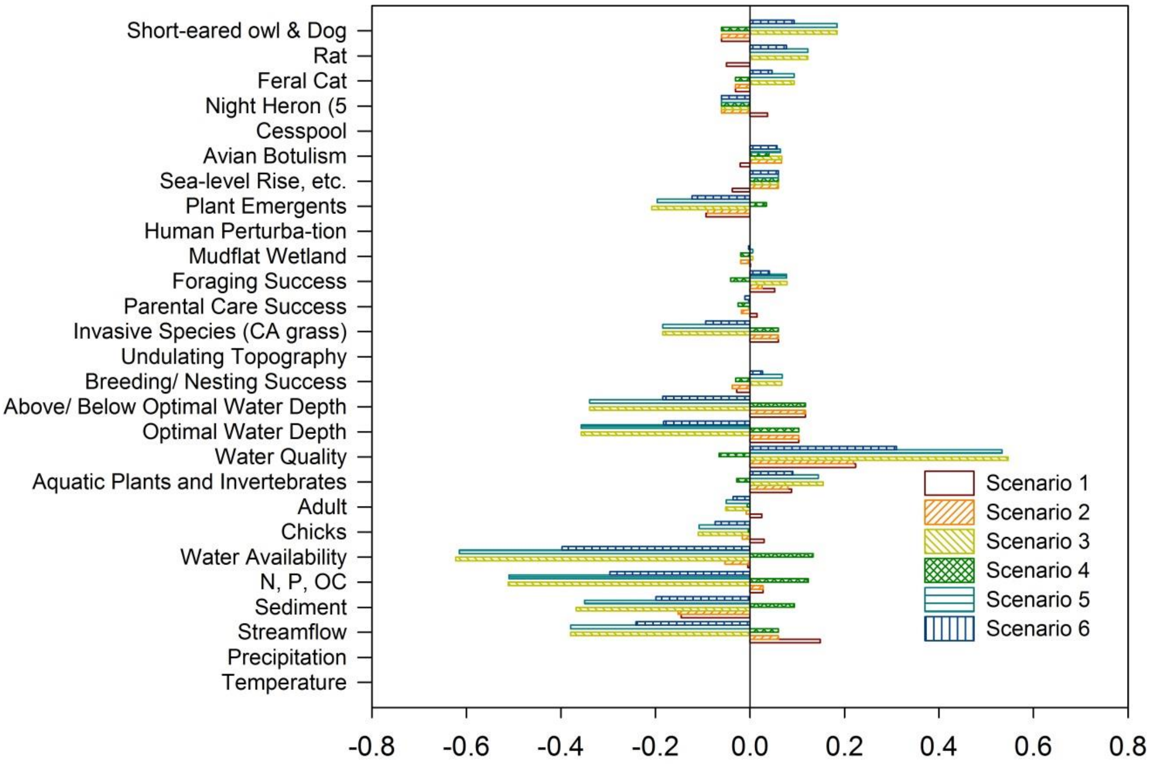

*Figure 16. Fuzzy Cognitive Mapping model scenario results for Hawaiian Coot and Moorhen under six climate change scenarios.*

*Model Evaluation*

Structural metrics implied management policy would have to focus on a number of controlling forces with influence distributed evenly across the structure of the system (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004). Both FCMMs had nine transmitters, zero receiver and 18 ordinary components, low density (0.11), small hierarchy index (0.02), zero complexity, highest centrality for breeding/nesting success, and lowest centrality for small crabs and insects as well as undulating topography. Low density reflected fewer highly-influential components, capable of altering the system function drastically (Gray *et al.*, 2014). Small hierarchy index and zero complexity indicated democratic FCMMs with many controlling forces affecting the wetland bird abundance.

In addition, the models were sensitive to their structure and the defined influences between components; however, this was dependent on species and scenario. For Hawaiian Stilt, reduced precipitation may have caused relative adult abundance values to change from negative (decreasing trend) to positive (increasing trend) in scenarios 3, 5, and 6. Chick abundance also increased for the same scenarios. On the other hand, increased precipitation in scenario 4 reduced stilt abundance. Though not distinct, increasing temperatures (scenario 1 and 2) were expected to decrease stilt population. For Hawaiian Coot and Hawaiian Moorhen, reduced precipitation scenarios did not produce trend changes (positive to negative or vice versa) in abundance; the results indicated abundance would only increase. Reduced precipitation (scenario 4) and increased temperature (scenario 1 and 2) all resulted in population decrease. Therefore, the model results indicated that these relationships were indeed essential for all three wetland bird species and may have substantial impact on the chick and adult abundance.

In addition, relationships were removed one at a time to determine the most sensitive (or insensitive) one that would affect wetland bird abundance. For all wetland bird species, removal of precipitation effect on cat caused the highest abundance increase under scenario 5. In addition, highest decrease was observed with temperature impact on Night Heron under scenario 5 for Stilt chick, precipitation effect on feral cat under scenario 4 for Stilt adult, temperature impact on night heron for under scenario 2 for Coot and Moorhen chick, and temperature effect on rat under scenario 1 for Coot/Moorhen adult. On the other hand, above/below optimal water depth effect on mudflat wetland caused the least abundance change.

Monte Carlo simulation (see Appendix 2B) showed that optimal water depth and foraging success drove the chick and adult abundance to a maximum, but avian botulism decreased the abundance to a minimum for all the wetland birds. In addition, breeding/nesting success was found to be the most important variable for the survival and existence of the birds, while food and topography were least significant.

### ***Discussion***

Model results suggest climate change impacts on endangered wetland birds and their abundance mediated through their life functions (i.e., parental care, breeding/nesting, and foraging success). More precipitation increases Stilt abundance, but decreases Coot and Moorhen abundance. Nevertheless, persistent decreasing precipitation may have reducing effect for all the birds. Such results indicate differential effects of climate change on endangered species that will require tailored wildlife management plans.

Among others, a major difference between Hawaiian Stilt, Coot and Moorhen is that Stilt is a carnivore whereas Hawaiian Coot and Moorhen are omnivores, creating two different FCMMs of the same wetland ecosystem. Each FCMM includes 27 components and 84/85 relationships that define selected locally managed Hawaiian Stilt, Coot and Moorhen with climate components, watershed components, life history and habitat characteristics (Figure 10 and Figure 11). Nearly half of the relationships (i.e., 43) are negative indicating that a quantity increase of these particular components (predators, avian botulism, non-native species and climate components) decreases the others, and therefore wildlife managers should attend to these stressors specifically. Furthermore, these components are mostly exogenous and thus effected very little by other wetland system components (i.e., sea-level rise, storm surge and salt-water intrusion and predators), presenting wildlife managers with unique challenges to maintaining viable populations. In addition, climate components impact other components in various ways, for example positively to life history as well as food, and negatively to predators and non-native species. Precipitation and streamflow have the highest positive impact while sea-level rise, storm surge and salt-water intrusion the highest negative impact. Breeding/Nesting success is found to be connected to more components and therefore central to the population models and affect wetland bird abundance more than foraging and parental care success. Similarly, chicks are more susceptible than adults as indicated by twice as more connected relationships. Explicit discussion of such networked relationships provides a way for managers: to discuss alternative potential management options; and to identify variables that lie outside the control of refuge managers and present unique challenges.

In term of regional physical watershed changes, my modeling efforts are similar to other reported estimates (Oki, 2004; Safeeq & Fares, 2012) and predict that the increased streamflows will produce high sediment and nutrient runoff (Table 10). By using a similar approach but linking these changes to expert-driven ecological models, my approach indicated that all three wetland birds will be affected by climate change, but the degree and direction are dependent upon the nature of the change. For example, more intense storm events would likely flood the wetland regions and therefore not only affect the chicks by flushing them down the waterways but also lead to unfavorable habitat through increased contaminant transport. Additionally, my model results indicate that indirect water quality impacts (considering smaller molarity of nutrients and sediments associated with higher rainfall) would be insufficient to impact the wetland birds' life cycle (e.g., breeding/nesting, foraging and parental care) even with the interactive effects of sea level rise, storm surge and salt-water intrusion. Ultimately, though population increase or decrease is a combined effect from the success of all life cycle stages for each species, individual life function processes are observed to be impacted differentially. In addition, model coupling indicate that in some cases the same climate change scenario would have positive impacts on some birds, while negative impacts on others (Figure 13 and Figure 15).

My ensemble modeling approach appears to provide better results than separate individual models. For example, a watershed model alone could not reveal the final impact on bird abundance unless significant amounts of empirical data are collected over time, nor could it predict intermediate impacts on predators and essential habitats that are important for conservation and sustainable bird population. Likewise, standalone physical models could not capture the direct and indirect climate change impacts on predators (cat, rat, and owl) and ultimately on the population dynamics without the aid of connectivity in a system model approach as shown in the FCMMs (Figure 10) and (Figure 14). Additionally, the expert-based model, although useful as a conceptual learning tool (Gray *et al.*, 2014), could not easily translate global IPCC scenarios into justifiable projections thereby limiting its ability to be used as a standalone modeling effort with confidence.

Previous studies have documented factors and their impacts on the abundance of the study wetland birds as well. For instance, Hawaiian stilt abundance increases as a result of the removal of invasive pickleweed and red mangrove at Nuʻupia on Oʻahu (Rauzon & Drigot, 2002). Overall, Hawaiian stilt abundance have been shown to increase during periods of relatively dry weather associated with El Niño events as drought events can expose more mudflats providing more breeding habitat (Engilis & Pratt, 1993). Increased rainfall has shown to result in a decrease in the total numbers of both Hawaiian Stilt and Hawaiian Coot (Engilis & Pratt, 1993; Reed *et al.*, 2007). Although subsequent studies have suggested that rainfall did not affect wetland bird abundance, and instead attributed the population increase in all three species to wetland management activities (Reed *et al.*, 2011). Despite the differences in these studies, all the wetland bird abundance have increased over the last few decades on National Wildlife Refuges across Hawaiʻi as a result of active management including the removal of invasive plant species, the removal of predators, and the management of water levels and flow (Underwood *et al.*, 2013). Ultimately, my approach combines the potential impacts of management activities in addition to climate and environmental impacts in order to create a better modeling approach.

### *Erratum on Climate Change Scenarios*

I found that climate change scenarios from this study (Table 7) were incorrect due to two factors: 1) correct annual $CO_2$ concentrations in the study period (2003 and 2004); and 2) recently updated local as well as global climate change predictions. Based on observations at Mauna Loa, average $CO_2$ concentration rate for 2003 and 2004 was found to be 376.195 ppm (374.88 + (377.51-374.88)/2 = 376.195 ppm). It was different from the value (330ppm) used in this study. In addition, the latest IPCC V report (and 2010 to 2017 observations) indicated that $CO_2$ emission in the year 2100 might be over ~940ppm (Van Vuuren *et al.*, 2011). Next, the latest local climate change studies revealed that projected precipitation (relative to 1978–2007 historical precipitation) would decrease 20%–40% in the wet-season and increase 1%-10% during the dry season, resulting in an annual decline up to 15% in the Hanalei watershed (Elison Timm *et al.*, 2015). Projected temperature change in 2100 (relative to 1957–1981 (Giambelluca *et al.*, 2014)) is 3–3.5°C in Hanalei (Elison Timm *et al.*, 2016), while global mean surface temperature change would be 4.8°C (IPCC, 2013) (compare to 6.4°C from the previous IPCC III report used in the analysis).

Therefore, current climate change, “Reference” scenario (with 330ppm $CO_2$) from Table 7 has 46.196 ppm less than the correct concentration. For future climate change, “Scenario 5” (with 970ppm $CO_2$, -15% Precipitation, and +6.4°C Temperature) was not very different from the updated climate change scenario. As a result, there would be slightly more evapotranspiration and less streamflow from the watershed model in the “Reference” scenario. As the difference between “Scenario 5” and latest climate change predictions are slight, there would be slightly less relative change in water quality and quantity than reported for scenario 5. Therefore, FCMM simulation results are still valid for scenario 5. However, the rest of the scenarios are not likely to happen in the future.

### ***Management Implications***

“Fuzzy” modeling approach in the field of decision support for ecosystem management has been receiving increased attention (Jakeman & Letcher, 2003), because it is considered to be more easily interpretable (Casillas *et al.*, 2002) and it is flexible and easy-to-adapt the modeling activity to a wide range of contexts and environmental issues (Adriaenssens *et al.*, 2004). My study demonstrates that FCM in general, and Mental Modeler specifically, can be used as a tool along with climate data to interpret and model complex process that occur at smaller scales to inform local scale management actions, where the majority of resource management decisions are made. Additionally, the components included in the model can be defined in terms directly relevant to managers given their local mandates (e.g., predation, brooding habitat availability). This tool alone does not provide solutions, rather, provides contextual information during scenario planning to inform optimal adaptation solutions. We therefore suggest that this approach can be used alongside other more common climate change decisions support tools (DSTs) such as GIS web applications that often utilize coarse data inputs or planning documents to guide the decision-making process. Conceptual approaches, in addition to spatial approaches, are also useful in understanding and projecting the local-scale impacts of climate change since these methods require less data while also comprehensively accounting for complex biological interactions and nuanced processes that most local-scaled resource managers have to consider. FCM can incorporate the nuanced local scale differences to reduce the level of uncertainty for management actions and can inform research and monitoring by making the assumptions transparent (Kok, 2009) which may facilitate management responses (Pahl-Wastl and Hare 2004; Henly-Shepard et al. 2015).

For example, regarding climate change impacts on the Stilt population, if scenario 3 (20% precipitation decrease) is likely, managers may need to respond to water quantity issues by augmented chick rearing programs or artificial water provisioning at nesting sites . Alternatively if scenario 4 is more likely, then water quality issues need to be addressed by limiting input of N, P, OC and sediment perhaps through increased water quality monitoring programs and outreach to municipal or private land-owner management extension programs. However, my model results also provide temporal context. Results show that current and short-term threats, specifically non-native predation, will negatively impact all bird species regardless of scenario. Investments in adaptation strategies must balance addressing short term and long term threats. Otherwise long-term adaptation strategies may become a moot effort if short term population level limiting factors are not mitigated. In addition to temporal context, local scale FCM results also allow managers and policymakers to optimize their suite of management actions, from habitat alteration to regulatory actions, for the proposed scenarios' adaptation and mitigation strategies. Current management actions are typically framed by short term (five to 15 years) planning documents that aim to accomplish longer term goals. In addition to informing current management actions, FCM results can help inform the next iteration of long and short term resource management planning and prioritize management action while considering what scenarios are most likely, what impacts can (and cannot) be addressed through management action and the relative cost and benefits of potential management policies (Gray *et al.*, 2015; Henly-Shepard *et al.*, 2015; Nyaki *et al.*, 2014).

### *Limitations*

Although my results provide promising and novel integration of the strengths of empirical local-scale hydrological modeling and conceptual knowledge-based modeling, several aspects of study are, to date, underdeveloped with regard to model coupling and FCMM structure and analysis including: threshold prediction, insufficient sensitivity analysis methods, limited model visibility and precision, model selection, and interviewee selection.

Given current analytical methods, FCMM could not address questions to system thresholds, for example, the exact threshold impacts of water on some of the ecological components (e.g., predators, life cycle components). Moreover, FCMM sensitively analysis techniques are not well developed (Henly-Shepard *et al.*, 2015) except a few basic methods: adding or deleting components, changing values of components (Cheng *et al.*, 1996; Ducey & Larson, 1999), as well as removing relationships. In my sensitivity analysis, manipulation of relationships gives partial insight into the FCMM sensitivity, for example, precipitation effect (both increase and decrease) on cat caused the least abundance change. In addition, direct relationships to high centrality components (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004) are essential. However, Principle Component Analysis on FCMM  (Hobbs *et al.*, 2002) does not always provide useful information, for example unclear results for this study. An approach similar to the Monte Carlo simulation in System Dynamics has more recently suggested (Jetter & Kok, 2014) but never applied on FCMM before. Therefore, questions remain about optimal approaches to sensitivity analysis in participatory FCM environmental modeling, and it is an area that would benefit from further research.

Moreover, FCMM, like any other conceptual model, with more than 20 components is hard to visualize clearly, thereby limiting its usefulness as a decision and communication approach, although this is rarely discussed in the literature. Limited components lead to constrained precision and in many cases may be an overly reductionist approach. In addition, we lose additional precision when converting quantitative watershed dynamic values into semi-quantitative FCMM components. However, decision making accepts less certain predictions (Guswa *et al.*, 2014), endorsing the validity of  my analysis to inform environmental managers of climate change impacts on the wetland birds when used as a tool for deliberation, communication and model-based reasoning with natural resource managers.

In addition, there are other factors that could substantially impact model results. For example, the choice of watershed model, and the expertise of the interviewees determine the level of precision and prediction provided by the framework. While AnnAGNPS was previously calibrated and tested in my study area (Polyakov *et al.*, 2007), it may or may not be suitable for other watersheds. In addition, depending on the availability, access and ecological knowledge level of interviewees, FCMM results vary even for the exact ecological system (Gray *et al.*, 2012). Next, as with all future predictions (Cornell *et al.*, 2012), there is uncertainty in my estimates, especially with the extreme climate conditions with less occurrence likelihood. Finally, though my study may not inform the likelihood of the extreme scenarios or sensitivity of the model under less extreme circumstances, I believe adaptation and mitigation based on the extremes would definitely prepare us for the less severe environmental conditions.

Finally, the integration of empirical models with conceptual or ‘mental’ models, as with all scientific models, is meant to be formal and functional rather than complete or accurate representations of reality, allowing people to interact with the world (Jones *et al.*, 2011; NRC, 2007). Owing to cognitive limitations, it is neither possible nor desirable to characterize every possible reality detail (Jones *et al.*, 2011) in mental models.

### ***Conclusion***

This study analysis is an effort to represent the interaction between global climate processes, local-scale hydrological and ecological systems for decision-support. Additionally, my approach aims to promote learning about climate change and its impacts in a relatively easy-to-use and quick modeling framework that links empirical and conceptual datasets. We suggest that wildlife managers need emerging ways to model and deal with climate change impacts at the local scale given constrained resources, data poverty, and the high degree of complexity in these issues. Although climate change is expected to alter hydrologic ecosystem services in terms of water quantity and quality, my results indicate that these impacts on wildlife species are not uniform and are sensitive to multiple and unique stressors such as food availability, predator/prey interactions and disease that can be identified through expert interviews and collaborative modeling practices. Therefore, system model-based approaches that rely on the unique strengths of both empirical environmental projections and conceptual understanding of management systems will likely lead to better learning outcomes and therefore adaptation action among local-scale resource managers.

## Study 3 - Forecasting Climate and Land Use/Cover Change Impacts on Freshwater Ecosystem Services in Maui through Integration of Biophysical and Participatory Models

### *Abstract*

Diverse stakeholder groups are likely to conceptualize social-ecological systems (SES) differently and thus perceive environmental change and policy according to their own concerns and interests. Understanding diverse perspectives could be important to managing ecosystems and natural resources in a sustainable and equitable manner. In this study, my overarching goal was to model how freshwater ecosystem services (FES) would be affected by environmental and policy changes. I used a self-developed modeling framework, ecosystem services-based integrated water resources management, which couples biophysical and participatory modeling to explore stakeholder conceptualizations of freshwater SES, and how stakeholders will perceive the effect of land use, climate, and policy change. I focused on five watersheds on the island of Maui, using the biophysical model SWAT to predict water quality and quantity outcomes under different future land use and climate scenarios. I coupled these with fuzzy cognitive mapping models (FCMM) of the SES elicited from 22 stakeholders to predict outcomes for conditions of concern to each stakeholder. Water resource managers, conservationists, agriculturalists and cultural practitioners had described varied complexity and structure of the SES. Some common elements were water quality, quantity, and freshwater ecosystem services. My ex ante hypothesis that similar stakeholders would have similar conceptions of SES did not fully bear out, so I also grouped people by the structure of their SES; grouping by centrality resulted in completely different groups. Despite different models of the SES, stakeholders had similar perceptions of outcomes under changed conditions. For instance, water quantity will decline, though some outliers predicted future actions that would mitigate projected declines. Similarly, future water quality improved for the majority of stakeholders under all scenarios. In nearly all case, freshwater ecosystem services declined. Stakeholders' SES models suggested actions to improve freshwater management outcomes. Local farmers emphasized diverting enough water for agriculture operations while supporting instream flow standards. Some proposals to avoid costly litigation over water use were universal, for example taking only what is necessary and sharing diminishing freshwater resources. For mitigating and adapting to declining freshwater resources, stakeholders suggested improvements in management, law, and policy, enforcement as well as education of multiple users with diverse and conflicting interests. Managers and policymakers were urged to pay extra attention to reforestation, water storage, and improvements of aging infrastructure. Understanding how stakeholders perceive SES and eventual impacts of change is important because it can help managers tune policies and educational and outreach efforts to the stakeholder group and outcomes of concern. This study adds to the literature coupling biophysical and participatory models as an approach to understanding SES. Such approaches are important as managers move towards ecosystem-based management and seek ways to integrate biophysical and social issues.

### ***Introduction***

Freshwater ecosystem services (FES) refer to natural processes related to the hydrological functioning of an ecosystem that deliver benefits to humans (Brauman, 2015). Examples of these benefits include drinking water, groundwater recharge, flood protection, water retention, as well as surface and groundwater quality, which are a function of natural water filtration and sediment retention (Brauman, 2015; Capon & Bunn, 2015). The benefits are essential to people globally, but particularly for populations living on many oceanic islands, including Hawaiʻi, where groundwater provides 99.7% of Hawaii's domestic water and 63% of all freshwater use (Polyakov *et al.*, 2007; USGS NWIS, 2015; Wallsgrove & Penn, 2012).

A functioning ecosystem is necessary for these benefits (Brauman, 2015; Brauman *et al.*, 2007; Capon & Bunn, 2015; MEA, 2005). Unfortunately, climate change (Sakai *et al.*, 2002; Wagner *et al.*, 1999; Wood *et al.*, 2007) and land use/cover changes (Foley *et al.*, 2005) are undermining key natural processes. In Hawaiʻi, climate change is driving decreasing trends in precipitation and stream base flow (Chu *et al.*, 2010; Oki, 2004), and it is impacting freshwater ecosystems and aquatic species (Oki, 2004), and water supplies. Drinking water supplies are dependent on groundwater, but alien species invasion and urban development have reduced groundwater recharge (Burnett *et al.*, 2007; Shade, 1995). Moreover, terrestrial ecosystems with diverse functional species appear to be more efficient in retaining nutrients than simpler ones (Hooper & Vitousek, 1997, 1998), implying that the former are better at delivering natural water purification ecosystem service (Engelhardt & Ritchie, 2001). Impervious surfaces accelerate overland flow, resulting in sediment discharge harmful to nearshore environments (Wolanski *et al.*, 2009). Also, the built environment that expands impermeable surfaces and increases flood risk can alter stream habitat critical for endangered species, recreation, and wetland agriculture. Ironically, as the growing population demands continuously more ecosystem goods and services, the ecosystem's capacity to produce these are increasingly undermined.

Management policies can help maintain ecosystem function and improve delivery of freshwater ecosystem services, but only if it takes a system perspective of the relevant watershed dynamics and their interactions with social values (Zorrilla *et al.*, 2010). Viewing the freshwater environment as a system, the Ecosystem Services-based Integrated Water Resources Management (ES-IWRM) approach couples quantitative and qualitative models to assess ecosystem service flows, thereby integrating ecological and social systems (Roy *et al.*, 2011). The ES-IWRM approach could bring more efficient, cost-effective, equitable, and collaborative water resources management (Crossman *et al.*, 2015; Kumar *et al.*, 2013; Maynard *et al.*, 2015). ES-IWRM integrates expert-based knowledge to aid in understanding local scale dynamics of systems (Griffiths *et al.*, 2007; Mac Nally, 2007; O'Leary *et al.*, 2009). Expert knowledge is suitable for situations with relatively little data, a moderate amount of uncertainty (Kuhnert *et al.*, 2010), a coexistence of traditional and expert knowledge, and a stakeholders' support enhancement (Ozesmi & Ozesmi, 2004).

To integrate expert-knowledge in ecological (Roy *et al.*, 2011) models to evaluate FES, ES-IWRM uses two main participatory modeling methods, Bayesian approaches and Fuzzy-Cognitive Mapping (FCM). Bayesian approaches apply expert knowledge in a range of contexts (Crome *et al.*, 1996; Denham & Mengersen, 2007; James *et al.*, 2010; Marcot *et al.*, 2006), and incorporate into ecological models. For example, Bayesian methods have been applied to resolve wetland degradation conflicts between stakeholders (Zorrilla *et al.*, 2010), and to determine the habitat suitability of the threatened Australian brush-tailed rock-wallaby (*Petrogale penicillata*) (O'Leary *et al.*, 2009). Similarly, FCM approaches have been employed as a way to conceptually define network relationships found in a range of ecosystem contexts characterized by high degrees of complexity with poorly understood causal linkages (Gray & Zanre, 2013). Contrary to Bayesian approaches, FCM allows feedback relationships, enabling any additional variable to influence existing components (Jetter & Kok, 2014).

FCM’s flexibility makes it useful for many purposes. In one case, models were used to capture local expert knowledge on the interactions of human and wildlife (Nyaki *et al.*, 2014). In another, they were used in environmental risk assessments to facilitate comparison of varying knowledge and perceptions (Henly-Shepard *et al.*, 2015). FCM has been used to understand agricultural production under various farming practices and environmental scenarios in Nepal (Halbrendt *et al.*, 2014). FCM can facilitate public involvement in policy making and thereby increasing community support for management decisions (Ozesmi & Ozesmi, 2004). For example, FCM has been used to inform management decisions for the Lake Erie ecosystem (Hobbs *et al.*, 2002), and in fisheries (Gray *et al.*, 2012).

The ES-IWRM approach has been applied globally from Australia (Liu *et al.*, 2013) to West Africa (Niasse & Cherlet, 2015), however islands present a challenging study context because of complex ecosystems and multiple competing interests. The local-scale impacts of global climate change on water resources management and island communities are complex because island ecosystems have high spatial (i.e., windward vs. leeward), temporal (i.e., wet vs. dry season) variation (Barnett, 2005). There are multiple competing freshwater stakeholders (e.g., water resources managers, conservationists, agriculturalists, and cultural practitioners) with multiple interests as indicated by Waiahole ditch water surplus reallocation dispute and *Reppun v. Board of Water Supply* (1983) case (Gopalakrishnan *et al.*, 1996; MacKenzie, 2015). Competing interests mean that different stakeholder groups experience environmental changes differently and have contrasting perceptions on the freshwater system, according to their functional roles as watershed managers, conservationists, cultural practitioner, and agricultural producer. Therefore, the ES-IWRM approach that incorporates competing interests is necessary for better water resources management. In this study, a novel application of the ES-IWRM approach was used to explore the impacts of freshwater resources on these pluralistic interests and the management of freshwater users on the resources in return.

In this study, my overarching goal was to model how FES would be affected by changes in freshwater resources that come about from environmental and policy changes. I explored a few research questions. The first set of questions related to stakeholder perceptions of the freshwater social-ecological system: What are the stakeholders' perceptions of key features, relationships, drivers, and ecosystem services delivered by the local freshwater system? What are the patterns of the stakeholder perceptions, and do they correlate with stakeholder grouping? What differences in perceptions exist between and within the groups? A second set of questions addressed how these system conceptions translate to perceived outcomes: How do environmental and policy changes affect different stakeholder groups? Finally, I conclude with some interpretations of the study results regarding implications for water resources management in island ecosystems.

### *Methods*

The study site consists of six watersheds (see Figure 17): five in west Maui (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua) and one in central Maui (ʻĪao). Four groups of stakeholders namely, water resources managers, conservationists, agriculturalists, and cultural practitioners, manage the supply and demand of freshwater, and its quality and quantity in Maui. West Maui watersheds are part of the West Maui Ridge-to-Reef initiative, including one of the top two priorities sites for Hawaiʻi's coral program for the next few years. The ʻĪao watershed was of interest because of the diverse users and possible contrast on freshwater values from the windward watershed aspect.

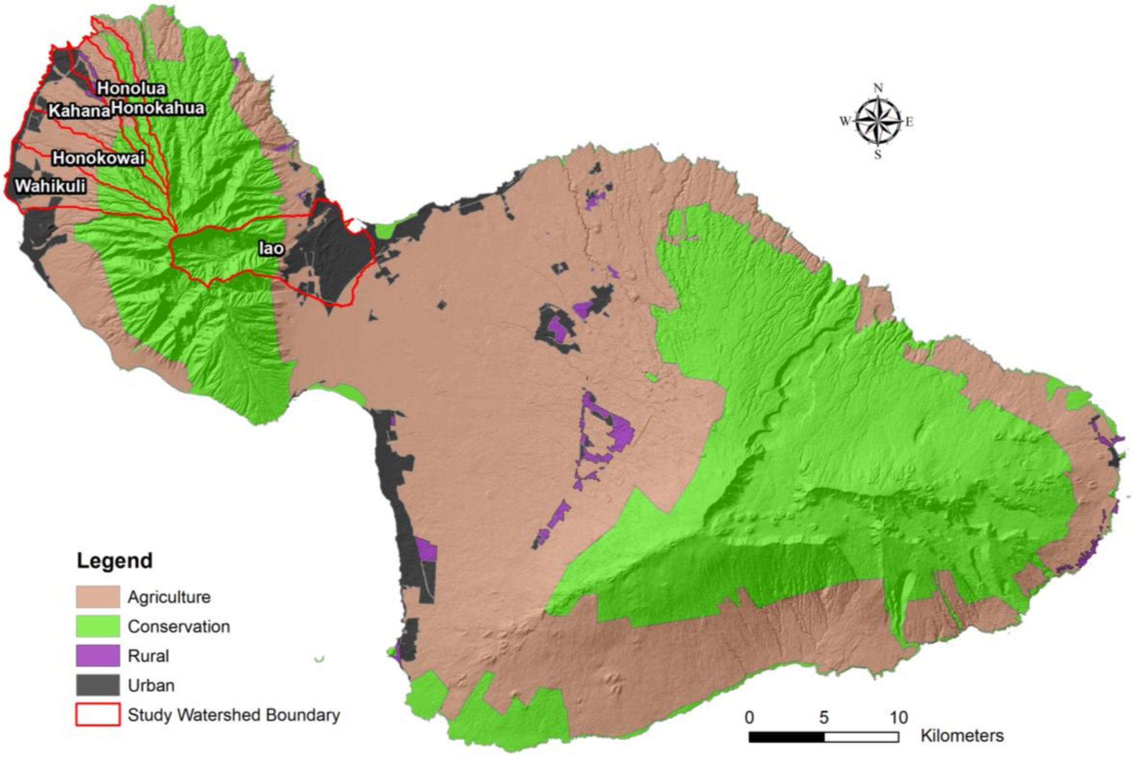

*Figure 17. Study sites and state land use districts - Maui. Source: Hawaiʻi Statewide GIS Program, 2014. State Land Use Districts are indicated in color.*

To understand the perspectives of different stakeholder groups on freshwater system, and the impacts of change on conditions they value, I modeled the ecohydrology and stakeholder viewpoints following six specific steps below.

### A. *Ecohydrological Modeling*

Step 1: Defining Environmental Scenarios

To understand local scale eco-hydrologic dynamics and their interactions with social values in the study site, the ES-IWRM approach assesses the local ecosystem goods and services, environmental changes and their potential to alter these goods and services, and major stakeholders' freshwater management roles as well as values, and current management policy (Scott *et al.*, 2014).

In the study area, freshwater is essential for economic, ecologic, cultural, and aesthetic reasons (Lau & Mink, 2006; Oki, 2003; USGS NWIS, 2015). West Maui Mountains are home to at least 175 native plants and animals, as well as high-elevation aquatic fauna (WMP-WC, 2012). Socio-economically, freshwater is essential for the mountainous scenery, supporting the tourism industry responsible for 80% of Maui County's economic productivity, and 75% of all private sector jobs. There were 2,186,279 visitors to Maui in 2010, with average spending of $173 per day per visitor (CM, 2012).

Unfortunately, invasive species has been a prominent cause of biodiversity loss in Hawai‘i for over a century (WMP-WC, 2015). Over 200 non-native weed species (Swarzenski *et al.*, 2013) fish and crustaceans are also found in the conservation, agricultural and urban districts (Brown, 2008; WMP-WC, 2012). Invasive plant and feral animals in the upper Conservation District of Wahikuli and Honokōwai Watersheds pose a threat to the watershed and its water resources. Non-native invasive plants degrade native ecosystem by altering the fire regime, limiting native plant growth, and promoting growing herbivore (WMP-WC, 2012). Feral pig presence causes increased runoff and soil loss (Browning, 2008) through increased erosion, while feral cats (Curran & de Sherbinin, 2004) ecosystem.

In addition, anthropogenic activities have degraded freshwater benefits by diverting streams and altering land use. The ditch system (Figure 18) in Maui has been diverting streams for irrigation and potable uses while altering the runoff flow(Swarzenski *et al.*, 2013) rate and sediment discharge from the agricultural areas, and the natural streamflow towards the ocean. In West Maui, Honokōwai Ditch diverts water from Amalu and Kapaloa Streams, and Honokohau Ditch from Honokohau, Kaluanui and Honolua Streams. In ‘Īao watershed, Waihee Ditch and Spreckels Ditch are still in use. Furthermore, agricultural land use decline in 1926–2004 decreased groundwater recharge ~44% (2.6 to 1.5 x $10^6$ $m^3$/day) in central and west Maui (Engott & Vana, 2007). Meanwhile, water quality in the study area is degraded due to land-based pollutants from agriculture (Dailer *et al.*, 2010; WMWMAC, 1997), residential and resort land use activities (WMP-WC, 2012), wastewater injections at Lahaina and Kahului Wastewater Reclamation Facilities (Dailer *et al.*, 2010; Hunt & Rosa, 2009), and cesspools (Dailer *et al.*, 2010; WMP-WC, 2012, 2015). Accordingly, nitrogen and silica concentrations were found to be higher in submarine groundwater discharge than coastal waters at study sites near golf courses and bare land within a 5-km radius of the coastline (Knee *et al.*, 2010).

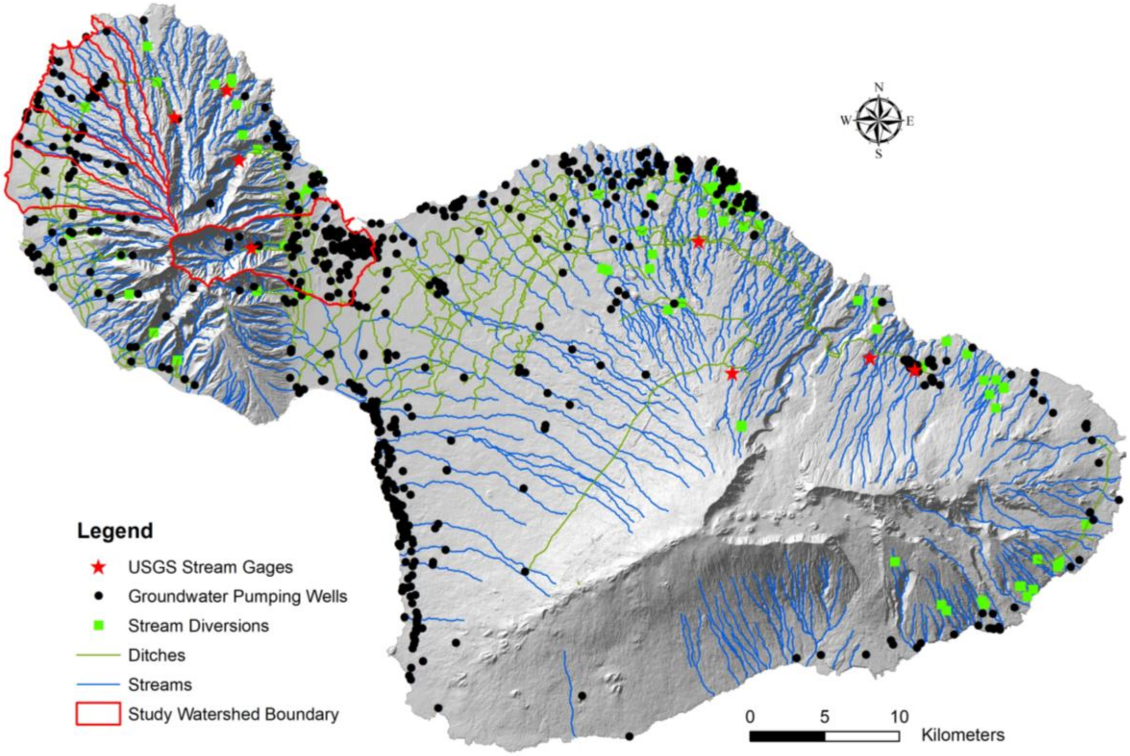

*Figure 18. Surface and Groundwater extractions in Maui are indicating the intricate nature of the local freshwater system. USGS stream gauges available for SWAT model calibration are shown here as well.*

Despite declining freshwater systems, the population in Maui has increased over the years with higher domestic and industrial water demands (Figure 19). Reduced water system features and higher water demand are expected to affect human well-being (economic, social or personal through freshwater services, and the delivery of these services will be affected by future environmental changes, population dynamics, management policies, and cultural (Dailer *et al.*, 2010; WMWMAC, 1997).

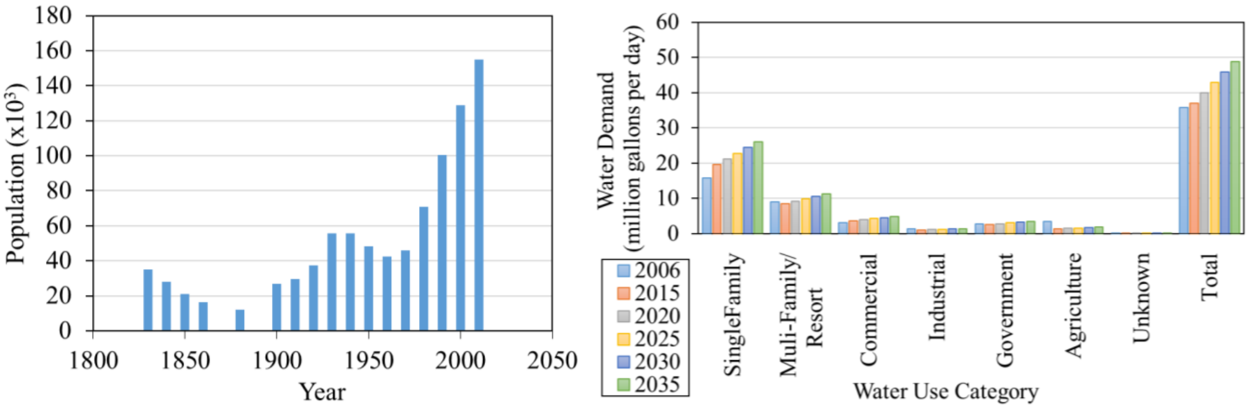

*Figure 19. Rising Maui County population from 1830 to 2013 (USCB, 2010) (left), and water demand from 2006 to 2035 (right). 2035 population is projected from 2015. Source: CWRM 2008 and Maui Department of Water Supply, January 7, 2014 Email.*

Climate Change Scenarios

Current and future climate change scenarios (see *Figure 20*) were expected to affect freshwater ecosystem services in the study area. The baseline daily rainfall (Figure 20) and temperature of 1990-2009 (Longman et al., 2017) were used for the current scenario. For climate change in 2081-2100, I used predicted rainfall and temperature from the statistically downscaled long-term (30-yr average) data based on 32 global climate models according to the IPCC's Representative Concentration Pathway (IPCC) RCP 4.5 and 8.5 (Elison Timm et al., 2015). To calculate future absolute daily rainfall and temperature, I multiplied the median predicted anomalies for the late-century climate with baseline scenario. As the data is only available for seasonal timescale (wet and dry), the same anomalies were assumed at the daily time step. The wet season is defined as November-April and dry season as May-October rainfall (Elison Timm *et al.*, 2015). In addition, for relative humidity, wind speed and solar radiation, I used projected values from the dynamically downscaled long-term (30-yr average) data based on Hawaiian regional climate model (Zhang *et al.*, 2016b).

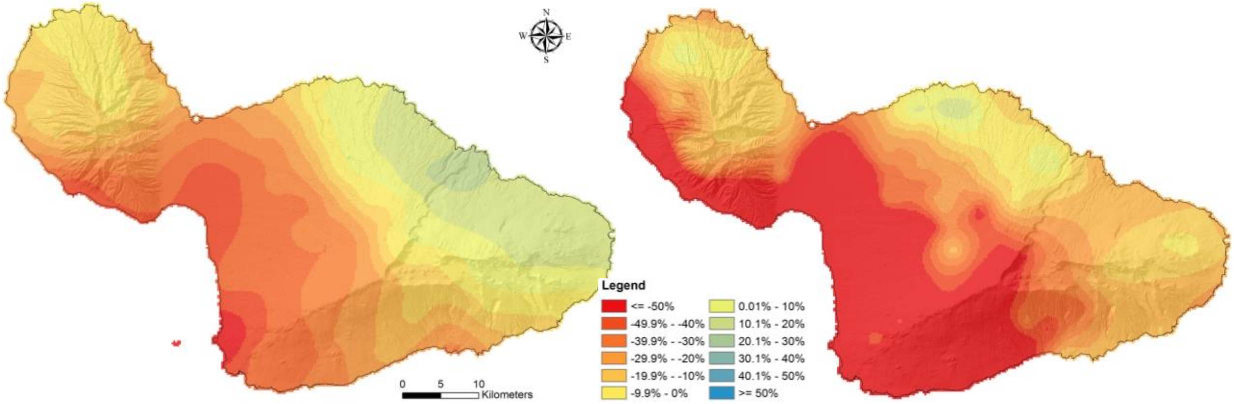

*Figure 20. Seasonal average rainfall anomaly from 2070 to 2100 based on RCP 8.5 scenario (wet season – left and dry season – right).*

While some claim there is minimal or no cloud water interception (fog drip) in the leeward watersheds (Engott & Vana, 2007; Scholl *et al.*, 2004), others (Gingerich & Engott, 2012; Johnson *et al.*, 2014) assumed it is possible to see fog interception and calculated accordingly. So, I also calculated fog interception based on the approach used in (Johnson *et al.*, 2014). Final precipitation included approximately 2 mm per day of fog in addition to the daily rainfall.

In addition, the hydrological model required $CO_2$ as an input. Mauna Loa Observatory measurements indicated average $CO_2$ value from 1990 to 2009 (354 + (387-354)/2 = 370.5 ppm) was 370 ppm (MLO, 2016).

## Land Use/Cover Change Scenarios

Land use/cover scenarios (current and future,) were expected to impact on freshwater ecosystem services (see Figure 21). Current land use/cover for the study watersheds in Maui (see Figure 22) was based on modified 2010 LandFire GIS coverage (USGS, 2010). Future land use/cover maps in 2100 (i.e., Green, Managed Growth, and Growth) were based on 2010 map with different levels of development with growth boundaries, and active environmental concerns resulting in alien plant and animal expansion. Moreover, energy demand for population and tourism growth was also considered by replacement of sugarcane with diversified agriculture (potential biofuel crops). In addition, varying degrees of stream restoration in combination with development, water demands (PacRISA, 2015) were reflected in the future land use/cover scenarios.

Future land use/cover scenarios were not created with a unified stakeholder vision of occurring at the end of the century, and it was possible that they might occur sooner [personal communication with original project investigator]. Therefore, I assumed that the future land use/cover scenarios were indeed likely to occur from 2080 to 2100 for this study.

(a) (b) (c)

*Figure 21. Water supply (a) can be altered by environmental as well as anthropogenic changes. Erosion (b) and sediment export (c) into the coastal waters have profound environmental*

*impacts. Photo credits: (a) The Nature Conservancy, (b) Kirsten Oleson and (c) Kenneth Bagstad.*

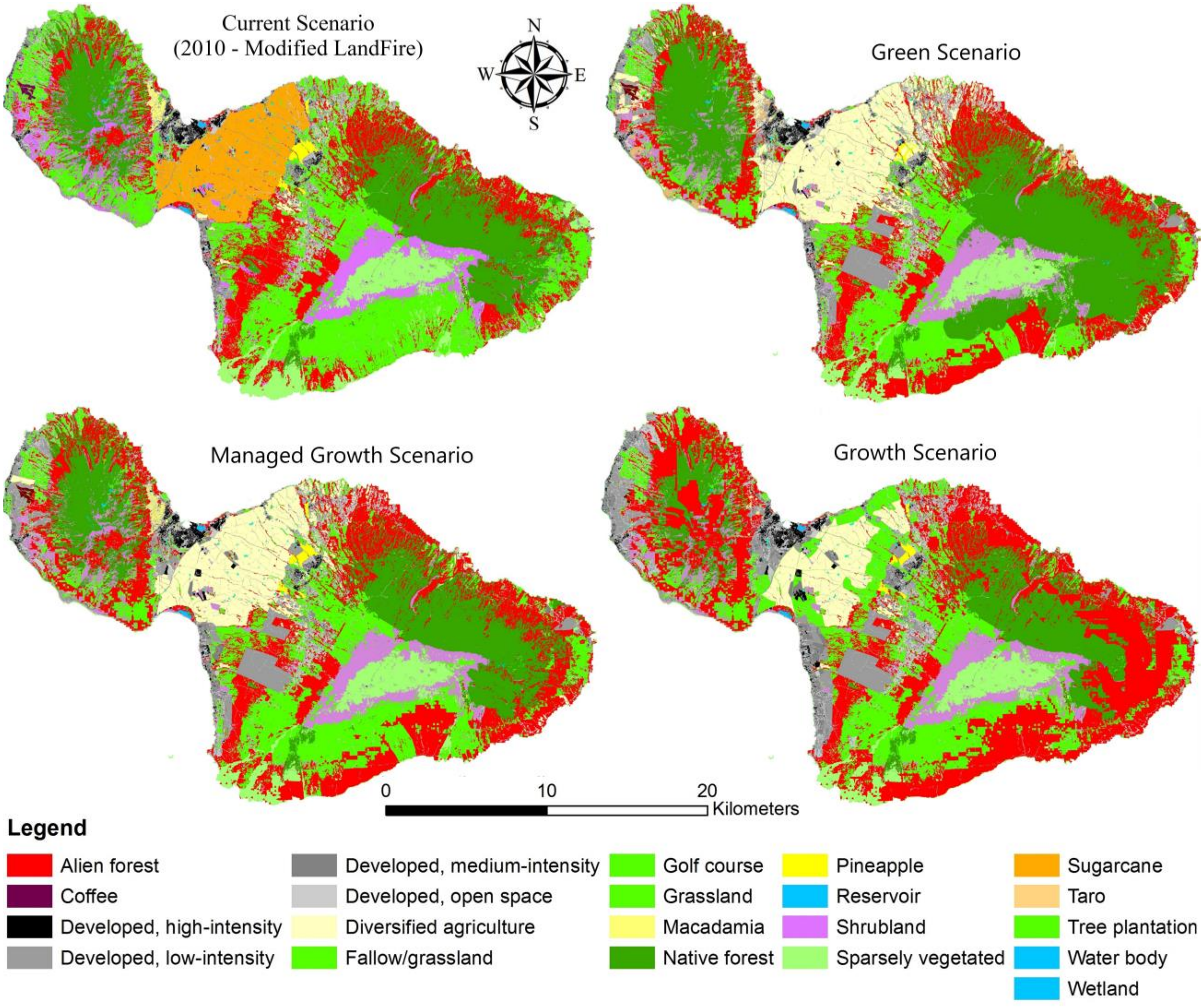

*Figure 22. Current (2010) Land Use/Cover – Johnson et al. 2014, and Future Green, Managed Growth and Growth Land Use/Cover (2100) –(PacRISA, 2015). Future maps (2050) represent different levels of aggressive development (approved in 2013), native forest area reduction, alien plants expansion (modeled by the USGS and US-FWS) and inactive environmental control. Fallow/grassland and diversified agriculture (potentially biofuel) replace sugarcane for growing energy demands in response to population and tourism growth. Restoration of streamflow is incomplete: streams stay at their current levels.*

### Management Policy Scenario

A particular management policy, instream flow standard, and its impacts on the freshwater ecosystem goods and services are important for understanding the freshwater system. Under the State Water Code (Code), Chapter 174C, Hawaiʻi Revised Statutes (HRS), the Commission on Water Resources Management (CWRM) establishes instream flow standards for each stream to regulate the amount of flowing water (with natural variability) according to its conditions in

1988 and 1989. These standards are specified to protect freshwater flora and fauna, instream and non-instream uses (CWRM, 2008; Miike, 2004). A comprehensive instream flow standard assessment includes information about hydrology, instream uses, and non-instream uses. It encompasses water transfers, their advantages and disadvantages the users are facing in the study watersheds.

Considering the local water resources to understand the impacts and stakeholders' responses, the first step of ES-IWRM approach includes imposing current and projected environmental changes. Informed by Study One, I used SWAT (Soil and Water Assessment Tool) to model the watershed dynamics under current and projected conditions.

Step 2: Modeling Surface Water

Land use and climate scenarios were modeled using SWAT. Hydrological model inputs for SWAT included a digital elevation model, soil, land cover, rainfall, temperature, relative humidity, solar radiation, and wind speed (Table 13) at 1km resolution. Then, model outputs were calibrated using observed streamflow, sediment, and nutrient, as well as published model runoff for areas with no observed streamflow. The base flow separation program estimated surface runoff and baseflow (a combination of groundwater discharge and subsurface flow) (Wahl & Wahl, 1995) from observed streamflow.

*Table 13. SWAT model inputs, calibration data, and sources.*

| Model Inputs | Source |
|---|---|
| **Digital elevation model** | NOAA Coastal Services Center (NOAA-CSC, 2014) |
| **Soil** | Soil Survey Geographic Database (USDA NRCS, 2014b) |
| **Land cover** | Pacific RISA, NOAA (Brewington *et al.*, 2016) |
| **Current Climate Variables (1990-2009)** | |
| **Rainfall, temperature (minimum and maximum)** | Rainfall Atlas of Hawaiʻi (Longman *et al.*, 2017) |
| **Relative humidity, solar radiation, wind speed** | IPRC, UH Manoa (Zhang *et al.*, 2016a) |
| **Future Climate Variables (2080-2099)** | |
| **Rainfall, temperature (minimum and maximum) at a seasonal timescale** | DAES, UAlbany (Elison Timm *et al.*, 2015) |
| **Relative humidity, solar radiation, wind speed** | IPRC, UH Manoa (Zhang *et al.*, 2016b) |
| **Calibration Data** | |
| **Observed streamflow data** | USGS (USGS NWIS, 2016) |
| **Published actual evapotranspiration** | Evapotranspiration of Hawaiʻi, UH Geography (Giambelluca *et al.*, 2014) |
| **Published direct runoff** | USGS (Johnson *et al.*, 2014) |
| **Observed sediment and nutrients** | USGS (USGS NWIS, 2016) and HI DOH (HDOH - CWB, 2017) |

Next, I ran SWAT model for seven different climate/land use/cover scenarios (Table 14): current climate and current land use/cover, as well as two future climate and three different future land use/cover scenarios. Detailed subbasin delineation was necessary for representing high spatial variation for the island. For study watersheds, 168 subbasins were in leeward study watersheds, and 100 were in windward, ‘Iao, watersheds (Appendix 3A).

*Table 14. Hydrological model, SWAT, scenarios.*

| **Scenarios** | **Climate** | **Land Use/Cover** |
|---|---|---|
| **Reference** | Current (1990 to 2009) | Current (2010 – modified LandFire) |
| **Scenario 1** | Future (2080 to 2099) – RCP 4.5<br>(or) Medium Climate Change (MCC) | Growth |
| **Scenario 2** | Future (2080 to 2099) – RCP 4.5<br>(or) Medium Climate Change (MCC) | Managed Growth |
| **Scenario 3** | Future (2080 to 2099) – RCP 4.5<br>(or) Medium Climate Change (MCC) | Green |
| **Scenario 4** | Future (2080 to 2099) – RCP 8.5<br>(or) High Climate Change (HCC) | Growth |
| **Scenario 5** | Future (2080 to 2099) – RCP 8.5<br>(or) High Climate Change (HCC) | Managed Growth |
| **Scenario 6** | Future (2080 to 2099) – RCP 8.5<br>(or) High Climate Change (HCC) | Green |

Then, SWAT model results were used as inputs into the participatory model, FCMM. SWAT gives precise change in watershed outputs (streamflow, sediments, and nutrients) under the environmental scenarios for the coupling of the eco-hydrological model and the participatory model. A participatory model enables the integration of both contemporary and traditional knowledge for successful policy adoption and implementation in ecosystem-services based water resources management. Both forms of knowledge are essential for the local communities to learn and adapt to the growing population and changing climate as well as land use/cover.

### *B: Participatory Modeling*

The overall approach to eliciting local freshwater benefits followed a procedure similar to the one in Stier *et al.* (2017), and it included:

1. Do initial interviews (3-5) with several members of different stakeholder groups to define concerns of water quality and quantity changes, to understand the freshwater-supported human well-being, and to understand perceived drivers of change;
2. Identify and create an email list of stakeholders (55) to administer a larger survey;
3. Listen to the interview recording for proof and complete the FCMMs.
4. Group survey results into four stakeholder classifications:
    a. using the respective interviewee's career, interest, and knowledge of the FES or perceived impacts on their freshwater values.
    b. using centrality, an FCMM structural metric, and multivariate statistics including Hierarchical Clustering (with dendrogram), K-Means clustering, PAM

(Partitioning Around Meoids), CLARA (Clustering Large Applications), and Model-based Clustering in R (R Core Team, 2016); Five methods were used to increase accuracy. I compared the results from five clustering methods using three clustering metrics: Within Cluster Sum of Squares, Average Silhouette Width, and Dunn Index. Within Cluster Sum of Squares indicates how closely related stakeholders are in clusters; the smaller the value, the more closely related objects are within the cluster. Next, Average Silhouette Width shows how well stakeholders are clustered, and how well clusters are separated from each other. The silhouette value usually ranges from 0 to 1; a value closer to 1 suggests the data is better clustered. Finally, Dunn Index determines if the data set contains compact and well-separated clusters, indicated by higher index. Accordingly, I looked for smaller Within Cluster Sum of Squares and higher Average Silhouette Width and Dunn Index.

5. Run FCMM scenarios on these models to understand how human well-being will change due to climate and land use/cover trends in the area;
6. Analyze similarities and differences across/within groups in which human well-being will be impacted by environmental and policy/behavior changes.

### Step 3a: Defining stakeholder groups

There are several stakeholders (governmental and non-governmental), who manage the supply and demand of freshwater, and its quality and quantity in Maui. It is essential to understand stakeholders' roles for ecosystem services-based water resources management. Four groups of stakeholders exist in Maui - water resources managers, conservationists, agriculturalists, and cultural practitioners. I compared the freshwater values of stakeholders in leeward (west Maui) and windward (ʻĪao) watersheds to investigate any differences in wet and dry areas.

#### Water Resources Managers

A water resources manager is anyone who manages freshwater quality and quantity. While CWRM primarily manages freshwater quantity, DOH regulates freshwater quality. In addition, Department of Land and Natural Resources (Division of Aquatic Resources) enforces appurtenant rights, upholds existing correlative and riparian uses of Hawaiʻi's water resources, and manages the state's aquatic resources and ecosystems. Management of water includes planning, surveying, regulating, monitoring, and conservation (CWRM, 2008). In Maui, management extracts surface and groundwater (see Figure 18), and plans storage and allocation for current and future users (see (). For conservation, resource managers implement agricultural road drainage improvements, sediment retention basins, and vegetated filter strips for reducing land-based source pollutants. Moreover, alternative wastewater disposal plans are in effect to limit nutrients in SGD (WMP-SI, 2012).

### Conservationists

Conservation of native plants and animals reduces pollutant load and conserves freshwater resources. Most of the Hawaiian Islands' streams begin in the tropical montane cloud forests where protection and conservation efforts are in motion (Loope & Giambelluca, 1998). West Maui Mountain Watershed Partnership has fenced certain forest regions to protect them from feral ungulates and removed the weeds and pests (WMMWP, 2015).

### Agriculturalists

Since ancient Hawaiian times, agriculture has been a way of life. In the early 20th century, plantations in the west and central Maui used about 100 billion gallons per year of mostly stream-diverted water (Engott & Vana, 2007). Irrigation of these plantations artificially recharged groundwater, yet less water was available for downstream smaller agriculturalists. Around the 1990s, Major plantations dwindled, but most diversions have not been released for natural streamflow. Downstream farmers, as well as environmentalists, have pressed for the release of diversions so that they can have their water rights for farming operations. Meanwhile, agriculturalist's traditional and customary rights are protected by CWRM and inflow stream standards.

To preserve the FES goods and services, agriculturalists manage the water quantity and quality related to farming operations. Following the water quality permits from Dept. of Health Clean Water Branch, agriculturalists conserve water and control the field-runoff so that fewer pesticide and sediment outflow down the streams or watercourses into the ocean. Local small farm owners take pride in their agricultural culture as their heritage and identity.

### Cultural Practitioners

For a cultural practitioner, water resources management means preserving several culturally important ecosystem benefits such as recreation, education, aesthetics, and heritage sites (Plieninger *et al.*, 2013). Stream preservation is important for cultural practitioners. Historically, land tenure system was centered on streams (kahawai) with land divisions called ahupuaʻa (DAR, 2015; Kaneshiro *et al.*, 2005). Further, continuously flowing freshwater is required to grow kalo (taro or *Colocasia esculenta*), while eating kalo as poi is a ritual that brings family and friends together, and regarded as showing appreciation of ancestors (ʻaumakua) (Canoeplants, 2015). In addition, prehistoric Hawaiians built loko iʻa kalo, freshwater irrigated agricultural fishponds, for breeding fish and growing taro (Kikuchi, 1976). A 1990 survey estimated 488 fishponds statewide (Hlawati, 2001), and they are significant cultural heritage sites (Sproat & Higuchi, 2015). There is a bonding stemming from sharing of knowledge, talking stories of traditional experiences, place-based legends of gods/goddesses, volunteering/helping one another in weeding, planting kalo fields. Next, for spirituality, flowing stream is required for the growth of aquatic species to make lei and adorn hula altar. According to a legend, Kāne, one of the four Hawaiian gods, struck the earth bringing springs and streams alive for use (Handy, 1972). Locals believe the life-giving energy of Kāne still flowing within the waters. Furthermore, cultural practitioners preserve the cultural identity that links humans and their environment (MEA, 2005;

Tengberg *et al.*, 2012). Hawaiʻi has 2082 flora and 2656 fauna (~50% endemic) (Evenhuis & Eldredge, 2002), and they require abundant and good quality water. These species provide a unique cultural experience through activities including hiking and bird watching (Chan *et al.*, 2012). Also, abundant native species, complex hydrogeology, and diverse microclimates make Hawaiʻi a unique place of learning for scientific research as well as culture-based education (i.e., from elders (kūpuna) and petroglyphs (kiʻi pōhaku)).

Traditions and knowledge systems reveal people's connection with and management of their freshwater system in the past (Triandis, 1994). Their inclusion in current and future sustainable management (Tengberg *et al.*, 2012) is highly pertinent for solving current water resources management issues (Kaneshiro *et al.*, 2005).

### Step 3b: Eliciting and Building Fuzzy Cognitive Mapping Models

I elicited stakeholders' perceptions and built individual FCMMs for each stakeholder including water resource managers, ecologists, conservationists, and agriculturists.
After obtaining Human Subjects Research program certificate and filing documents including Consent Form, I received approval from University of Hawaiʻi Internal Review Board as an exempt research study (ID - CHS #23424) (see Appendix 3B). Using an email list from a previous research project, and snowball approach, I developed a new email list for my research and reached out to fifty-five potential informants. Thirty people responded, twenty-seven people were interviewed, and twenty-two people completed their FCMMs.

Following an interview script (see Appendix 3B), I started each interview with a brief introduction of the study objectives and FCM software, mental modeler (Gray, 2016). All the interviews were one-to-one in-person interviews that lasted an average of sixty minutes. While the interviewee elaborated on my research questions, I drew FCMs on his/her perceptions of the freshwater system with its components and relationships. Interviews were recorded upon consent. In each FCM, freshwater system features were connected to the stakeholders’ freshwater values.

### Step 4: Coupling Models including Developing Fuzzy Cognitive Mapping Model Scenarios

I coupled the SWAT and FCMMs by translating the watershed model outputs in a form appropriate for the FCMM. First, ecohydrologic model outputs were converted into relative values (in percentages) from a baseline (2010) scenario. Next, the relative values were further translated into FCMM scenarios by converting them into one of the seven levels of change in comparison to the baseline scenario using fuzzy-logic approximation between +1 and -1, inclusive. Each set of FCMM values for individual environmental scenario was used for FCMM scenario analysis.

To compare and contrast the mental-model predictions of stakeholders, certain structural metrics (e.g., concept and relationship counts, centrality, density, and hierarchy index) were calculated for the mental model adjacency matrices. These metrics gave me estimates of the degree of shared knowledge across individuals or groups (Gray *et al.*, 2012; Ozesmi & Ozesmi, 2004). For example, concept and relationship counts of different mental models indicated increase/decrease in structural complexities and connectivity of the same system. The centrality of a given component represented its relative importance in the whole system (Gray *et al.*, 2014). In addition, density indicated the number of components capable of changing the system while hierarchy index revealed stakeholder's view of system structure as either hierarchy (i.e., top-down influence) or democratic (equal influence) (Gray *et al.*, 2014; MacDonald, 1983).

### *C: Model Evaluation*

Mental model validation for informing decision support is done by assessing if model behavior coincides with human expert's responses under different scenarios (van der Werf & Zimmer, 1998). There are two available processes: (a) statistical approach on calibration data using bootstrap, cross-validation or Jack-knife techniques; (b) comparison approach using predicted and observed values (Guisan & Zimmermann, 2000). I performed a sensitivity analysis (SA), accompanied by the comparison approach between mental model predictions and observations based on published literature. Next, uncertainty analysis (Appendix 3A) of the coupled model is evaluated using first order uncertainty analysis (FOUA).

#### Step 5: Sensitivity analysis

For sensitivity (SA), a "one-variable-at-a-time" approach was used to examine the sensitivity of the SWAT model output due to each important input parameter (Saltelli *et al.*, 2000). Specific parameters were chosen based on published literature and, more importantly, calibration and validation in the study area. For the FCMM, I computed structural metrics (see Appendix 2B) including indegree, outdegree, transmitter and receiver components, density, complexity, and hierarchy index (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004). In addition, I conducted Monte Carlo simulation suggested for FCMM sensitivity analysis (Jetter & Kok, 2014).

#### Step 6: First-order Uncertainty Analysis

First-order Uncertainty Analysis (FOUA) used the SA-identified and -selected sensitive model parameters. FOUA quantified the contribution of each selected parameter to the overall variances of model outputs (Wu *et al.*, 2006). SA gave parameters, as well as a variance from a predefined range of values. "Means" were calibrated values, and variance were calculated based on range values reported in SWAT manual and FCMM range [-1, 1]. For variance values, probability distributions were estimated for the sensitive parameters. Next, FOUA assumed that model uncertainty followed truncated Taylor's series linear approximation, and the parameters were uncorrelated Wu *et al.* (2006).

***Results***

*Hydrological Model*

The SWAT model predicted direct runoff, sediment and nutrients (nitrogen and phosphorus) for the seven scenarios reported in Table 15. All the scenarios were run considering surface water diversions: ditches and their diverted water came from CWRM's 2002 inventory (CWRM, 2008).

*Table 15. The SWAT model outputs used as watershed dynamics in Fuzzy Cognitive Mapping modeling. "W" is for windward ('Īao or Wailuku) watershed, and "L" is for leeward (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua) watersheds. All values are annual means.*

| **Scenarios** | **Climate** | **Land Use/ Cover** | **Streamflow ($m^3/s$) x $10^{-1}$** | | **Sediment Load (ton/yr) x $10^2$** | | **Nitrogen (kg/yr) x $10^4$** | | **Phosphorus (kg/yr) x $10^3$** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | W | L | W | L | W | L | W | L |
| **Reference** | Current | Current | 13.3 | 20.7 | 2.67 | 30.4 | 5.08 | 5.91 | 4.09 | 12.4 |
| **1** | MCC | Growth | 8.69 | 17.2 | 2.18 | 39.3 | 5.27 | 6.27 | 2.95 | 13.9 |
| **2** | MCC | Managed Growth | 8.70 | 17.2 | 1.80 | 32.5 | 4.79 | 6.03 | 2.65 | 12.7 |
| **3** | MCC | Green | 8.54 | 17.7 | 1.83 | 26.8 | 4.85 | 5.57 | 2.43 | 10.9 |
| **4** | HCC | Growth | 7.55 | 16.5 | 2.01 | 37.1 | 5.62 | 6.14 | 2.67 | 13.5 |
| **5** | HCC | Managed Growth | 7.58 | 16.6 | 1.64 | 31.5 | 5.12 | 5.94 | 2.40 | 12.5 |
| **6** | HCC | Green | 7.39 | 17.0 | 1.67 | 26.5 | 5.10 | 5.50 | 2.19 | 10.8 |

The SWAT model outputs which include several water budgets and quality components, were calibrated against observed as well as previously published data. Modeled direct runoff under current climate and land use (Table 16) was within an acceptable range of USGS stream gauge (16604500) data for the Wailuku River at Kepaniwai Park (Figure 23), as well as published runoff data for leeward watersheds from USGS (Johnson *et al.*, 2014).

Water quality values for the east of West Maui were available for only one USGS stream gauge (16618000), Kahakuloa stream. I used Kahakuloa as a proxy for nearby 'Īao watershed. For Kahakuloa stream, simulated sediment, nitrogen, and phosphorus were close to the observed data.

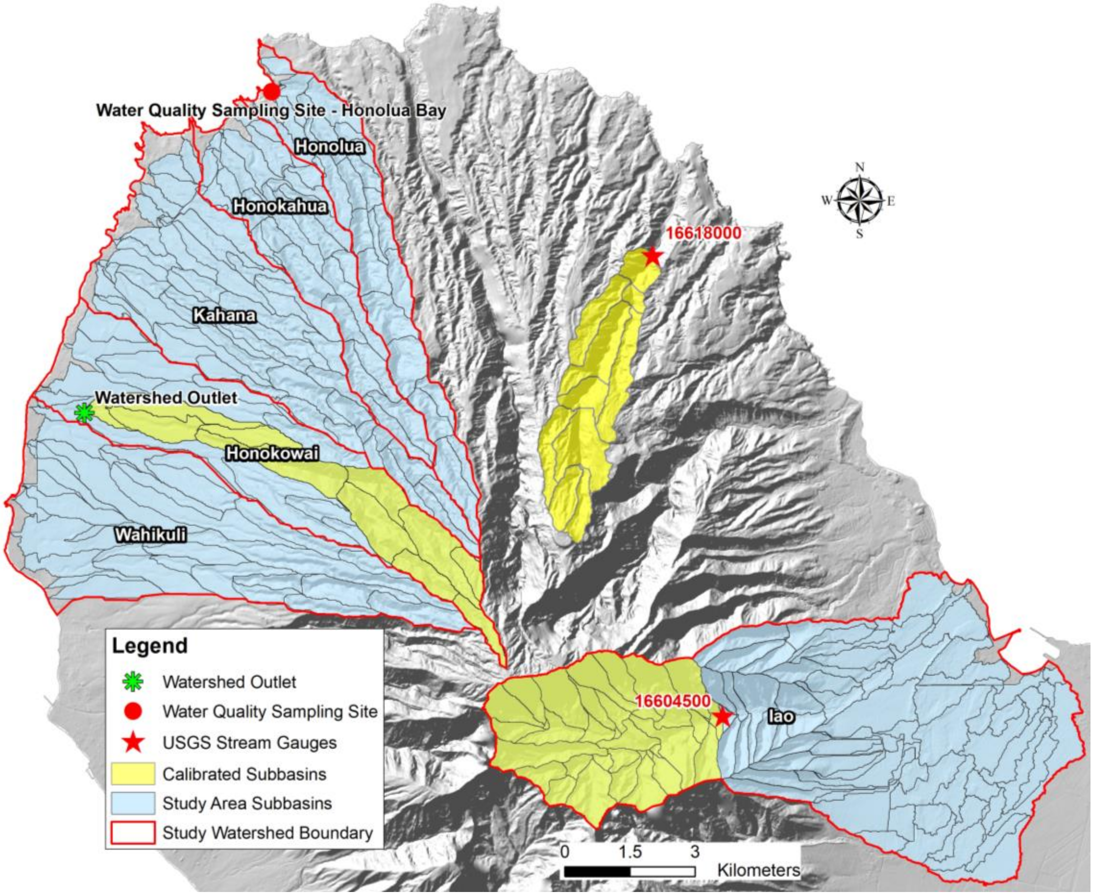

*Figure 23. Water quantity and quality calibration data observation and sampling sites with Wahikuli, Honokowai, Kahana, Honokahua and Honolua watersheds (left), and ʻĪao and Kahakuloa watersheds with their subbasins and USGS stream gauges (right).*

*Table 16. Water budget components calibration results (modeled or observed) for annual and daily means. For leeward watershed, sediment output is compared against published data (Stock et al., 2016), while nitrogen and phosphorus are from an offshore water quality site at Honolua Bay.*

| Freshwater Components | Windward (%) | Leeward (%) |
|---|---|---|
| **Model over Observed Water Quantity Values (Annual Mean)** | | |
| **Surface Runoff** | 99.87 | 93.14 |
| **Streamflow** | 107.8 | Not Applicable |
| **Evapotranspiration** | 104.3 | 95.35 |
| **Model over Observed Water Quality Values (Daily Mean)** | | |
| **Sediment** | 93.68 | 105.1 |
| **Nitrogen** | 92.86 | 105.8 |
| **Phosphorus** | 100.8 | 73.59 |

Differences in the water budget components were due to residual error from climate variables and structural error from the SWAT model itself. Modeled evapotranspiration was higher than observed on the windward side because of possible high solar radiation values, which I was unable to calibrate. Further, observed daily sediment and nutrient data were sparse (52 days for Honolua and 27 days for Honokowai watersheds). Therefore calibration was done for daily mean, rather than daily values. While sediment and nitrogen were calibrated well, observed phosphorus in the leeward watersheds was still far from the observed values. The only available data for the leeward watersheds was measured near shore rather than at the river mouth. Therefore, dilution and dispersion of stream discharge with seawater may be the reason for the gap.

### *Fuzzy Cognitive Mapping Models*

Individual in-person interviews produced FCMMs of stakeholders’ perceptions of freshwater system characteristics, and impacts of changes. To conceal the identity of the twenty-seven interviewees, I used codes such as I-1, I -2, etc. Twenty-two individuals completed an FCMM (see Appendix 3A), three respondents finished partial FCMMs and two wanted to relay information without drawing FCMMs. The count of components and relationships from all twenty-seven interviews are described below and summarized in Table 17.

The minimum component count was 10, and the maximum was 25. The fewest relationships was 8, and the most 46. Interviewees described water quantity as streamflow, groundwater quantity or recharge, and water quality as either surface or groundwater quality. When prompted, twenty people discussed climate change and twenty-two mentioned water transfer (via diversions) that affect the local freshwater system. Twenty-five people mentioned provisioning FES in the form of agricultural irrigation for food security and sovereignty, groundwater recharge for drinking water purposes. Seventeen interviewees highlighted one or more form of cultural services, including traditional agricultural and cultural practices, such as gathering plants, shrimps, snails, and fish, as well as inspiration, aesthetic, viewshed, tourism, and contribution to a pleasant life. Eight people connected these services to a healthy and functioning watershed (ahupuaʻa) and estuary (muliwai). Finally, seventeen interviewees emphasized the essential link between management, policy, enforcement, and the continued supply of FES using a tool such as the instream flow standards.

*Table 17. Fuzzy cognitive mapping models with their characteristics. The values 0 and 1 denote presence and absence of mentioning of a particular item.*

| **Interviewee Codename** | **Component Count** | **Negative Relationship Count** | **Total Relationship Count** | **Cultural FES** | **Provisioning FES** | **Supporting FES** | **Management, Policy, Education, and Enforcement** |
|---|---|---|---|---|---|---|---|
| **I-1** | 21 | 9 | 21 | 0 | 1 | 1 | 0 |
| **I-2** | 21 | 16 | 42 | 0 | 1 | 0 | 0 |
| **I-3** | 23 | 18 | 39 | 1 | 1 | 0 | 1 |
| **I-4** | 20 | 10 | 23 | 1 | 1 | 0 | 1 |
| **I-5** | 23 | 13 | 30 | 1 | 1 | 0 | 1 |
| **I-6** | 19 | 10 | 20 | 1 | 1 | 0 | 1 |
| **I-7** | 24 | 19 | 27 | 1 | 1 | 1 | 0 |
| **I-8** | 24 | 15 | 32 | 0 | 1 | 0 | 0 |
| **I-9** | 23 | 10 | 34 | 0 | 1 | 0 | 1 |
| **I-10** | 18 | 8 | 18 | 0 | 1 | 0 | 0 |
| **I-11** | 25 | 7 | 27 | 0 | 1 | 0 | 1 |
| **I-12** | 20 | 18 | 46 | 1 | 1 | 1 | 1 |
| **I-13** | 10 | 3 | 8 | 1 | 1 | 0 | 0 |
| **I-14** | 24 | 10 | 30 | 1 | 0 | 0 | 1 |
| **I-15** | 18 | 9 | 25 | 0 | 1 | 0 | 1 |
| **I-16** | 19 | 10 | 23 | 1 | 1 | 1 | 1 |
| **I-17** | 21 | 19 | 39 | 1 | 1 | 0 | 0 |
| **I-18** | 23 | 10 | 27 | 1 | 1 | 1 | 1 |
| **I-19** | 27 | 7 | 37 | 1 | 1 | 0 | 1 |
| **I-20** | 16 | 10 | 19 | 1 | 1 | 0 | 0 |
| **I-21** | 17 | 13 | 29 | 0 | 0 | 0 | 1 |
| **I-22** | 25 | 12 | 36 | 1 | 1 | 0 | 0 |
| **Total Count** | | | | 14 | 20 | 5 | 13 |
| **Incomplete FCMM** | | | | | | | |
| **I-23** | 33 | - | - | 1 | 1 | 1 | 1 |
| **I-24** | 34 | - | - | 1 | 1 | 1 | 1 |
| **I-25** | 18 | - | - | 0 | 1 | 0 | 0 |
| **I-26** | 18 | - | - | 0 | 1 | 0 | 1 |
| **I-27** | 20 | - | - | 1 | 1 | 1 | 1 |
| **Grand Total Count** | | | | 17 | 25 | 8 | 17 |

### *FCM Translation to Develop FCMM Scenarios*

To couple the SWAT model with the stakeholder FCMMs, quantitative watershed model outputs (Table 15) were converted into the qualitative levels of change (i.e., H+/-, M+/-, L+/- or N) as in Table 18. Levels of change described the relative influence of each component on others (Lin & Lee, 1996), and were accompanied by membership weights (Glykas, 2010). And, these membership weights were defined using triangular membership functions (Figure 24).

The x-axis in Figure 24 indicates the watershed components, and the y-axis represents the weights for membership function. The horizontal line segment at the ends of the figures represent high negative or positive. For example, scenario 4 for the windward watershed (see Table 15) produced the lowest streamflow (0.755 $m^3/s$) would be less than, 0.94 $m^3/s$ (Figure 24), and therefore it was denoted as a high negative (H-) level of change for streamflow (Table 18). Scenario 4 belonged to the H- function with a membership function weight of 1, as do all the scenarios with RCP8.5 climate change. Next, watershed component with values between the extremes were defined using triangular membership functions as shown in Figure 24. The y-value from the individual straight-line equation gives weight of the level corresponding to the x-value. For instance, nitrogen output under the scenario 1 for the windward watershed would have both M+ and H+ levels of change. M+ has a straight-line equation of y = -13.793*10^(-4)*x + 73.069, and H+ has y = 13.793*10^(-4)*x - 72.069. For 5.27*10^4 kg of nitrogen, y-values for M+ and H+ are 0.38 and 0.62 respectively. That is, the scenario had 0.38 M+ and 0.62 H+ level of change (Table 18).

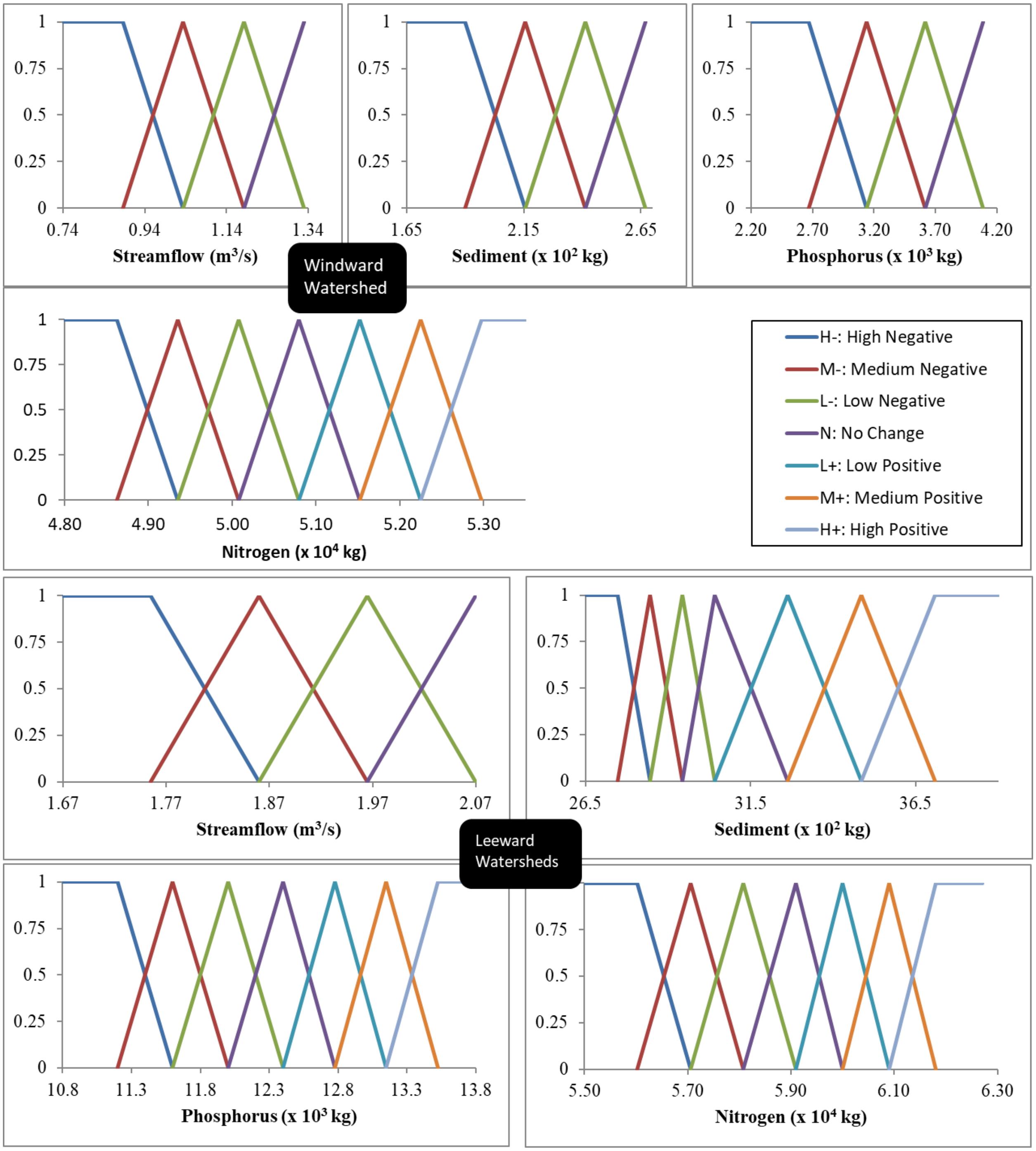

*Figure 24. Real space to fuzzy space conversion of climate change and watershed model outputs in terms of levels of change (i.e., N, H-, M-, L-, H+, M+, and L+). Line graphs indicate a change (i.e., y-value) at an x-value with a range of uncertainty in the expert opinion. For example, the leeward watersheds could see a low negative change of nitrogen at 5.8x$10^4$ kg/year with a range of uncertainty from 5.72*$10^4$ to 5.9*$10^4$ kg/year. Fuzzy space recognizes and enables the overlapping of levels of change, as indicated by the overlapping of line graphs. For instance, a 5.8*$10^4$ kg/year of nitrogen would be 0.07M- & 0.93L- in fuzzy space.*

*Table 18. Interpretation of watershed model outputs to fuzzy space levels of change (N = No Change, H- = High Negative, M- = Medium Negative, L- = Low Negative, H+ = High Positive, M+ = Medium Positive. "W" is for windward ('Īao or Wailuku) watershed, and "L" is for leeward (Wahikuli, Honokōwai, Kahana, Honokahua, and Honolua) watersheds.*

| Scenarios | Climate | Land Use/ Cover | Streamflow | | Sediment Load | | Nitrogen | | Phosphorus | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | W | L | W | L | W | L | W | L |
| | Current | Current | N | N | N | N | N | N | N | N |
| 1 | MCC | Growth | H- | H- | 0.90M- & 0.10L- | H+ | 0.38M+ & 0.62H+ | H+ | 0.40H- & 0.60M- | H+ |
| 2 | MCC | Managed Growth | H- | H- | H- | 0.85M+ & 0.15H+ | H- | 0.67L+ & 0.33M+ | H- | 0.20N & 0.80L+ |
| 3 | MCC | Green | H- | 0.86H- & 0.14M- | H- | H- | H- | H- | H- | H- |
| 4 | HCC | Growth | H- | H- | 0.56H- & 0.44M- | H+ | H+ | 0.44M+ & 0.56H+ | 0.99H- & 0.01M- | 0.07M+ & 0.93H+ |
| 5 | HCC | Managed Growth | H- | H- | H- | 0.87L+ & 0.13M+ | 0.45N & 0.55L+ | 0.67N & 0.33L+ | H- | 0.73N & 0.27L+ |
| 6 | HCC | Green | H- | H- | H- | H- | 0.72N & 0.28L+ | H- | H- | H- |

### *Stakeholder Clustering*

I interviewed twenty-seven stakeholders from various organizations (governmental and non-governmental) as well as residents. For further analysis, I divided interviewees into different stakeholder groups according to their expertise, interest, occupations revealed through the interviews and FCMMs. According to their focus on the freshwater values, I classified seven as water resources manager, ten as conservationists, five as agriculturalists and five as cultural practitioners.

A key hypothesis of this research was that different ex ante-defined stakeholder groups would have similar conceptions of the SES. To test this, I used metrics of centrality to compare ex ante clustering against FCMM structure-defined clustering. The centrality-derived process started with qualitative recoding of the components in all of the FCMMs, which resulting in collapsing ~278 components to 51. Only water quality and water quantity were common to nearly all of the interviewees. In addition, I found five variables namely, land use/cover change (n = 18), diversion (n = 18), cultural ecosystem services (n = 15), climate change (n = 18), and precipitation (n=20). Based on the results of qualitative recoding, clustering exercise indicated that FCMM for I-19 had the maximum centrality value (13.5) across all 22 FCMMs, a score much higher than other FCMMs, causing it to be an outlier. Therefore, I modified its centrality for water quantity so that it is the same as the next highest value (8) so that it can be grouped with the rest of the water resources managers with whom had very similar components. In addition, I replaced NA with zeros for components that appeared in fewer than 22 FCMMs, because clustering techniques required no inclusion of NA values.

I compared the results from five clustering methods, looking for smaller Within Cluster Sum of Squares and higher Average Silhouette Width and Dunn index. K-Means had the smallest Within Cluster Sum of Squares, second largest Average Silhouette Width, and largest Dunn Index (Table 19), and therefore, K-Means was selected for further analysis. I plotted using silhouette width and determined the optimal number of clusters as four (Figure 25). Positive silhouette width values from the silhouette plot indicated that all the stakeholders were in the correct groups.

*Table 19. Clustering statistics for centrality-derived stakeholder classification. Smaller "Within Cluster Sum of Squares"indicates more agreement of stakeholders within the assigned groups. Positive and higher "Average Silhouette Width" means stakeholders fall correctly in the assigned groups. Higher Dunn index means higher separation among the assigned groups.*

| | **Within Cluster Sum of Squares** | **Average Silhouette Width** | **Dunn index** |
|---|---|---|---|
| **Hierarchical** | 148.506 | 0.218294 | 0.40107 |
| **K-Means** | 145.054 | 0.225913 | 0.444262 |
| **PAM** | 171.802 | 0.139439 | 0.289346 |
| **CLARA** | 169.366 | 0.154933 | 0.289346 |
| **Model-based** | 226.526 | 0.245254 | 0.304997 |

There are similarities and differences between ex ante and centrality-derived clustering, resulting in different combinations of stakeholders. For instance, ex ante clustering had all three stakeholders in cluster 1 of centrality-derived clustering in different groups (Figure 25). However, centrality-derived clustering placed them together, possibly due to their mutual concern over diversion and change in land use/cover. Further, cultural practitioners dominated cluster 2, and conservationists were the majority in cluster 4. Finally, cluster 3 had a mixture of stakeholders with mostly either conservation or water resources management in mind.

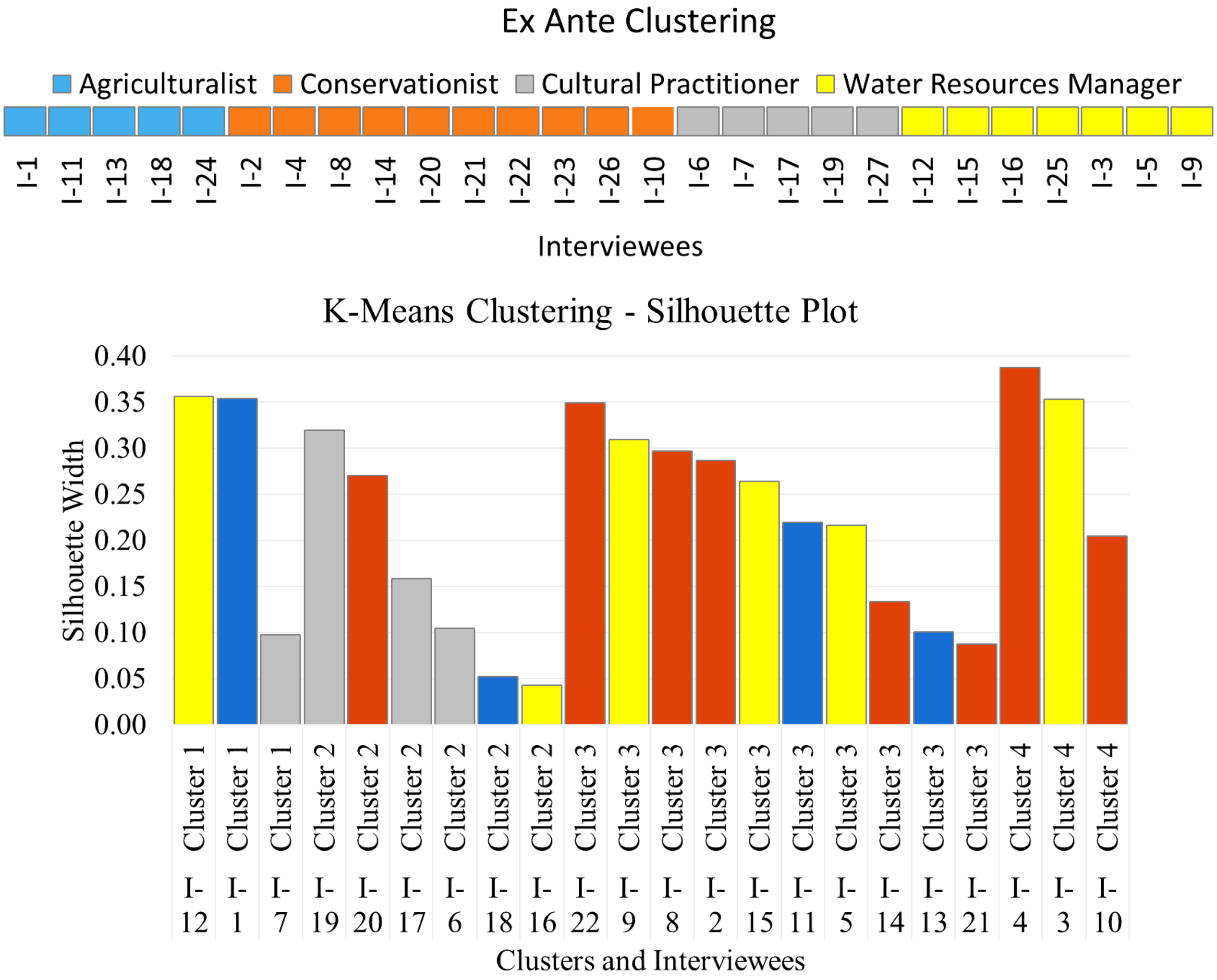

*Figure 25. Clustering stakeholders using ex ante approach (top) and centrality metrics of their FCMMs (bottom). Blue bars represent agriculturalists, orange represents conservationists, gray represents cultural practitioners, and yellow represents water resources managers. Ex ante clustering groups all 27 stakeholders based on their main FES interest or concern. In the silhouette plot, stakeholders (x-axis) have positive silhouette widths (y-axis), indicating correct placement of stakeholders within clusters. Silhouette plot groups only those stakeholders with complete FCMM while their main FES interest or concern are still unaccounted for in the clusters, producing unclear results.*

Both methods revealed insights into the stakeholders' perceptions regarding the freshwater resources. However, only the ex ante method considered stakeholders' interests, concerns, occupations, and expertise, and all the twenty-seven stakeholders including the five incomplete FCMMs. Moreover, centrality-based clustering depended entirely on the component with the most relationships, and the results did not indicate stakeholder groups clearly (Figure 25). For example, cluster 1 had three interviewees with three different water interests, but they were grouped together because they have similar components affecting water quantity. However, careful observation of FCMM from interviewee I-12 and the personal interview itself indicated that I-12 had concerns and interests for water resources management (Appendix 3A). FCMM for I-12 had high centrality values for the ecosystem function enabling cultural FES such as gathering plants and growing taro, management via instream flow standards and fencing, and concerns over the sustainable yield of groundwater and future water demand. Therefore, grouping I-12 as a water resources manager was more appropriate as in the ex ante clustering results; and the ex ante clusters were used for further analysis.

### *Model Coupling to Reveal Impacts of Change on Conditions that Stakeholders Value*

Seven FCMM scenarios were run on each stakeholder model to predict how climate and land use/cover change would impact freshwater quality- and quantity-related outcomes to stakeholders. All of the FCMMs are presented in Appendix 3A. Below, I present a comparison of the scenario outcomes for some conditions common to many of the FCMMs: water quantity, water quality and freshwater ecosystem services (Figure 26). I selected one model from each ex ante-defined stakeholder group to discuss in detail of some common conditions for the group.

As shown in Figure 26, the majority of the FCMMs predicted that water quantity available for use would decline in the future. The few exceptions (i.e., I-3, I-5, and I-6) expected some management action or adaptation policy in their FCMMs, namely low impact developments, conscientious homeowners, alien species removal, and instream flow standards. In contrast, water quality was predicted to improve in the future, except for I-5 (under four out of six scenarios), I-15, and I-21 (very slightly). Water quality declined for these stakeholders because of high pollutant concentrations under Growth scenarios for I-5, and mainly under Growth and Managed Growth scenarios for I-19.

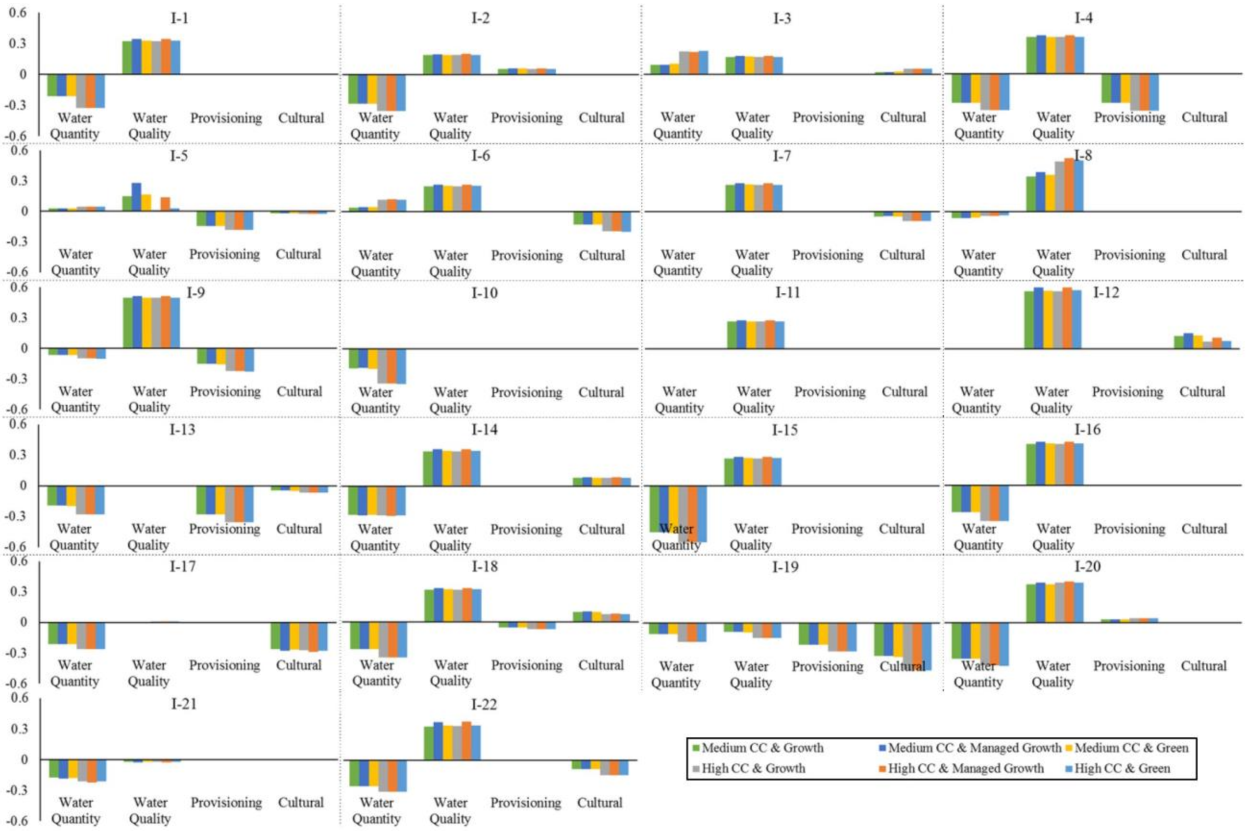

*Figure 26. Model results for all complete FCMMs under the six climate and land use/cover change scenarios. CC stands for Climate Change. A positive number indicates an improvement, and a negative number represents a decline.*

Water Resources Managers

Seven individuals were classified as water resources managers based on the ex ante approach. Manager I-5, in particular, perceived that water quantity and quality would improve slightly despite the decline in streamflow under some of the scenarios for both windward and leeward watersheds (Figure 27). Manager I-5 also expected water quality improvement for Managed Growth and Green scenarios. I-5 indicated that proper management could still improve available water quantity and its quality. The slight increase in water quantity and quality was not enough to improve traditional agricultural practices and groundwater recharge in the future, however, so FES declined. In addition, diversion, as well as storage and transmission of freshwater, would decrease.

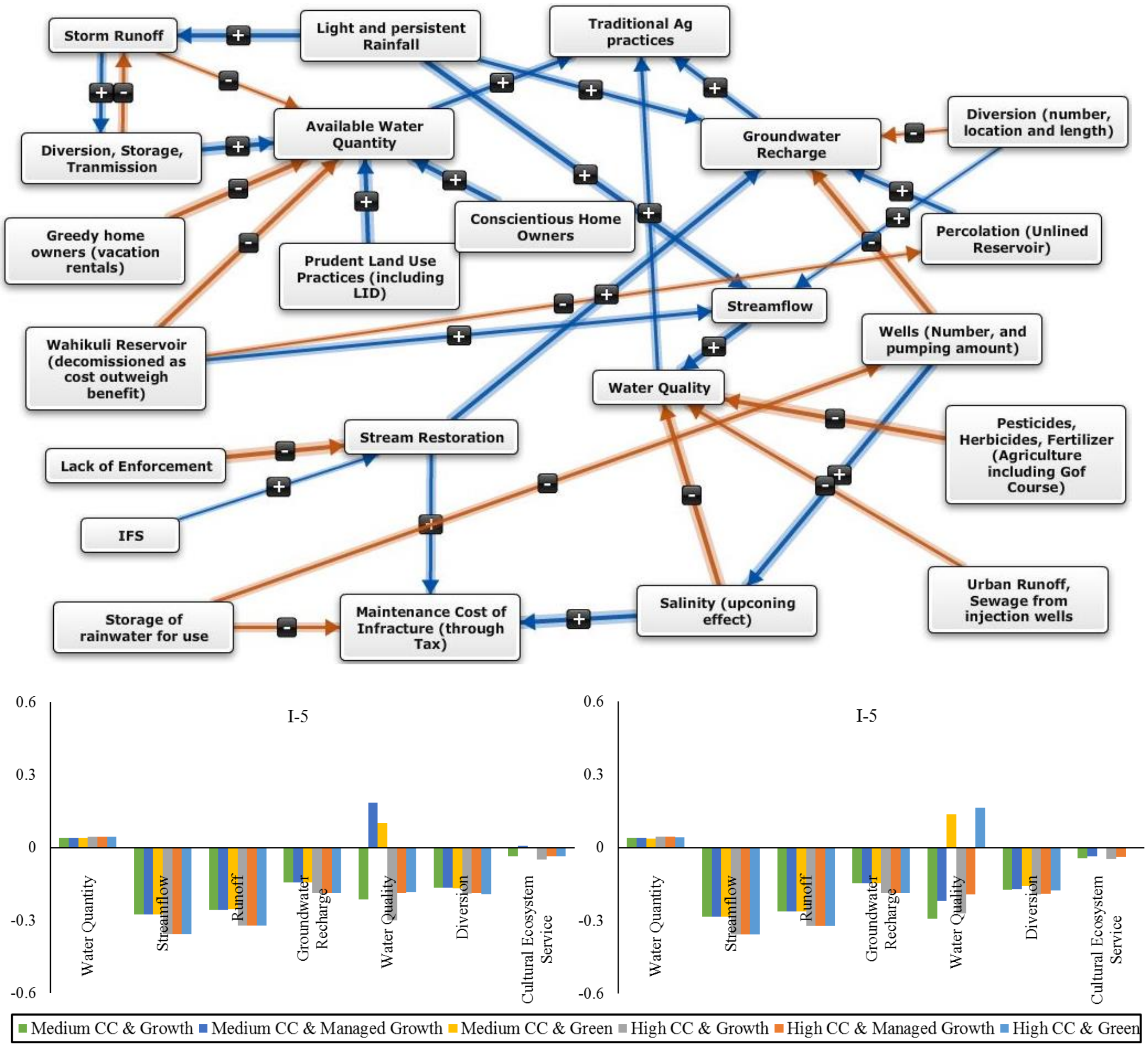

*Figure 27. FCMM for I-5 (top) and relative change in some freshwater system components under the fuzzy cognitive map scenarios for the windward (bottom left) and the leeward watersheds (bottom right).*

Water resources managers had similar perceptions on watershed-scale management, mitigation plans, and policy implementation. I-3, I-5, I-9, and I-15 indicated that better management, enforcement, and agricultural practices are essential for groundwater recharge. Further, I-3 mentioned the need for improvement in current management for better-funded future management of invasive species, forest fires, and surface runoff. An example of management practice, low impact development, was pointed out by I-15 to help mitigate negative urbanization impacts on streamflow quantity. Also, I-9 indicated that improvements in policy for sustainable and local agriculture are important for reducing pollutant runoff and stream diversion while promoting native plant species. Moreover, instream flow standards were cited by I-5, I-12, and I-16 as necessary regulations for stream restoration, water quality improvement, and support of cultural practices. Specifically, I-12 perceived that the regulations have positive impacts on traditional practices such as growing taro and gathering aquatic plants while reducing stream diversion and commercial agriculture. The cultural significance of gathering aquatic plants is also particularly important for I-12. Finally, I-16 emphasized that meaningful long-term policy and planning is essential for ecosystem functioning and cultural uses of freshwater.

Conservationists

Ten individuals were classified as conservationists. For I-2, water quantity decreased, but quality improved under the future environmental conditions (Figure 28). Positive water quality promoted the freshwater needs of the instream organisms, and the nearshore marine community. However, water quantity decline reduced agricultural production and increased fire in the future.

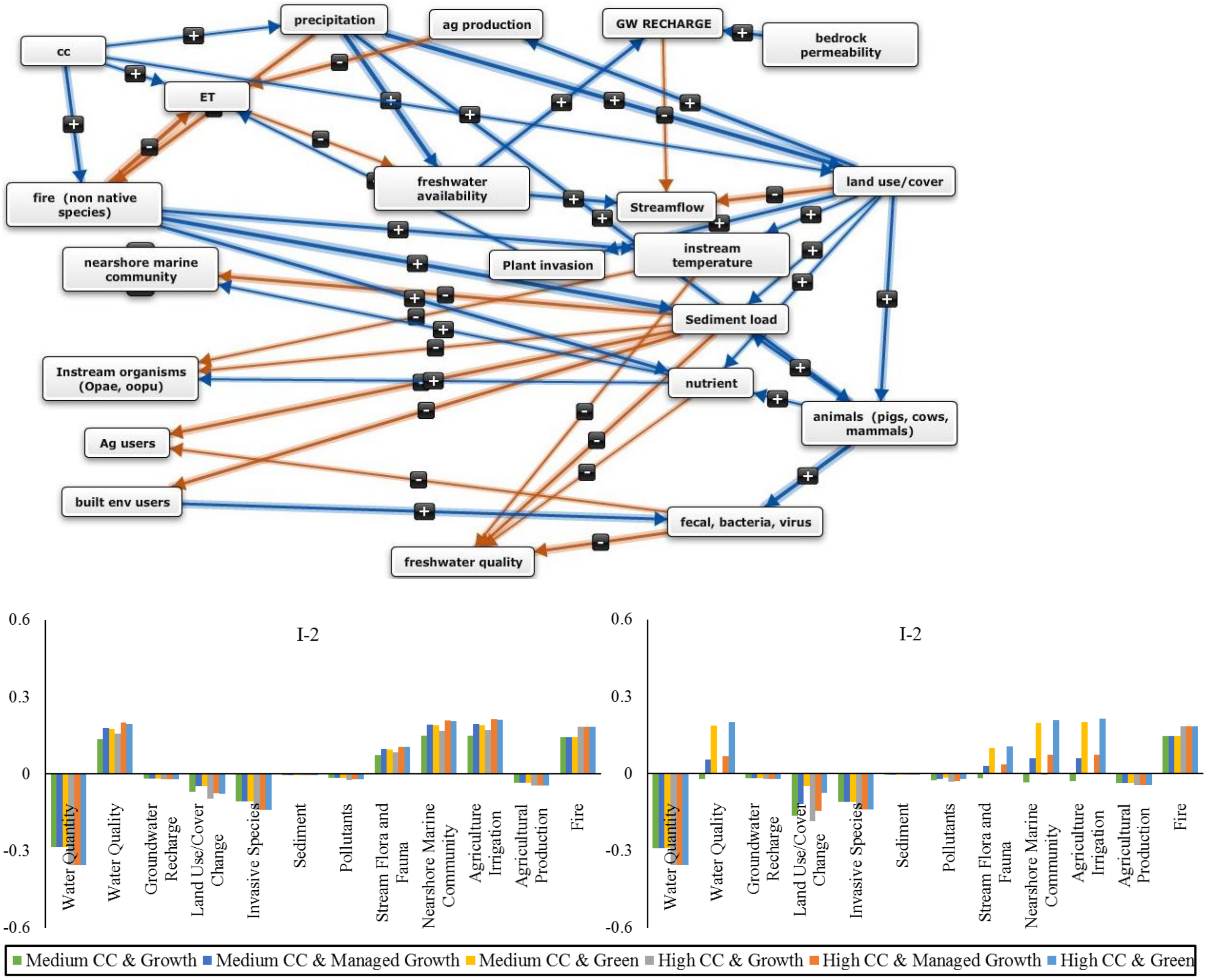

*Figure 28. FCMM for I-2 (top) and relative change in some freshwater system components under the fuzzy cognitive map scenarios for the windward (bottom left) and the leeward watersheds (bottom right).*

Common components across conservationists were the restoration of streams and instream native species, remediation actions to limit land-based source pollutants, and education of public on environmental issues. I-2, I-4, I-8, I-14, I-21, and I-22 noted that declining land use/cover due to urbanization increases instream temperature for the aquatic species, sediment, pesticides, and pollutant runoff. On the other hand, I-8 and I-14 emphasized the importance of native forests with shrubs and mosses in improving water quality and water quantity. I-4 mentioned the negative impacts of aging wastewater infrastructure on water quality and cited best management practices as a solution. While I-14 mentioned urbanization as a source of degradation for taro farming due to seepage from cesspools and septic tank, I-20 pointed out that cultural practices promote pollutant retention. Further, while I-4 indicated the importance of education on proper onsite disposal systems maintenance for improving water quality, I-21 mentioned that education on the benefits of green infrastructure and water use efficiency could help mitigate water scarcity. For I-22, regulating stream flow is important for a greener environment, cultural uses of water and promoting a happy life. One major deviation from the rest of the conservationists is that urban development is noted as a necessary component for a robust local economy.

### Agriculturalists

Five individuals were classified as agriculturalists. Particularly, I-18 perceived available water quantity reduction but water quality increase (Figure 29) for all the scenarios in the windward watershed, and some in the leeward watersheds except the growth scenarios. Declining precipitation and increasing temperature caused groundwater recharge to drop. On the other hand, water quality improvement encouraged a slight increase in kalo (taro) weight and quality as well as kalo field as habitat for stilts and other native species in all scenarios in the windward watershed and green scenarios in the leeward watersheds.

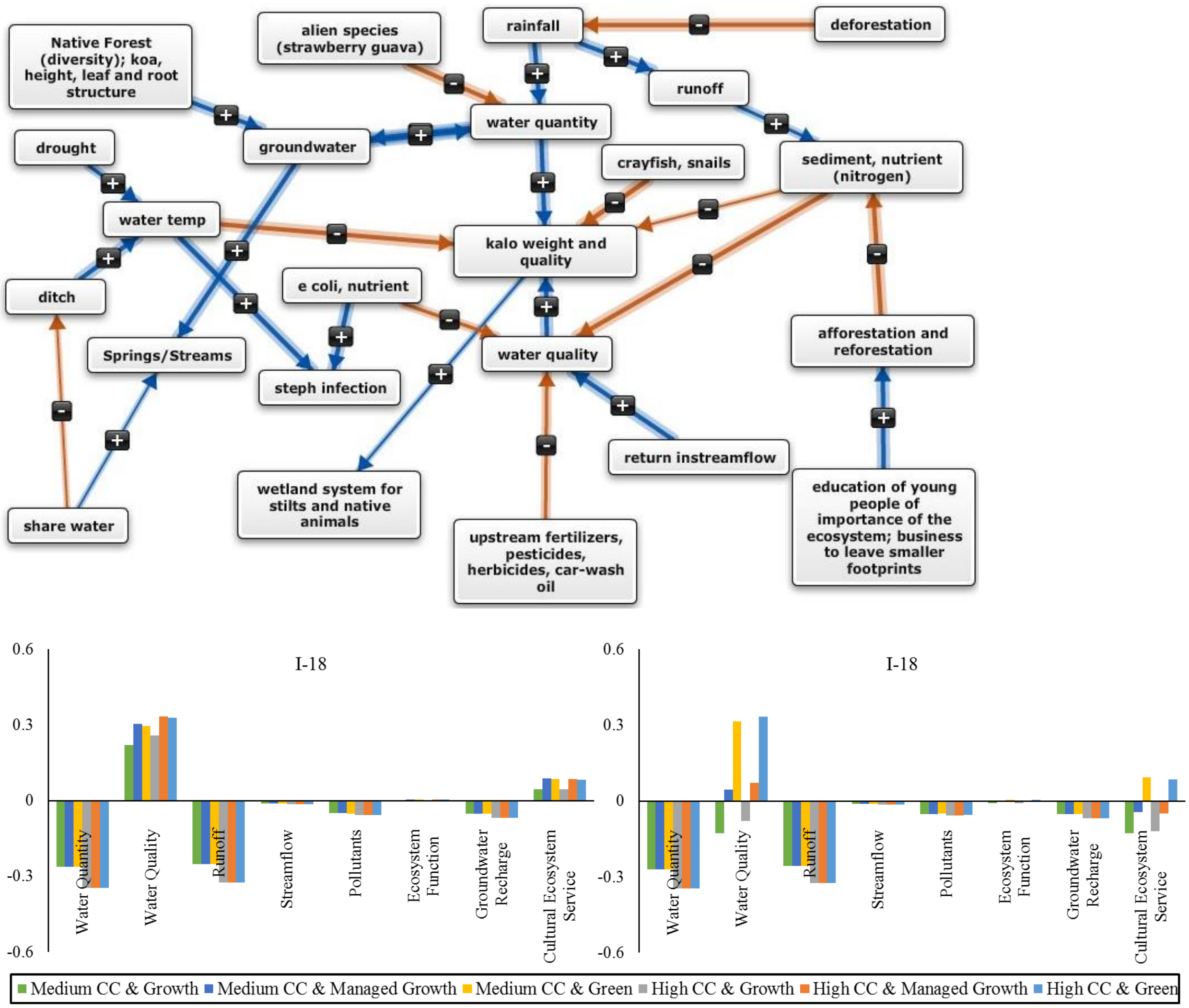

*Figure 29. FCMM for I-18 (top) and relative change in some freshwater system components under the fuzzy cognitive map scenarios for the windward (bottom left) and the leeward watersheds (bottom right).*

Agriculturalists highlighted the importance of water resources for agricultural operations. Loss of freshwater resources meant the loss of livelihood as well as loss of cultural identity for agriculturalists. As a sustenance farmer, I-11 stated that food security and sovereignty depend on freshwater availability. Also, I-1 and I -11 stated stream diversion is helpful for farming that largely depends on diverted water. However, I-1 and I-13 also argued that uncontrolled diversion is decreasing water quantity (i.e., streamflow), and causing loss of ecological and hydrological functions. Moreover, I-1, I-11, and I-18 identified land-based source pollutants as the source of water quality degradation. But, I-11 also pointed out that improved biological control and organic farming leads to better water quality. Finally, I-1, I-13, and I-18 mentioned the importance of freshwater for cultural practices such as fishing and taro farming. I-18 specifically mentioned that taro weight and quality is very much dependent on water quantity and quality. Also, the taro field is a wetland system, creating a habitat for stilts and native animals.

### Cultural Practitioners

Five individuals were classified as cultural practitioners. I-6 expected quantity and quality to increase for freshwater resources (Figure 30) due to contested cases and instream flow standards. Diversion reduction in the future would be good for taro farming with very little change in taro yield, as well as agricultural production. However, for the projected environmental conditions, a decline in water quantity was a negative driver for the cultural identity of wai (water), fishponds and stream fauna and flora.

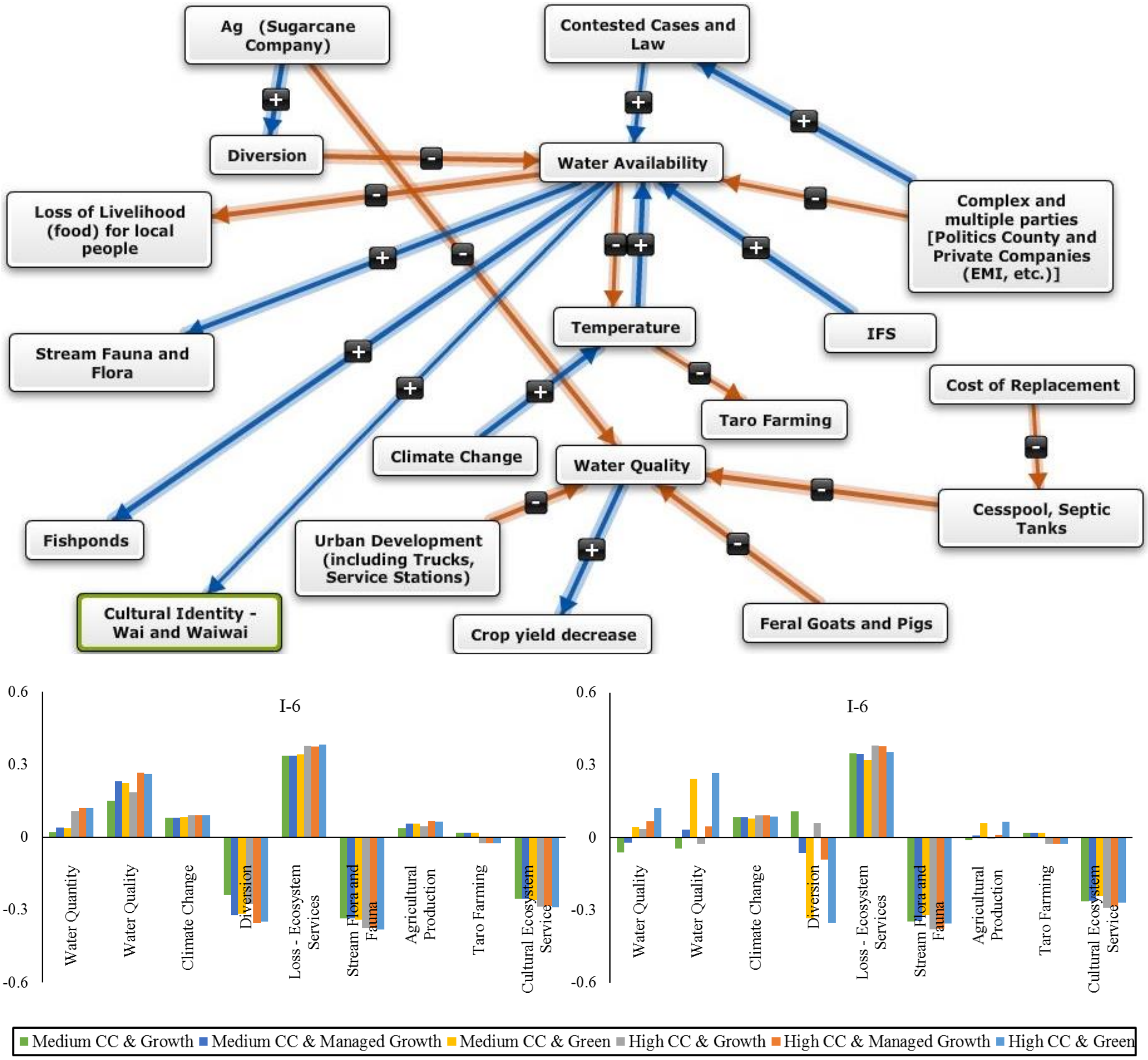

*Figure 30. FCMM for I-6 (top) and relative change in some freshwater system components under the fuzzy cognitive map scenarios for the windward (bottom left) and the leeward watersheds (bottom right).*

Cultural practitioners stressed the importance of water (wai) for cultural practices (i.e., taro farming), native flora and fauna, inspiration, and prayer (oli). All stakeholders in the group perceived that anthropogenic pollutants degrade the water quality. Also, they believed that the availability of freshwater resources affects taro farming, particularly taro weight and quality. Further, I-19 stated that while water quantity is important for the traditional taro farming, the farming practice itself promotes water quality. Besides taro farming, I-6 stated that water availability has impacts on cultural practices such as fishponds, and stream fauna and flora for gathering. I-7 mentioned that water quality is essential for productive regions for seaweeds and fishponds that have cultural significance. I-17 pointed out that water quantity and quality are crucial for native stream biota as well as inspiration and cultural identity. I-17 and I-19 stated that healthy native flora and fauna is important for water quantity and quality, recharging groundwater. Finally, I-19 mentioned that prayer is said during the drought for rain since ancient times.

*Model Evaluation*

For sensitivity analysis, the SWAT model outputs were first divided into two sets (i.e., ten years each) for calibration and validation. Adequate observed data was only available for the windward watershed, and therefore, leeward was not included in the analysis. I then compared annual average values in the Wailuku watershed (Table 20). Both calibration and validation had good statistics, including NSE, PBIAS, and RSR. The results from the validation are also illustrated using daily streamflow and 95% uncertainty bands around it (Figure 31).

*Table 20. Model over observed water quantity values (annual average) for windward – Wailuku watershed.*

| | **Calibration (1990-1999)** | **Validation (2000-2009)** |
|---|---|---|
| **Surface Runoff (%)** | 105.90 | 101.06 |
| **Streamflow (%)** | 109.56 | 107.05 |
| **Evapotranspiration (%)** | 106.34 | 104.35 |
| **$R^2$** | 0.95 | 0.97 |
| **Nash-Sutcliffe efficiency (NSE)** | 0.39 | 0.63 |
| **Percent Bias (PBIAS)** | -9.56 | -7.05 |
| **RSR** | 0.78 | 0.61 |

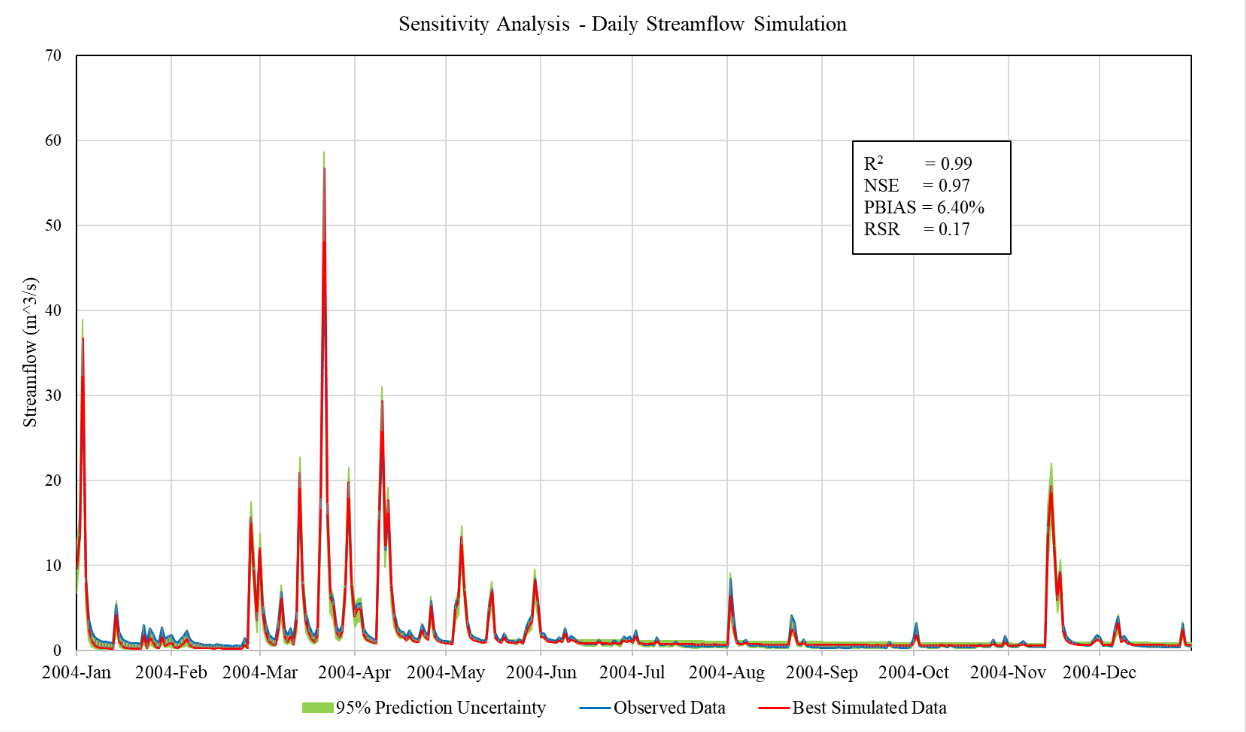

*Figure 31. Daily streamflow comparison in 2004 for the Wailuku River.*

## Sensitivity Analysis

Following a similar approach described by Wu *et al.* (2006), eleven input parameters (Table 21) were determined to be sensitive parameters (p-value <0.05) in the SWAT model using the SWAT-CUP model (Arnold *et al.*, 2012). Based on their parameter ranges and mean (calibrated) values, distribution for each parameter was estimated.

*Table 21. SWAT model sensitive parameters and their ranges. [a]Gamma or normal distribution (mean, standard deviation). [b] Triangular distribution (minimum, maximum, mode)*

| No. | Parameter | Parameter Explanation | t-Stat | P-Value | Specified Parameter Range | Distribution |
|---|---|---|---|---|---|---|
| 1 | SLSOIL | Slope length for lateral subsurface flow | 169.91 | 0.000 | 0 to 250 m | Gamma (15, 15)[a] |
| 2 | LAT_TTIME | Lateral flow travel time | 56.97 | 0.000 | 0 to 180 days | Triangular (0,120,180) [b] |
| 3 | SOL_K | Saturated hydraulic conductivity | -41.89 | 0.000 | 0 to 500 mm/hr | Gamma (20, 20) [a] |
| 4 | SOL_BD | Moist bulk density | -23.02 | 0.000 | 0.9 to 2.5 g/cm$^3$ | Normal (1.5, 0.44) [a] |
| 5 | SOL_AWC | Soil available water content | 11.77 | 0.000 | 0 to 1 | Gamma (0.010, 0.014) [a] |

| No. | Parameter | Parameter Explanation | t-Stat | P-Value | Specified Parameter Range | Distribution |
|---|---|---|---|---|---|---|
| **6** | CN2 | Initial SCS runoff curve number for moisture condition II. | 11.49 | 0.000 | 35 to 95 | Normal (76.33, 7.841) [a] |
| **7** | ESCO | Soil evaporation compensation factor | -9.46 | 0.000 | 0 to 0.95 | Triangular (0,1,1) [b] |
| **8** | ALPHA_BF | Baseflow alpha factor | 7.42 | 0.000 | 0 to 1 day | Gamma (0.048, 0.023) [a] |
| **9** | GWQMN | Shallow aquifer threshold depth for return flow | -3.98 | 0.001 | 0 to 5000 mm | Normal (1000, 475) [a] |
| **10** | SOL_CBN | Organic carbon content (% soil weight) | -2.63 | 0.017 | 0.05 to 10 % | Gamma (2.9, 2.9) [a] |
| **11** | EPCO | Plant uptake compensation factor | 2.58 | 0.019 | 0 to 1 | Gamma (0.10, 0.04) [a] |
| **12** | GW_DELAY | Groundwater delay time before becoming shallow aquifer recharge | 0.10 | 0.919 | 0 to 500 day | N/A |

For the FCMM sensitivity analysis, I conducted Monte Carlo simulation (see Appendix 3B) suggested by Jetter & Kok (2014). First, to determine FCMM characteristics and assess the quality of the participatory models, I computed FCMM structural metrics (see Appendix 2B) including indegree, outdegree, transmitter and receiver components, density, complexity, and hierarchy index (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004). Using a Monte Carlo simulation, I used a random function to simulate 10,000 FCMM scenarios (see Appendix 2B) for each of the ordinary components (i.e., components with both a non-zero indegree and outdegree) for the water quantity and quality, as well as freshwater ecosystem goods and services such groundwater recharge, taro farming, instream flora and flora, and cultural identity. The resulting tables in Appendix 3A and the following graphs (Figure 32) are structural metrics and Monte Carlo sensitivity outputs for the four representative stakeholders of each group.

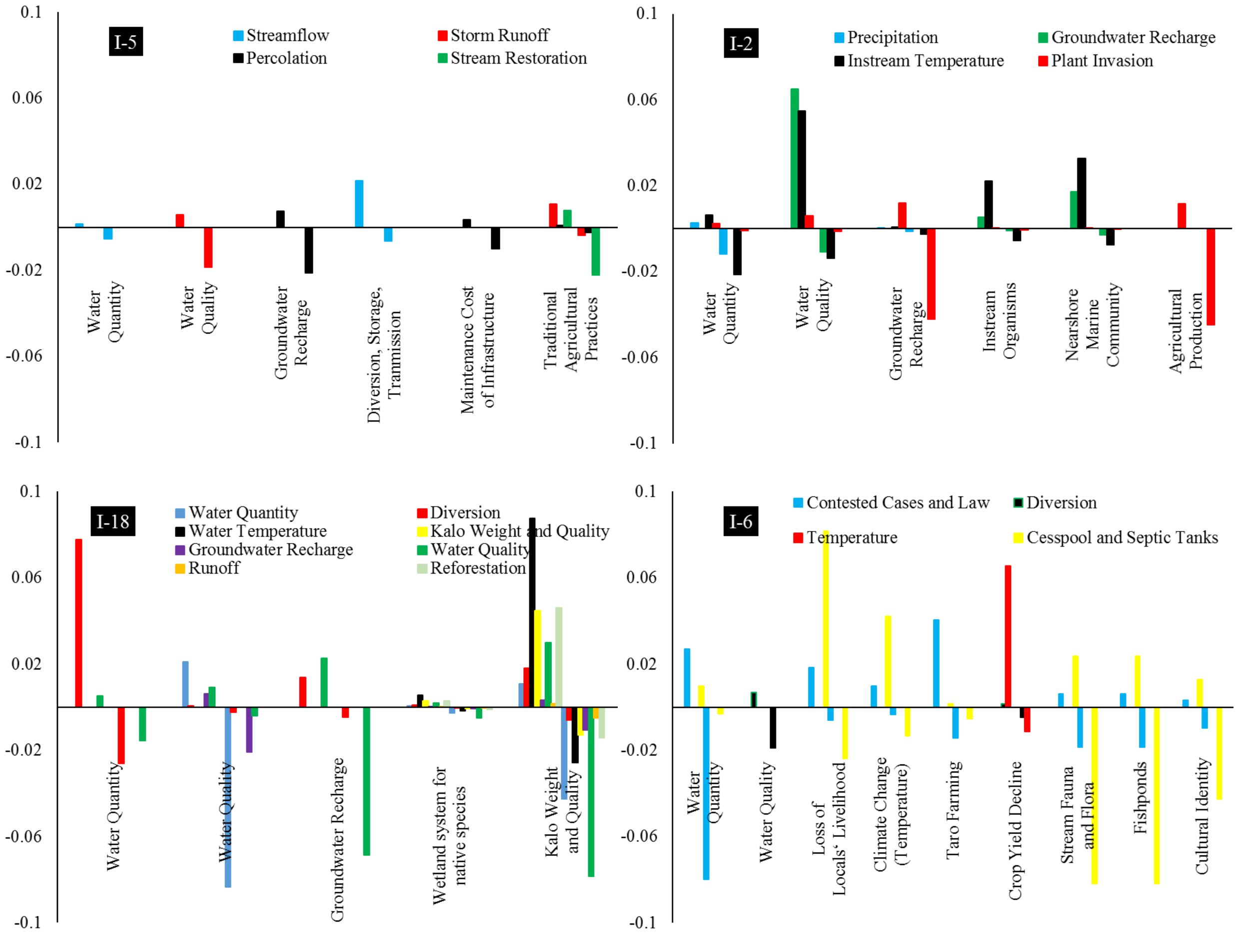

*Figure 32. Monte Carlo simulation outputs for the four representative stakeholders and their ecosystem goods and services they value: I-5 as the water resources manager (top left), I-2 as the conservationist (top right), I-18 as the agriculturalist (bottom left), and I-6 as the cultural practitioner (bottom right).*

Monte Carlo simulation altered ordinary components (Table 3A - 2) in each of the four FCMMs. While some components (x-axis components) were related to their sensitive components (drivers in the legend) directly, others inversely (Figure 32). These relationships were more clearly visible in the FCMMs. I-5's model revealed that water quantity changes had a direct relationship to fluctuations in streamflow, while those of water quality had an indirect connection with storm runoff. Increases in traditional agricultural practices were most sensitive to decreased storm runoff and associated water quality improvement. Groundwater recharge fluctuations were due to percolation. Next, for I-2, water quantity was inversely related sensitive to instream temperature, meaning increases in water quantity causes instream temperature to decline. Similarly, for I-18, water quantity increase was due to decline in ditch water diversion. Further, improvements in kalo weight and quality were sensitive to advances in water quality and reductions in water temperature. Finally, for I-6, water quantity was most sensitive to contested cases and law on freshwater. Cultural identity declined the highest due to cesspools and septic tanks because of their probable seepage to freshwater bodies, and reduction of water quality essential for instream fauna and flora.

First-Order Uncertainty Analysis (FOUA)

Based on the approach in Wu et al. (2006), influence of sensitive SWAT input parameters over streamflow, sediment and nutrients were calculated. For instance, different parameters have varying influence on streamflow (Table 22). Then, I calculated parameter variance contribution to overall output variance in streamflow, sediment, nitrogen, and phosphorus (Table 23) for ʻĪao watershed. CN2, ALPHA_BF, GWQMN had an influence on 51.48% of the variation in streamflow components, i.e., surface runoff, lateral flow and groundwater discharge respectively. Streamflow was most sensitive to ESCO that controlled soil evaporation. In addition, SOL_AWC and ESCO accounted for 42.84% of the variation in evapotranspiration, causing reduction of streamflow. CN2 also contributed to 92.20% of the total variance in phosphorus loads. Furthermore, soil properties had an influence on variations of sediment and nitrogen loads. SOL_BD and SOL_CBN were responsible for 81.19% of total sediment variance, and 71.01% of total nitrogen variance. Moreover, FOUA results (Table 24), specifically large CVs, indicated that uncertainty in key parameters had an influence on water quality outputs from SWAT. Streamflow output had the smallest CV (5%), while sediment had the largest CV (102%). As streamflow generated sediment and nutrients, CV values showed that small changes in water quantity caused large changes in water quality. In addition, water quality values were more sensitive to the input parameters.

*Table 22. Streamflow variance ($SC_i$) due to each sensitive SWAT input parameter.*

| | **Scenarios** | | | | | |
|---|---|---|---|---|---|---|
| | **Max** | **+1SD** | **+2SD** | **-1SD** | **-2SD** | **Min** |
| LAT_TIME | 5.68E-6 | 3.49E-9 | 5.06E-6 | 8.48E-5 | 5.19E-5 | 4.10E-5 |
| CN2 | 7.51E-4 | 8.46E-5 | 5.04E-4 | 5.53E-6 | 2.07E-7 | 7.48E-8 |
| SOL_AWC | 6.77E-5 | 2.12E-5 | 1.01E-4 | 2.17E-4 | 3.65E-4 | 3.05E-4 |
| SLSOIL | 2.74E-7 | 2.43E-8 | 4.01E-6 | 5.08E-5 | 1.49E-5 | 9.23E-6 |
| SOL_K | 1.56E-7 | 2.24E-5 | 7.07E-6 | 9.56E-6 | 3.72E-7 | 1.34E-6 |
| SOL_BD | 4.89E-6 | 5.81E-5 | 1.45E-5 | 1.80E-5 | 8.89E-6 | 5.46E-6 |
| SOL_CBN | 1.68E-6 | 1.89E-5 | 4.75E-6 | 1.79E-5 | 4.47E-6 | 2.74E-6 |
| ESCO | - | - | - | 2.19E-03 | 7.03E-04 | 1.26E-05 |
| ALPHA_BF | 4.94E-06 | 2.16E-05 | 5.52E-06 | 1.89E-05 | 1.25E-06 | 1.73E-03 |
| GWQMN | 1.22E-03 | 5.33E-05 | 8.88E-05 | 2.10E-04 | 5.25E-05 | 2.94E-05 |
| EPCO | 9.01E-07 | 1.40E-05 | 2.27E-06 | 2.98E-05 | 1.06E-05 | 5.77E-07 |

*Table 23. The contribution of key parameters of SWAT to variance of outputs.*

| Parameters | SWAT Output | | | |
|---|---|---|---|---|
| | **Streamflow (%)** | **Sediment (%)** | **Nitrogen (%)** | **Phosphorus (%)** |
| **SLSOIL** | 0.85 | 0.63 | 0.91 | 0.37 |
| **LAT_TIME** | 2.03 | 0.01 | 0.00 | 0.00 |
| **SOL_K** | 0.44 | 0.22 | 0.17 | 1.15 |
| **SOL_BD** | 1.18 | 42.45 | 25.90 | 2.82 |
| **SOL_AWC** | 11.59 | 1.17 | 1.22 | 0.19 |
| **CN2** | 14.47 | 16.03 | 26.55 | 92.20 |
| **ESCO** | 31.25 | 0.72 | 0.13 | 0.36 |
| **ALPHA_BF** | 19.18 | 0.01 | 0.00 | 0.00 |
| **GWQMN** | 17.83 | 0.01 | 0.01 | 0.00 |
| **SOL_CBN** | 0.54 | 38.74 | 45.11 | 2.91 |
| **EPCO** | 0.63 | 0.01 | 0.00 | 0.00 |

*Table 24. First-order uncertainty analysis results for water quantity and quality.*

| | Streamflow (m^3/s) | Sediment (ton/day) | Nitrogen (kg/day) | Phosphorus (kg/day) |
|---|---|---|---|---|
| **Mean** | 1.913 | 0.5801 | 78.08 | 11.67 |
| **Variance** | 0.01 | 0.3499 | 3877 | 88.35 |
| **SD** | 0.096 | 0.5915 | 62.27 | 9.400 |
| **CV (%)** | 5.0 | 102.0 | 79.74 | 80.53 |

*Table 25. FCM Scenarios based on streamflow, sediment, nitrogen and phosphorus outputs resulting from variations in SWAT input parameters.*

| | Streamflow | Sediment | Nitrogen | Phosphorus |
|---|---|---|---|---|
| **Max** | 0.38 | -1.00 | -1.00 | 0.37 |
| **+1SD** | -1.00 | -0.32 | 1.00 | 0.99 |
| **+2SD** | -0.65 | -0.87 | -0.57 | 1.00 |
| **-1SD** | 1.00 | 1.00 | 0.54 | -0.07 |
| **-2SD** | -0.28 | 0.86 | -0.27 | -0.52 |
| **Min** | 0.44 | 0.11 | -0.67 | -1.00 |

For participatory modeling, quantitative SWAT model outputs were converted to qualitative FCMM scenarios (Max, +2SD, +1SD, -1SD, -2SD, and Min) as seen in Table 25, and example FCMM simulations were carried out for stakeholders, I-5 and I-2, as example simulations. The results (Figure 33) showed slight changes in water quantity, but large changes in quality, as well as important freshwater ecosystem services, particularly for I-2. Water quality was improving overall, leading to better water available for agricultural irrigation for I-2. However, water quantity did not change enough to affect traditional agricultural practices as in the case of I-5. Therefore, better water quality with small quantity increase was available for agricultural irrigation. Increases in input parameters together with stakeholders' perception on reduced water transfer led to water quantity to increase slightly.

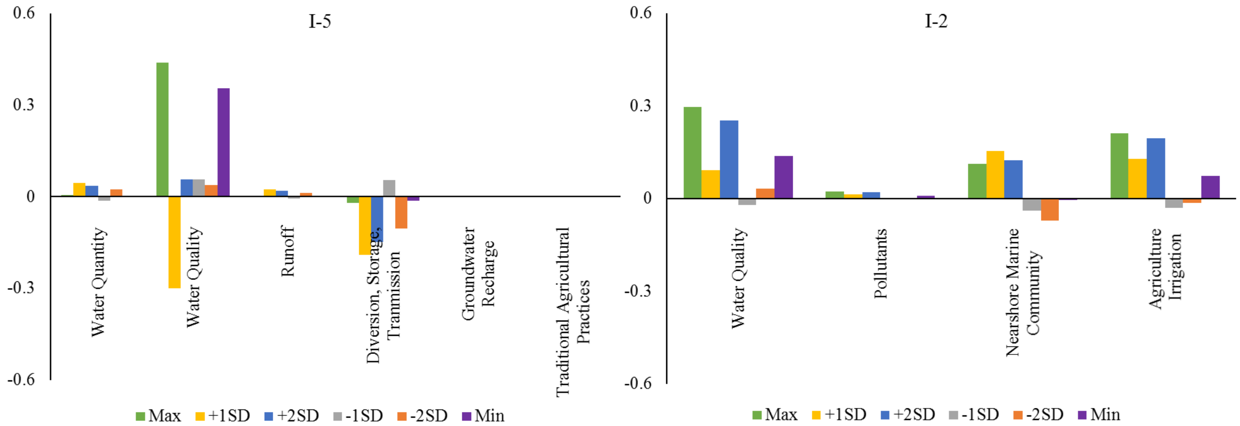

*Figure 33. FOUA results indicating changes in water resources and freshwater ecosystem services for stakeholder I-5 (representative water resources manager) and I-2 (representative conservationist).*

Overall, FOUA showed that water quantity and quality were sensitive to SWAT model input parameters, quality being the most affected. As seen in Table 25 (and

Table 23), uncertainty in water resources changed from one scenario to the next, depending on the parameter in control (i.e., that parameter with the largest influence in each column in

Table 23). For example, streamflow was highest in -1SD scenario, decreased about 30% in -2SD but increased again in the minimum scenario. The highest increase in streamflow was in -1SD scenario due to highest ESCO value. ESCO caused the reduction in soil evaporation, the most sensitive water budget component for streamflow (

Table 23) for that scenario. Accordingly, as ESCO decreased in -2SD scenario, soil evaporation increased, and therefore streamflow decreased. However, as ESCO decreased more in the minimum scenario, ALPHA_BF replaced ESCO as the responsible input parameter for streamflow variation. Minimum ALPHA_BF promoted lateral flow and thereby increasing streamflow again. Therefore, as more water was available for evapotranspiration, less streamflow was simulated until the extreme scenario. In the minimum scenario, the lateral flow became the prominent water budget.

## ***Discussion***

### *Perceptions of SES*

There were similarities and differences in the way stakeholder groups perceive key features, drivers, and relationships of the local SES. Indeed, differing perceptions of SESs are common because these views come from experience or studies, and FCMM components to describe SESs are human constructs based on qualitative, imprecise human cognition (Doswald *et al.*, 2007), and there are multiple water users with diverse and conflicting interests in this study. However, stakeholders play a key role in decision-making, and their opinions on complex SESs involving freshwater ecosystems are often elicited to identify matters of value to complement existing data (Dietz, 2013).

All the stakeholders identified climate change, native and alien species (i.e., plants and animals), and pollutants including sediment and nutrients affect the freshwater system in the study area. They believed that climate change, alien species would have negative on the water resources, while the native species would be beneficial for the preservation of resources. However, one particular water resources manager suggested that there was not enough evidence to prove that native species performed better in promoting percolation and groundwater recharge.

### *Patterns and Differences Across Stakeholder Groups*

Water resources managers focused on mitigation plans and policy implementation. They discussed watershed-scale management, low impact developments for an urban zone. Regarding climate change details, they mentioned the different effect in the leeward and windward, and wet as well as dry trends. I-3 perceived that effective management requires resources and current management did not have all the resources to achieve an optimal level. I-5 mentioned that maintenance was costly, and managers balanced between cost and maintenance to reduce tax. Next, I-5 indicated that management also involved storage and transmission of storm runoff (especially during wet days) for available water quantity for use later when necessary. In addition, the behavior of homeowners also affected available water quantity for others through either conserving or wasting. For water quality, I-12 indicated that improvements of watershed functionality would promote estuary health important for traditional plant gathering. Conversely, traditional taro fields retained sediment and nutrients and improved water quality. In addition, I-3 and I-12 observed that fire cleared all plants promoting sediment and nutrients export while decreasing groundwater recharge. Concerning planning, I-16 indicated that meaningful long-term planning accompanied by political will and incentive was important for continued efforts and substantial results. Next, I-25 mentioned that multiple users with multiple water interests led equitable allocation of water problematic to litigious. It was problematic because of liability, and cost of distribution (including the cost of permits) and maintenance. In addition, court cases in Maui were tedious and costly. Therefore, I-25 suggested that collaboration and management between different users and experts (e.g., kuleana, hydrologists, farmers, etc.) was a better approach and economical option for the local community. Moreover, a thriving ecosystem required: reservoir system to store and release water when needed; all parties working together with the best interest for one another; and careful water extraction to balance between human needs and biological needs. I-25 also pointed out that increased water quality monitoring was essential for improved water resources management.

Conservationists emphasized restoration of streams and instream native species, reforestation of native plants, remediation actions to limit erosion and mitigate pollutants, education of public on environmental issues. They also discussed the importance or danger of reusing wastewater. I-8 and I-14 emphasized the importance of native trees, shrubs and mosses in capturing rainfall, promoting groundwater recharge, reducing sediments and nutrients, and improving water quality. On the other hand, I-4 specified that vegetation removal for urban development in the study watershed increased the sediment export, and ultimately degrading water quality. It resulted due to poor permitting and inspection of the officials, and inadequate BMP installation by developers in favor of more profit. Regarding water allocation, I-20 and I-26 stated that treating freshwater as a private resource was the underlying issue, for example, private company’s monopoly of water distribution in West Maui. Though Maui county distributed >50% water using Honolua-Honokohau ditch water in West Maui, more water was supplied by the private company than the rest of the county. Accordingly, the public has less say in the water distribution. Regarding water quantity, I-22 mentioned that conservation, for example, based on instream flow standards, could lead to less water rationing and pricing, lusher environment, happier life, and more robust local economy. Also, I-23 stressed the significance of continuous streamflow from mauka to makai as breeding and survival of native species considering their amphidromous life cycle. Therefore, I-26 stated that management would be more effective if based on a modern lawful perspective than 19th-century perspective when a few company control water use and rights. It should be cooperative with nature while treating water as a public trust as outlined the state water code. Next, I-4, I-14, and I-21 cited education, community awareness, efficient plumbing, and regenerative farming as essential tools of effective conservation efforts. In addition, I-4 recommended upgrading aging wastewater infrastructure to prevent seepage. Similarly, I-21 expressed concern over seepage of wastewater reuse with likely pharmaceutical and other chemicals. Finally, I-20 mentioned that cultural practices and belief promoted freshwater quantity and quality by revering water as a valuable commodity.

Agriculturalists highlighted the importance of water resources for agricultural operations. Loss of freshwater resources was equated with loss of cultural identity because a reduction of freshwater quantity and quality caused loss of cultural practice (i.e., taro farming, gathering native instream species). Meanwhile, returning 100% streamflow was not a plausible, sensible, and economical option. Removal of ditches (and returning water completely) was a problem for some agriculturalists who obtained irrigation via ditches. Next, part-time farmers and gardeners lobbied for returning total streamflow, but in reality, they may not become full-time farmers if 100% streamflow was returned. In addition, returning full streamflow would increase higher-price water, and drive some local small farmers out of business. On the other hand, water banking by the developers reduced water available to the public. Similarly, I-13 expressed concern over the county water extraction by the county and population increase, affecting natural streamflow. Therefore, according to I-11, instream flow standards were beneficial for the agriculturalists, and they would be fully functional with more enforcement. In general, I-1 stated that decline in quantity and quality of water was the loss of ecological, social and cultural problem. Local agriculture was important, and the residents should hold on to the farming operation than relying more on imports. Next, to conserve water, I-11 mentioned that dryland farming and good monitoring system were effective tools. In addition, biological control and organic farming were operational methods for controlling water quality running off agricultural fields. Finally, I-18 stressed that it was necessary to educate of young people of the agricultural ecosystem, and businesses to leave smaller water footprint.

Finally, cultural practitioners stressed the importance of water (wai) for cultural practices (i.e., taro farming), inspiration, loss of livelihood, prayer (oli), and the connection between nature and human. They talked about caring for the land (malama aina) because they believed that “land is the chief and they are the servants.” I-6 reaffirmed that water was culturally significant because its reduction meant a loss of cultural identity. Since the return of streamflow and springs in the private land (previously dry for many water-diverted years) in Waiheʻe watershed, native species had started to re-appear and kalo was flourishing again, suggesting that adequate streamflow was fundamental for culturally important flora and fauna. I-7 stated that flowing stream from mauka to makai was essential for creating healthy ecosystems and productive habitats (i.e., estuaries) for seaweeds and fishponds. These culturally important species had been the staple food for generations. Therefore, diversion of freshwater depleted not only freshwater species but also marine life by disrupting the trophic level. In addition, I-17 mentioned that flowing freshwater was also a source of inspiration because it enabled healthy native vegetation and stream biota. Again, water resources were also essential for cultural identity as it secured food security and sovereignty for the local people. Finally, I-19 revealed the importance of prayer in Hawaiian culture related to freshwater availability. During droughts, locals prayed for water. Overall, flowing adequate water was the source of sustenance, life, and culture in Hawaiʻi.

There are some differences in the perceptions between stakeholder groups. While some conservationists believed that stream diversions were negatively impacting the ecosystem and should be removed totally, agriculturalists with direct access to streams (or those from leeward watersheds) relied upon diverted streamflow for irrigation. Therefore, local farmers emphasized diverting enough water for agriculture operations while supporting instream flow standards. However, streamflow restoration would lead to less cheap water in the future due to reduced ditch water for some farmers. In addition, maintaining both ditches and streams by the state in the future would cost more, and therefore imply more property tax.

*Implications of Change*

In addition to similarities and differences among stakeholders, the stakeholder FCMMs revealed that changes in climate and land use/cover are diminishing the freshwater ecosystem goods and services. In West Maui, local residents as well as visitors enjoy provisioning ecosystem goods and services (drinking water via groundwater recharge, irrigation for commercial and sustenance farming), regulating ecosystem services (flood control, sediment and nutrient retention), cultural ecosystem goods and services (inspiration, aesthetic, viewshed, traditional agriculture and fishpond practices, and tourism). However, climate change stresses freshwater resources through shifts in the Tradewinds, Kona wind, and inversion patterns, rising sea level and temperature, declining precipitation, flood, drought, and fire. Land use/cover change stressors included sediment, nutrients from fertilizers, wastewater injection, cesspools and septic tanks, herbicides, pesticides, and oil, as well as pathogens from wastewater.

To mitigate declining freshwater resources, stakeholders requested improvements in management, law, and policy, enforcement as well as education of multiple users with diverse and conflict interests. Sustainable farming actions to maintain soil health and microbial activity including keyline plowing, dryland farming, usage of a monitoring system for water and fertilizer use, deploying sand filters are currently in use. Reforestation, fencing to exclude feral ungulates, stream restoration, use of low impact developments by the government agencies and conscientious homeowners are also cited as effective measures. In addition, stakeholders expressed concern over lack of enforcement for land development permitting and inspection. Education, community awareness, and research are also essential for effective management of freshwater resources. Some stakeholders, specifically water resources managers and conservationists, stated that cost of infrastructure maintenance or upgrade, remediation, and funding for conservation, could impede effective management operations.

Instream flow standards, a management policy, affect stakeholders differently. Conservationist believed that it will lead to less water rationing and pricing, lusher environment, happier life, and more robust local economy. Agriculturalists, on the other hand, prefer equal distribution of freshwater by diverting enough water for agriculture operations while leaving adequate streamflow to meet the policy. Since the return of streamflow and springs in the private land (previously dry for many water-diverted years) in Waiheʻe watershed, native species had begun to re-appear and kalo was flourishing again, indicating positive impacts of the policy for culturally important flora and fauna.

### *Stakeholder Classification*

Classifying interviewees into different stakeholder groups in ex ante and centrality-derived methods had some issues. In grouping individuals ex ante, I assumed that members within each group would have similar FES of interest. However, in reality, when reviewing the FCMMs, some stakeholders had more than one dominant interest and could belong to more than one category. Centrality-derived clustering (Stier *et al.*, 2017) couldn't account for the five stakeholders with incomplete FCMMs. In my approach, the stakeholders had to identify the components describing the local freshwater system before providing the connections, and some models were incomplete.

### *Biophysical Model and Evaluation*

The SWAT model simulated water quantity and quality with reasonable accuracy. Two layers of soil for percolation and recharge enabled subsurface flow, a major component of streamflow in steep watersheds. Moreover, since SWAT is a semi-distributed model, it was able to capture the temporal and spatial variation of the watersheds reasonably well. At annual average time step (from 1990 to 2009), water quantity values were accurate within ± 10% from the observed or published data. In addition, SWAT was able to subtract the water diversions from the sugarcane and pineapple fields. Next, SWAT enabled the use of three methods for calculating evapotranspiration (a major water budget component in Hawai‘i), but only Penman-Monteith was appropriate because it led to a better correlation of simulated streamflow with measured streamflow.

Differences in simulated and observed values were probably due to residual error from climate variables and lack of adequate observed data. SWAT required daily data, and there was no daily (only seasonal) precipitation and temperature available for the future. Therefore, future seasonal variation was used for calculating future daily data. It might not be appropriate at the daily time step, but it was the only approach available. In addition, the study in this study required only values at the annual average time step (though simulated at daily time step), and therefore, the approach was satisfactory and acceptable. Similarly, Johnson calculated groundwater recharge at monthly time step but reported annual average values (Johnson *et al.*, 2014). Further, observed daily sediment and nutrient data in the leeward watersheds were sparse (52 days for Honolua and 27 days for Honokowai watershed), and too few for reasonable calibration results. However, they served as a minimum threshold.

The model evaluation indicated that the SWAT model performed well in a Hawaiian watershed with steep slopes and spatially variable climate. All the sensitive parameters indicated that lateral subsurface flow was dominant in the upper watershed, in agreement with the literature (Dunne & Leopold, 1978). Sensitive parameters for evapotranspiration, runoff, and baseflow implied that future changes in rainfall and temperature might decrease streamflow significantly. Monte Carlo confirmed the effect of future climate change on reduced streamflow.

### *Limitations of the Study*

There are some limitations to the SWAT model simulation. Lack of readily available daily future precipitation and temperature data may not lead to accurate prediction of future streamflow and nutrients. Further, observed daily sediment and nutrient data in the leeward watersheds were too few for reasonable calibration results. While SWAT model performed well at a daily time step, some of the extreme storm events that had the potential to produce flash flooding and substantial sediment plume were not covered by SWAT because these events happened at time steps less than an hour.

The FCM process had a number of limitations. The research questions and interview questions aimed to have a broad capture the local freshwater system, environmental and anthropogenic stressors, the ecosystem goods and services. However, covering broad topics could be the underlying reason that a few stakeholders did not complete their FCMMs. Furthermore, a few interviewees would not comment on water quality issues, and one interviewee specifically would not express any opinion on climate change impacts.

Moreover, FCM does not provide threshold prediction, and the interviews could be improved. For example, the exact threshold impacts of water on cultural and supporting FES cannot be obtained via modeling FCM. Moreover, interviewees results may improve with more interviewees, particularly at stakeholder group level results. And the limited scope of FES types (selecting two FES types out of four) could give the interviewees more time to elaborate on certain FCMM components. Finally, FCMMs and their representation of the freshwater systems are meant to be functional rather than accurate representations of reality (Jones *et al.*, 2011). Therefore, FCMMs allow stakeholders to better understand the local ecological impacts of environmental change, and encourage them to participate in the decision-making process. Accordingly, it is not possible to depict every possible reality detail (Jones *et al.*, 2011) in FCMMs.

### *Management Insights*

Managers can use the model outputs, as well as similarities and differences in stakeholders' perceptions, to guide their actions (Özesmi & Özesmi, 2003). For example, majority of stakeholders believe that climate and land use/cover changes are affecting ecosystem goods and services in West Maui and will continue to do so. Managers can take advantage of this by encouraging more stakeholders to provide feedback on climate change adaptation measures. In addition, more citizen science-based water quality monitoring across the island of Maui would be beneficial for decision-making. Further, more public education of the youth and even at younger age on the impacts of environmental changes mentioned as a possible solution by the interviewees have the potential to help the mitigation plans. Similarly, additional explanation on the management of aging infrastructure, reforestation, and water storage from the managers would be necessary to inform the public aware of the increased cost and budget allocation.

There have been disputes of neighboring users over water systems in Maui. For example, in the Waiahole ditch dispute, there was a reallocation of 0.102 x $10^6$ $m^3$/day surplus water between the developers of leeward and central Oʻahu with gain of potentially huge profits from discounted water, and farmers and conservationists of windward Oʻahu (Gopalakrishnan *et al.*, 1996). Further, Prior Appropriation Doctrine stipulates that sustained use of water for the original use is necessary for continued allocation the use of water for plantations. Therefore, when sugar and pineapple production stopped, the associated water right should have been lost, and the owners should have ceased the stream diversions as in *Alexander and Bald vs. Maui Farmers 2016*. However, this did not happen (Gopalakrishnan *et al.*, 1996) because Board of Land and Natural Resources approved Alexander and Baldwin to continue stream diversion with conditions.

Both plaintiffs and defendants agreed that litigation over water use between multiple users was costly, and sharing is the solution. However, for proper water sharing among multiple users, improvements in enforcement of state's water code should be a priority. Moreover, as sharing is based on instream flow standards hydrological and ecological studies, detailed and precise regulations are necessary for carrying out those studies. Reporting should also specify not only the amount of streamflow returned from diversions but also the interval and ambient conditions. I-23 mentioned that a streamflow report included values on a day with a heavy rain event: the reported amount may not be the truly returned streamflow. In addition, hydrological and ecological studies used to establish the instream flow standards might not be at an appropriate location. For future studies, it should be at a habitat where most native species are likely to be present. Finally, managers should focus on low impact developments, encourage conscientious homeowners, promote education, and community awareness. I-4, I-14, I-18, and I-21 believe that education and awareness are effective tools for improving management.

### *Conclusion*

The ES-IWRM approach considers relationships between biophysical, ecological, and social components of social-ecological systems to guide water management decisions. This research adopted an ES-IWRM approach, introducing a novel modeling framework to incorporate local knowledge and stakeholder values. Specifically, I integrated biophysical watershed and community knowledge-based participatory models to link environmental change to conditions of concern to stakeholders. The integration has multiple benefits. It allows stakeholders to be part of the modeling, and feel that their values are being represented. It incorporates local knowledge of systems. Stakeholders participating in the modeling process may better understand the local ecological impacts of environmental change. The associated policy is more understandable to different stakeholders, and therefore more likely to be adopted. Following the ES-IWRM approach, management policies approach may improve delivery of freshwater ecosystem services.

Applying the approach to watersheds in Maui, Hawai‘i highlighted the importance of sustainable water management of local ecological perceptions and values of multiple competing freshwater users. Stakeholders’ resounding concern regarding climate and land use/cover changes affecting FES can be indicative of a willingness to provide feedback on developing climate change adaptation measures and participate in materializing them. Different FES is important for different stakeholder groups; provisioning FES has direct benefits for agriculturalists, regulating FES for conservationists, cultural FES for cultural practitioners, and supporting FES for all groups. Improvements in the enforcement of regulations, education, and awareness will also add to the effective water resources management.

The similarities and differences of stakeholders’ perceptions of freshwater can be used by managers to tailor messages and understand values in contentious discussions, for instance, related to instream flow standards. Accounting for different views of stakeholders on this management policy revealed that practices of water sharing and taking only what you need are sustainable and should be a central theme as they avoid costly litigation. In conclusion, freshwater systems with multiple users and conflicting interests can be better managed by the inclusion of the different stakeholders in the policy development while considering the social-ecological implications, thereby improving delivery of freshwater ecosystem services.

## Conclusion

In Hawaiʻi, freshwater resources are significantly important for economic, ecological, cultural, and aesthetic purposes (Oki, 2003). Hawaiians derive ecosystem goods and services from streams, springs, and wetlands fed by groundwater discharges (Lau & Mink, 2006). However, freshwater resources in the Hawaiian Islands are projected to become scarcer due to a growing population, a changing climate (Diaz *et al.*, 2005; Oki, 2004; UH-SGC, 2014), and altered land use and land cover (Brauman *et al.*, 2014; Fortini *et al.*, 2013). In addition, there are multiple competing water users with diverse (USGS NWIS, 2015) and conflicting interests (CWRM, 2008). Finally, water resources management is fragmented with its information transfer and cooperation gaps between managers and users comprising watershed protection programs and entities (CWRM, 2008). For management decisions regarding water resources, we need a better understanding of the water socio-environmental system (including the biophysical, ecological, and social components).

Keeping the socio-environmental system in mind, I developed a modeling tool that evaluates freshwater ecosystem services to inform ecosystem-based approach for integrated water resources management. In my first study, I evaluated models for compatibility in Hawaiʻi for quantifying the hydrologic attributes (i.e., quantity, quality, location, and timing) of freshwater ecosystem services. Knowing which hydrological models work under what circumstances will facilitate integrated management because eco-hydrological modeling explicitly recognizes the role of natural ecosystems to benefit human well-being.

For my second study, following ES-IWRM approach (Janssen, 1992; Maynard *et al.*, 2011), I sought to couple an eco-hydrological model and a participatory model to predict the ecological benefit of three Hawaiian birds and their population change under projected climate change scenarios. Results indicated that impacts on wildlife species were not uniform and were sensitive to multiple and unique stressors that can be identified through expert interviews and collaborative, integrated modeling. The analysis represented the interaction between global climate processes, local-scale hydrological and ecological systems for decision-support in integrated management.

In my third study, I used ecohydrological-participatory modeling approach and predicted impacts on social values of different freshwater stakeholders under environmental changes and instream flow standards. Results indicated that impacts on stakeholders were not homogeneous and were sensitive to diverse, and often conflicting, social values that can be identified only through in-person interviews and integrated modeling. Unequal impacts revealed by integrated modeling inform decision-making on equitable allocation of freshwater resources in integrated management.

In Hawaiʻi, the ES-IWRM approach and results from these studies could help fill gaps in water resources management and have policy implications. With consideration of human and nature interdependence, Hawaiʻi compatible modeling tools from study one could inform a better statewide water resource investigation and assessment program. In addition, integrated modeling can help solve the existing jurisdictional and regulatory issues inherent in the government for water initiatives (CWRM, 2008). The process and results from participatory modeling in study three could provide different stakeholders with different perceptions on freshwater values, and close the gap in cooperation because stakeholders could learn from the similarities and differences of other. Integrated modeling proved that stakeholders with different backgrounds and water interests should work together to improve conservation efforts. In addition, CWRM's 2008 report suggested statewide monitoring and data collection program for both surface and groundwater. However, integrated modeling results indicated some stakeholders' concern over insufficient monitoring and data collection of freshwater resources. Based on this information, policy-makers could use the stakeholders' implied agreement to increase water quantity and quality monitoring programs. For more cooperation from the water users, there is a need to raise awareness of conservation efforts. Interviewees in study three supported education and research programs for raising awareness of freshwater ecosystem services.

Moreover, the Hawaiian Islands are suffering the same impacts as the other islands worldwide, but have resources (research, education, migration corridor, and infrastructure) for adaptation. Therefore, my research on freshwater ecosystem services and values can help inform other island nations as well. For example, Fiji, a developing country of volcanic origins (Burns, 2002), is expected to experience severe climate change impacts (Burns, 2001) on freshwater quality and availability (Keener *et al.*, 2012). Fiji has experienced El Niño Southern Oscillation-related droughts (1978, 1983, 1987, 1992 and 1997-98), affecting human well-being. UN-Water reported local but high-profile water shortages in Fiji (UNESCO, 2009) where surface water is the major source of supply (PacificWater, 2016). Similar to the Hawaiian Islands, sedimentation, salinization, solid waste disposal and over-pumping are sources of pollution of freshwater sources (SOPAC, 2007b). Moreover, local water agency is in need of updated equipment and training to reduce freshwater losses (SOPAC, 2007a).

My research built a decision support tool to inform an ecosystem services-based integrated water resources management in Hawai‘i. The approach is also adaptable for different ecosystems and scenarios easily and cost-effectively.

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## Appendix 1A

### *Glossary*

1. **Model**. A simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system (NRC, 2007). It is a formal (i.e., physical or conceptual) representation of the behavior of system functions and processes, usually in mathematical or statistical terms (NRC, 2007).
2. **Lumped model**. A model in which the physical characteristics of land units within a subwatershed unit are assumed to be homogeneous (USEPA, 1997).
3. **Distributed model**. A model that allows users to modify input data and give output data at GIS grid cells. It enables simulation of watershed's physical heterogeneities (USEPA, 1997).
4. **Mechanistic model**. A model that attempts to quantitatively describe a phenomenon by its underlying causal mechanisms (Shoemaker *et al.*, 2005; USEPA, 1997).
5. **Numerical model**. A model that approximates a solution of governing partial differential equations that describe a natural process. The approximation uses a numerical discretization of space and time components of the system or process (Shoemaker *et al.*, 2005; USEPA, 1997).
6. **Steady-state model**. A mathematical model of fate and transport that uses constant values of input variables to predict constant values of receiving water quality concentrations (Shoemaker *et al.*, 2005; USEPA, 1997).
7. **Dynamic model**. A mathematical formulation describing the physical behavior of a system or a process and its temporal variability (Shoemaker *et al.*, 2005; USEPA, 1997).
8. **Integrated model**. A combination of models often connected or "linked" together to describe an entire system when multiple features of the system cannot be sufficiently explained by one model (Shoemaker *et al.*, 2005).
9. **Stochastic hydrological model.** It performs statistical analyses of hydrologic data (e.g., precipitation, streamflow) to generate synthetic sequences of hydrologic data for infrastructure design or use in forecasting (Haan *et al.*, 1982). It predicts hydrological variables but also quantifies the errors in model outcomes. It predicts flood (Haan *et al.*, 1982) as well as drought (Mishra & Desai, 2005).
10. **Mental model**. It is a cognitive concept map that reflects mental processing, which is comprised of collected information and a series of cognitive abstractions by which individuals filter, code, store, refine and recall information about physical phenomena and experiences (Gray *et al.*, 2014).
11. **Transdisciplinary Approach**. It is an approach where people from different disciplines work jointly to create new conceptual, theoretical, methodological, and translational frameworks that integrate and transcend separate disciplinary approaches to address a common problem (Klein, 2008).
12. **Steady flow** has properties (i.e., pressure, velocity or density) at every point in the flow that does not depend upon time. Temporally invariant.

13. **Uniform flow** has properties (velocity, pressure or density) that do not change from point to point at any instant of time. Spatially invariant.

## *Surface Water Models*

*Table 1A - 1. Initial list of surface water models.*

| **Surface Water, Water Quality or Groundwater Recharge** | | **Surface Water or Groundwater Recharge** | | **Urban Watershed** | | **Wetland** | |
|---|---|---|---|---|---|---|---|
| 1 | AnnAGNPS | 12 | GSSHA | 25 | SWMM | 34 | DRAINMOD |
| 2 | SWAT | 13 | INFIL3.0 | 26 | PCSWMM | 35 | SLAMM |
| 3 | OpenNSPECT | 14 | CRT | 27 | XP-SWMM | **Ecosystem Service Modeling Suite** | |
| 4 | KINEROS2 | 15 | HydroTrend | 28 | FLDWAV | 36 | ARIES |
| 5 | STORM | 16 | HSPF | 29 | PRMS | 37 | Envision |
| 6 | WARMF | 17 | PIHM | 30 | HyDroDSS | | |
| 7 | WMS | 18 | Groundwater Toolbox | **Flood Forecasting** | | | |
| 8 | LWWM | 19 | VIC | 31 | NSS | | |
| 9 | MIKE SHE | 20 | tRIBS | 32 | PeakFQ | | |
| 10 | TopoFlow | 21 | HEC-HMS | 33 | WATFLOOD | | |
| 11 | InVEST NDR, InVEST SDR | 22 | CREST | | | | |
| | | 23 | MODHMS | | | | |
| | | 24 | Vflo | | | | |
| **Tools Excluded from Further Selection** | | | | | | | |
| **Captured in another Model** | | **Not Downloadable with Ease** | | **Limited Usability** | | 77 | SLAMM |
| 38 | EPIC | 50 | DWSM | 62 | AGWA | 78 | StreamStats |
| 39 | GLEAMS | 51 | ETD | 63 | ALAWAT | 79 | WTM |
| 40 | GSFLOW | 52 | OWLS | 64 | APEX | 80 | WWHM/BAHM |
| 41 | TOPMODEL | 53 | ParFlow | 65 | CREAMS | **Software Incompatibility** | |
| 42 | WinHSPF | 54 | SITEMAP | 66 | DR3M | 81 | ANSWERS/ANSWERS2000 |
| 43 | HUMUS | **Hydraulic Model** | | 67 | GEOtop | 82 | BASINS |
| **No GIS Linkage** | | 55 | Anuga | 68 | GISPLM | 83 | DHSVM |
| 44 | GWLF | 56 | CCHE1D | 69 | MEASURES | 84 | FESWMS-2DH |
| 45 | LSPC | **Difficult Usability** | | 70 | Mercury Loading Model | 85 | GLSNet |
| **Not Hydrological Model** | | 57 | EcoMetrix | 71 | MUSIC | 86 | HL-RDHM |
| 46 | EFDC | 58 | MIMES | 72 | P8-UCM | 87 | SLURP |
| 47 | WMOST | 59 | RRAWFLOW | 73 | PGC – BMP | 88 | WASSI |
| 48 | MIKE 11 and MIKE 11 RR | **Resolution Incompatibility** | | 74 | PondPack V | 89 | WBM-WTM (aka WBMplus) |
| 49 | STVENANT | 60 | DLBRM | 75 | REMM | 90 | WinTR-55 |
| | | 61 | SHETRAN | 76 | RHESSys | | |

*Table 1A - 2. Hydrological models with SW (surface water), WQ (water quality), and GWR (groundwater recharge) processes.*

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **1** | AnnAGNPS | SW & WQ | Potential Model | USDA-ARS | Free | Annualized Agricultural Non-Point Source Pollutant Loading Model. It was applied in Hawaiʻi. |
| **2** | SWAT | SW & WQ & GWR | Potential Model | Texas A&M University | Free | Soil and Water Assessment Tool is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. It was applied in Hawaiʻi. |
| **3** | OpenNSPECT | SW & WQ | Potential Model | NOAA | Free | Non-point Source Pollution and Erosion Comparison Tool |
| **4** | KINEROS2 | SW & WQ | — | USDA-ARS | Free | Kinematic Runoff and Erosion Model, v2 |
| **5** | STORM | SW & WQ | — | Dodson & Associates, Inc. | Commercial | Storage, Treatment, Overflow, Runoff Model (PC version) |
| **6** | WARMF | SW & WQ | — | Systech Engineering, Inc. | Free | Watershed Analysis Risk Management Framework |
| **7** | WMS | SW & WQ | — | Aquaveo, LLC. | Commercial | Watershed Modeling System (Version 7.0) |
| **8** | LWWM | SW & WQ | — | — | Commercial | LWWM (Linked Watershed/Waterbody Model) links SWMM 4.31 and WASP5 |
| **9** | MIKE SHE | SW, WQ, GW & GWR | — | Danish Hydraulic Institute | Commercial | — |
| **10** | TopoFlow | SW, WQ & GW | — | University of Colorado | Free | Spatially-distributed, D8-based hydrologic model |

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **11** | InVEST NDR, InVEST SDR | WQ | — | Stanford University | Free | Integrated Valuation of Ecosystem Services and Tradeoff – Nutrient and Sediment Delivery Ratio |

*Table 1A - 3. Hydrological models with SW (surface water), and GWR (groundwater recharge) processes.*

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **12** | GSSHA | SW | Potential Model | Aquaevo, LLC. | Commercial | Gridded Surface Subsurface Hydrologic Analysis |
| **13** | INFIL3.0 | GWR | Potential Model | USGS | Free | A grid-based, distributed-parameter watershed model to estimate net infiltration past the root zone |
| **14** | CRT | SW & GW | Potential Model | USGS | Free | Cascade Routing Tool that couples GSFLOW (Groundwater and Surface-water FLOW) and PRMS (Precipitation-Runoff Modeling System) |
| **15** | Hydro-Trend | SW & GWR | Potential Model | University of Colorado | Free | Climate-driven hydrological transport model |
| **16** | HSPF | SW & GW | — | USGS | Free | Hydrological Simulation Program – Fortran to simulate water quantity and quality for both conventional and toxic organic pollutants |
| **17** | PIHM | SW & GW | — | Pennsylvania State University | Free | Penn State Integrated Hydrologic Modeling System |
| **18** | Ground-water Toolbox | SW & GWR | — | USGS | Free | A graphical and mapping interface for hydrograph analysis programs BFI, HYSEP, PART, and RORA (with RECESS) |
| **19** | VIC | SW | — | University of Washington | Free | Variable Infiltration Capacity simulates water and energy balances. |

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **20** | tRIBS | SW | — | Arizona State University | Free | TIN-based Real-time Integrated Basin Simulator |
| **21** | HEC-HMS | SW | — | USACE | Free | Hydrologic Engineering Center – Hydrologic Modelling System |
| **22** | CREST | SW | — | University of Oklahoma | Free | Coupled Routing and Excess STorage (CREST) model is a distributed hydrologic model. |
| **23** | MODHMS | SW | — | Scientific Software Group | Commercial | It is a physically based, spatially distributed, and surface/subsurface model. |
| **24** | Vflo | SW | — | Vieux Inc. | Commercial | It is a distributed model for simulating stormwater runoff, for developing drainage infrastructure design, and for real-time forecasting of rainfall runoff and flooding. |

*Table 1A - 4. Hydrological models with SW (surface water) and WQ (water quality) for urban watersheds.*

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **25** | SWMM | SW & WQ | Potential Model | EPA | Free | Storm Water Management Model |
| **26** | PCSWMM | SW, WQ & Urban | Potential Model | Computational Hydraulics Int. | Commercial | Stormwater Management Model |
| **27** | XP-SWMM | SW, WQ & Urban | Potential Model | XP Software, Inc. | Commercial | Stormwater and Wastewater Management Model |
| **28** | FLDWAV | | | NWS | Free | National Weather Service - continuously accounting for water storage in surface and sub-surface zones |

| No. | Models | Process | Recom-mendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **29** | PRMS | SW | | USGS | Free | Precipitation-Runoff Modeling System is a modular-designed, deterministic, distributed-parameter modeling system that can be used to estimate flood peaks and volumes for floodplain mapping studies |
| **30** | HyDroDSS | Surface Water | | USGS | Free | Hydrologic Drought Decision Support System for **determining drought risk** from precipitation deficit or water withdrawals |

*Table 1A - 5. Flood forecasting models for planning flood protection measures.*

| No. | Models | Ecosystem Service | Recommendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **31** | NSS | SW - Flood Protection | Potential Model | USGS | Free | National Flood Frequency program for ungauged stations using regression equations |
| **32** | PeakFQ | SW - Flood Protection | Potential Model | USGS | Free | Flood-frequency analysis model based on Bulletin 17B |
| **33** | WATFLOOD | SW - Flood Protection | — | University of Waterloo | Free | It forecasts flood flows for watershed having response times ranging from one hour to several weeks. |

*Table 1A - 6. Wetland models to assess surface water (SW) and water quality (WQ) processes.*

| No. | Models | Process | Recommendation | Source | Cost | Note |
|---|---|---|---|---|---|---|
| **34** | DRAINMOD | SW & WQ | — | North Carolina State University | Free | It simulates wetland hydrology with poorly drained, high water table soils. |
| **35** | SLAMM | SW & WQ | — | University of Alabama | Free | Source Loading and Management Model |

*Table 1A - 7. Ecosystem service modeling suites.*

| No. | Models | Ecosystem Service | Recommendation | Source | Cost | Notes |
|---|---|---|---|---|---|---|
| **36** | ARIES | SW & WQ | — | ARIES Team | Free | Artificial Intelligent for Ecosystem Services |
| **37** | Envision | SW & WQ | — | Oregon State University | Free | Envision |

### *Groundwater Models*

*Table 1A - 8. Initial list of groundwater models.*

| **Flow and Transport** | | **Flow** | | **Transport** | |
|---|---|---|---|---|---|
| 1 | BIOF&T | 15 | SHARP | 23 | SUTRA |
| 2 | GMS | 16 | FEFLOW | 24 | SEAWAT |
| 3 | MODFLOW and related programs | 17 | MicroFEM | 25 | AT123D |
| 4 | GROUNDWATER VISTAS | 18 | MODFE | 26 | HST3D |
| 5 | HYDRUS2D/3D | 19 | GSFLOW | 27 | Hydrogeochem2 |
| 6 | MOC and MOC3D | 20 | MODFLOW-NWT | 28 | MT3DMS |
| 7 | MOCDENSE | 21 | MODFLOW-OWHM | 29 | PATH3D |
| 8 | MODFLOWT | 22 | SWB | 30 | PESTAN |
| 9 | PhreFlow | | | 31 | BIOMOC |
| 10 | SWIFT | | | 32 | R-UNSAT |
| 11 | SWMS_2D | | | | |
| 12 | VS2DI | | | | |
| 13 | PHAST | | | | |
| 14 | TopoDrive and ParticleFlow | | | | |

| Tools Excluded from Further Selection | | | | | |
|---|---|---|---|---|---|
| **Limited Usability** | | **Software Incompatibility** | | **Not Groundwater Model** | |
| 33 | Bioslurp | 57 | ASM | 79 | AQUACHEM |
| 34 | JDB2D/3D | 58 | BIOPLUMEIII | 80 | PMWIN |
| 35 | MODPATH | 59 | CAPZONE | 81 | TracerLPM |
| 36 | PULSE | 60 | EIS/Biorem3D | 82 | UCODE_2014 |
| **No download available** | | 61 | FLOWPATH II | 83 | Visual AEM |
| 37 | 3DADE | 62 | FTWORK | 84 | VS2DH |
| 38 | AQUIFEM-Salt | 63 | GWFLOW | 85 | VS2DI |
| 39 | CANVAS | 64 | HELP | 86 | VS2DT |
| 40 | DYNSYSTEM | 65 | HOTWTR | | |
| 41 | FEMWATER | 66 | ICE-1 | | |
| 42 | MIGRATE | 67 | MF2K-GWT | | |
| 43 | NETFLO | 68 | MF2K-VSF | | |
| 44 | PAT | 69 | MULAT | | |
| 45 | RAM2 | 70 | PHREEQM-2D | | |
| 46 | SLAEM/MLAEM | 71 | PLASM | | |
| 47 | SUMATRA-1 | 72 | POLLUTE | | |
| 48 | SWACROP | 73 | PRZM-2 | | |
| 49 | SWICHA | 74 | RAND3D | | |
| 50 | TRAFRAP-WT | 75 | RRAWFLOW | | |
| 51 | TWODAN | 76 | SESOIL | | |
| 52 | USGS-SOL | 77 | STANMOD | | |
| 53 | VERTPAK-1 | 78 | UNSAT1 | | |
| 54 | VIRALT | | | | |
| 55 | VIRTUS | | | | |
| 56 | WALTON35 | | | | |

*Table 1A - 9. Groundwater models with flow and transport processes.*

| No. | Models | Process | Cost | Notes |
|---|---|---|---|---|
| **1** | BIOF&T | Flow and Transport | Commercial | It models biodegradation, flow, and transport in the saturated and unsaturated zones in two or three dimensions in heterogeneous, anisotropic porous media or fractured media. |
| **2** | GMS | Flow and Transport | Commercial | GMS supports TINs, solids, borehole data, 2D & 3D geostatistics, and both finite element and finite difference models in 2D & 3D. Currently supported models include MODFLOW, MODPATH, MT3D, RT3D, FEMWATER, and SEEP2D. It was applied in Hawaiʻi. |

| No. | Models | Process | Cost | Notes |
|---|---|---|---|---|
| **3** | MODFLOW and related programs | Flow | Free - USGS | Three-dimensional finite-difference groundwater model, including MODPATH, RADMOD, and ZONEBUDGET. It was applied in Hawaiʻi. |
| **4** | GROUNDWATER VISTAS | Flow and Transport | Commercial | It supports MODFLOW, MT3D'99, MODPATH, PATH3D, MODFLOWT, and MODFLOW-SURFACT. |
| **5** | HYDRUS2D/3D | Flow and Transport | Commercial | It simulates water flow and solute transport in variably saturated media. |
| **6** | MOC and MOC3D | Flow and Transport | Free | It simulates water flow and solute transport in fractured or granular aquifers and is capable of treating both (leaky-) confined and water table systems. |
| **7** | MOCDENSE | Flow and Transport | Free | It is for analysis of saltwater intrusion. It simulates the conservative solute transport and dispersion of one or two constituents in a ground-water system with the density-dependent flow. |
| **8** | MODFLOWT | Flow and Transport | Commercial | It is a version of MODFLOW that includes modules for simulating 3D transport. |
| **9** | PhreFlow | Flow and Transport | Free | It models 3D unconfined transient groundwater flow and transport. |
| **10** | SWIFT | Flow and Transport | Commercial | It is a transient, 3D model for flow and transport of fluid, heat (energy), brine, and radionuclide chains in porous and fractured geologic media. |
| **11** | SWMS_2D | Flow and Transport | Free - USDA | It is for water and solute movement in 2D variably saturated media. It uses the Richards' equation for saturated-unsaturated water flow and the convection-dispersion equation for solute transport. |
| **12** | VS2DI | Flow and Transport | Free - USGS | It simulates flow and transport through variably saturated porous media. |
| **13** | PHAST | Flow and Transport | Free - USGS | It simulates water flow, solute transport, and multicomponent geochemical reactions. |
| **14** | TopoDrive and ParticleFlow | Flow and Transport | Free - USGS | It simulates flow and solute transport in 2D. |

*Table 1A - 10. Groundwater models with only flow.*

| No. | Models | Process | Cost | Notes |
|---|---|---|---|---|
| **15** | SHARP | Flow | Free - USGS | It is a quasi-three-dimensional finite difference model for simulating freshwater and saltwater flow, separated by a sharp interface. It was applied in Hawaiʻi. |
| **16** | FEFLOW | Flow | Commercial | It models flow and transport of dissolved constituents and/or heat transport processes. It was applied in Hawaiʻi. |
| **17** | MicroFEM | Flow | Commercial | It simulates flow in steady state and transient conditions. |
| **18** | MODFE | Flow | Free - USGS | It is 2D finite element model for simulation of steady-state or transient areal, cross-sectional, and axi-symmetric ground-water flow. |
| **19** | GSFLOW | Flow | Free - USGS | Coupled Groundwater and Surface-water FLOW model based on the USGS Precipitation-Runoff Modeling System (PRMS) and Modular Groundwater Flow Model (MODFLOW-2005). |
| **20** | MODFLOW-NWT | Flow | Free - USGS | A Newton-Raphson formulation for MODFLOW-2005 to improve the solution of unconfined groundwater-flow problems. |
| **21** | MODFLOW-OWHM | Flow | Free – USGS | MODFLOW-based integrated hydrologic flow model for the analysis of human and natural water movement within a supply-and-demand framework |
| **22** | SWB | Flow | Free - USGS | A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge |

*Table 1A - 11. Groundwater models with transport process.*

| No. | Models | Process | Cost | Notes |
|---|---|---|---|---|
| **23** | SUTRA | Transport | Free - USGS | It is a model for saturated-unsaturated, variable-density ground-water flow with solute or energy transport. It was applied in Hawaiʻi. |
| **24** | SEAWAT | Transport | Free - USGS | It is a MODFLOW/MT3DMS-based model for 3D variable-density groundwater flow coupled with multi-species solute and heat transport. It was applied in Hawaiʻi for salt-water intrusion. |
| **25** | AT123D | Transport | Commercial | It is an analytical solution for transient one-, two-, or three-dimensional transport of a dissolved chemical, radionuclide or heat in a homogeneous aquifer with uniform, stationary regional flow. |

| No. | Models | Process | Cost | Notes |
|---|---|---|---|---|
| **26** | HST3D | Transport | Free - USGS | It models Heat and Solute Transport in Three-Dimensional**.** |
| **27** | Hydrogeochem2 | Transport | Commercial | It solves hydrologic transport and geochemical equilibrium problems. |
| **28** | MT3DMS | Transport | Free | Modular three-dimensional transport model |
| **29** | PATH3D | Transport | Free | It helps visualize three-dimensional flow fields, for delineating contaminant capture zones or wellhead protection zones and evaluating the effectiveness of groundwater remedial scenarios under complex hydrogeological conditions. |
| **30** | PESTAN | Transport | Free - USEPA | It evaluates 1D vertical transport of organic pollutants (pesticide) through the homogeneous soil to groundwater. |
| **31** | BIOMOC | Transport | Free - USGS | A multispecies solute-transport model with biodegradation |
| **32** | R-UNSAT | Transport | Free - USGS | Reactive, multispecies transport in a heterogeneous, variably-saturated porous media. |

## ***Hydrological Processes underpinning Freshwater Ecosystem Services***

### *Evapotranspiration*

Potential evapotranspiration (PET) is evapotranspiration (ET) rate under the existing atmospheric conditions and non-restricting water supply conditions. PET can be calculated using Penman-Monteith (Monteith, 1965), FAO modified Penman-Monteith (Allen *et al.*, 1998), Priestley-Taylor (Priestley & Taylor, 1972), and Budyko curve (Zhang *et al.*, 2004). When the water supply is limited, the ET falls below the potential level because PET at that atmospheric condition and vegetation is too high for ET to meet (Lau & Mink, 2006).

### *Streamflow*

Water can reach a stream through three main pathways: surface runoff, groundwater discharge, and subsurface flow (aka lateral flow). Unit hydrograph (Sherman, 1932), SCS curve number (Mockus, 1972), Horton (Horton, 1941) and Green Ampt (Green & Ampt, 1911) methods are available to quantify surface runoff. Unit hydrograph theory estimates surface runoff based on a pre-determined volumetric flow rate (cubic feet/meter per second) from a unit (one inch or one cm) constant intensity uniform precipitation over the watershed. The SCS curve number is a function of the soil's permeability, land use, and antecedent soil moisture content. Runoff occurs when rainfall amount is more than the ground moisture (i.e., saturation excess runoff). Horton and Green Ampt methods calculate infiltration, and runoff occurs when the rainfall intensity is higher than infiltration rate (i.e., Horton excess runoff).

Subsurface flow is estimated based on Kinematic storage-discharge model (Sloan & Moore, 1984). Subsurface flow occurs down a hillslope when soil moisture exceeds its water holding capacity, and there is an impermeable or semipermeable layer at a shallow depth.

Discrete models

*Routing Runoff (Provisioning or Cultural Ecosystem Service)*
Timing and location of streamflow (or flood wave) are simulated using either hydrologic or hydraulic routing. Runoff routing balances inflow, outflow and storage volumes. Computer models take input rainfall, convert it to outflow (usually illustrated in hydrographs), and then route the outflow through stream networks. It has applications for watershed simulation, flood prediction and control actions, reservoir design and operation, and urban drainage design (Philip *et al.*, 2008).

Hydrologic routing, in the simplest form, is based on continuity equation (see below) in the form of inflow (I) minus outflow (Q) equals to change in storage (S). With beginning (subscript 1) and end (subscript 2) of the time period, continuity equation in terms of finite difference form is shown here. Storage routing also known as variable storage routing was developed by Williams (1969).

$$\frac{(I_1 - I_2)}{2} - \frac{(Q_1 - Q_2)}{2} = \frac{(S_2 - S_1)}{\Delta t} \tag{4}$$

However, streamflow (flood) routing requires an equation ((Chow, 1959) see below) with both continuity and the storage-outflow relationship of the freshwater system.

$$S = f\left(I, \frac{\partial I}{\partial t}, \frac{\partial^2 I}{\partial t^2}, \ldots, Q, \frac{\partial Q}{\partial t}, \frac{\partial^2 Q}{\partial t^2}, \ldots\right) \tag{5}$$

Continuity and storage function is solved by Muskingum for flood routing, Modified Puls for reservoir and detention basin routing, and Runge-Kutta methods (1st, 2nd, and 4th order PDE solutions) for detention basin routing (Philip *et al.*, 2008).

Hydraulic routing, which is more complicated and accurate than hydrologic routing, uses both continuity and momentum equations of Saint Venant.

1. Continuity equation (based on Law of Conservation of Mass)

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{6}$$

2. Momentum Equation (based on Law of Conservation of Momentum),

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \tag{7}$$

Then, Kinematic Wave (Steady Uniform), $\left(S_0 - S_f\right) = 0$

Diffusion (Non-inertia), $g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$

Steady Non-uniform, $\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$

Dynamic (Unsteady Non-uniform), $\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g(S_0 - S_f) = 0$

Kinematic and diffusion models are widely used in engineering applications. SWAT uses variable storage routing, while both SWAT and HEC-HMS use kinematic wave model.

*Hydrological Flood Forecasting (Regulating Ecosystem Service)*

Hydrological considerations in flood forecasting include prediction of the relationships in upstream and downstream water levels (for example, for a flood-risk site). Flood modeling now provides predictions of levels, timing, and extent of flooding presented as tables or graphs of level-to-level correlations and time of travel. While catchment modeling is just one of the crucial elements of an integrated flood forecasting and warning system, "the heart of any flow forecasting system is a hydrological model" (Serban & Askew, 1991). In the United States of America, a lead time of between 2 and 48 hours would be considered a short-term forecast, between 2 and ten days a medium-term forecast, while a long-term estimate would be one for which the lead time exceeds ten days (WMO, 2011).

*Groundwater Recharge*

Computation of groundwater recharge follows either baseflow method or soil water budget method. The baseflow method assumes that baseflow component of the streamflow is equivalent to groundwater recharge. Further, soil water budget uses the mass balance approach on the changes of soil moisture on a daily basis. USGS model follows Thornthwaite and Mather formula as follows (Engott & Vana, 2007).

$$X_i = P_i + I_i + F_i + W_i - R_i + S_{i-1} \tag{8}$$

where,

$X_i$ = interim soil-moisture storage for the current day [L],
$P_i$ = rainfall for the current day [L],
$I_i$ = irrigation for the current day [L],
$F_i$ = fog drip for the current day [L],
$W_i$ = excess water from the impervious fraction of an urban area distributed over the pervious fraction [L],
$R_i$ = runoff for the current day [L],
$S_{i-1}$ = soil-moisture storage at the end of the previous day (i–1) [L], and
i = subscript designating "current day."

*Sediment Retention/Export*

There are several sediment export processes and equations/models available. Sheet and rill erosion is calculated using USLE (Universal Soil Loss Equation), RUSLE (Revised USLE) or

MUSLE (Modified USLE) in many models. Next, sediment delivery from field to channel is simulated using HUSLE (Hydrogeomorphic Universal Soil Loss Equation) in AnnAGNPS (Bingner & Theurer, 2011). Then, gully erosion is computed using EGEM (Ephemeral Gully Erosion Model) (Merkel *et al.*, 1988), REGEM (Revised EGEM) or TIEGEM (Tillage-Induced Ephemeral Gully Erosion Model). Sediment production from roads is calculated using WARSEM (Washington Road Surface Erosion Model) or SEDMODL2.

*Nutrient Retention/Export*

Nitrogen and phosphorus processes follow their respective cycles (Neitsch *et al.*, 2011) or mass balance approach (Sharp *et al.*, 2014). Plant use of nitrogen and phosphorus is estimated using the supply and demand approach according to plant growth.  Then, nitrate, organic N, and soluble P may be removed from the soil via the mass flow of water with a loading function by McElroy (1976). Though mass balance approach is faster, following processes according to the nitrogen and phosphorus seems to be a more realistic approach.

*Groundwater Hydrology*

Models for groundwater hydrology differs based on the feature in consideration such as: dimensions (1, 2 or 3); numerical or analytical solution; steady or transient state; sharp or mixing fresh-salt interface; advective-dispersive or density-dependent reaction; confined or unconfined aquifer; porous or fractured; homogeneous or heterogeneous; isotropic or anisotropic media.

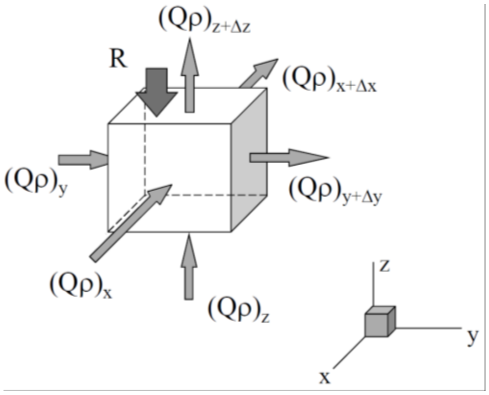
Darcy‘s Law is fundamental in describing the isotropic and homogeneous groundwater flow characteristics between specific discharge (q), hydraulic conductivity (K), unit hydraulic head (δh), and unit length (δl).

$$q = -K\frac{\partial h}{\partial l} \tag{9}$$

For one-direction flow affected by K in three dimensions (x, y and z directions),

$$q_x = -K_{xx}\frac{\partial h}{\partial x} - K_{xy}\frac{\partial h}{\partial y} - K_{xz}\frac{\partial h}{\partial z} \tag{10}$$

For a transient un-isotropic heterogeneous flow with direct recharge (R), specific storage (Ss) is as follows (Fetter, 2000).



$$S_s \frac{\partial h}{\partial t} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} - \frac{\partial q_z}{\partial z} + R \qquad (11)$$

Contaminant transport with dispersion coefficient (D) and uniform q takes the following form (Mustafa *et al.*, 2011).

$$C(x,t) = \frac{C_0}{2}\left[erfc\left\{\frac{(x-qt)}{2\sqrt{Dt}}\right\}\right] + exp\left(\frac{qx}{D}\right) * erfc\left\{\frac{(x+qt)}{2\sqrt{Dt}}\right\} \qquad (12)$$

Based on these relationships, the most widely-used model for groundwater flow analysis is MODFLOW developed by USGS (Harbaugh, 2005). It solves transient three-dimensional groundwater flow using finite difference method (Mustafa *et al.*, 2011). Most of the groundwater models base on MODFLOW and its outputs. For solute (i.e., nutrient) transport, MODPATH (Pollock, 1994) computes three-dimensional flow paths using the particle-tracking method. Next, MT3DMS (Zheng & Wang, 1999) uses species interaction reactions. For coastal aquifers, saltwater intrusion is modeled using SEAWAT (Langevin *et al.*, 2008), which is a combination of MODFLOW and MT3DMS models.

### ***Sensitive Parameters for OpenNSPECT and SWAT***

#### *OpenNSPECT*

The OpenNSPECT model was sensitive to the number of raining days. Raining days indicate the average number of storms that occur in a one-year period in Kalihi, Oʻahu. Therefore, raining days depend on spatial variation of local rainfall (Eslinger *et al.*, 2012). For calculating raining days, there are several required parameters including representative runoff curve number, initial abstraction (i.e., loss of rainfall due to evapotranspiration and storage in depressions, and infiltration before runoff occurs), rainfall conditions in the watershed.

After considering all the areas of land uses or covers, soil, and the associated CN, the cumulative CN for the watershed was found to be 0.675 using,

$$Cumulative\ CN = \frac{\sum_{i=1}^{n}(CN_i * A_i)}{\sum_{i}^{n} A_i} \qquad (133)$$

Then, I calculated initial abstraction (Ia) as 0.962 inch (or 24.43 mm) using,

$$Ia = 0.2 * \left(\frac{1000}{(Cumulative\ CN * 100)} - 10\right) \tag{144}$$

Then, rainfall data in the year 2005 from Kalihi Res Site 777 suggested that there were 175 raining days producing 2.54 mm, 66 days producing 12.7 mm, and 34 days producing 25.4 mm. Plotting these data and fitting a linear regression using a logarithmic equation suggested that the fitted line had a slope of -62.38 and an interception of 29.377. Using the linear regression equation and Ia, the number of raining days was 31.80 (or rounded to 32). The result (32 days) was close the precipitation normal (34 days) from NOAA (NOAA, 2016). Finally, calibration produced the raining days as 36.

*SWAT*

*Table 1A - 12. Sensitive parameters for SWAT.*

| Parameter | **Selected Value** | **Acceptable Range** | **Definition** |
|---|---|---|---|
| | | **Water Quantity** | |
| **ESCO** | 1 | 0.01 to 1 | Soil evaporation compensation factor |
| **EPCO** | 0.01 | 0.01 to 2 | Plant uptake compensation factor |
| **ICN** | 1 | 0 or 1 | Daily curve number calculation method |
| **CNCOEF** | 0.5 | 0.5 to 2 | Plant evapotranspiration curve number coefficient |
| **DEP_IMP** | 6000 | 0 to 6000 (mm) | Depth to impervious layer in the soil profile |
| **SHALLST** | 1000 | 0 to 5000 | Initial depth of water in the shallow aquifer (mm) |
| **DEEPST** | 2000 | 0 to 10000 | Initial depth of water in the deep aquifer (mm) |
| **ALPHA_BF** | 0.5 | 0 to 1 | Baseflow alpha factor |
| **ALPHA_BF_D** | 1 | 0 to 1 | Baseflow alpha factor for deep aquifer |
| **GWQMN** | 0 | 0 to 5000 | Threshold depth of water in the shallow aquifer for return flow to occur |
| **GW_REVAP** | 0.02 | 0.02 to 0.2 | Groundwater "revap" coefficient |
| **REVAPMN** | 1000 | 0 to 1000 | Threshold depth of water in the shallow aquifer for "revap" to occur |
| **RCHRG_DP** | 0.05 | 0 to 1 | Deep aquifer percolation fraction |
| **SOL_AWC** | | 0 to 1 | Soil available water content |
| | | **Water Quality** | |
| **USLE_K** | Varies | 0 to 0.65 | Soil erodibility factor |
| **USLE_P** | Varies | 0 to 1 | Support practice factor |
| **SOL_CBN** | Varies | 0.05 to 10 | Organic carbon content |
| **NPERCO** | Varies | 0 to 1 | Nitrogen percolation coefficient |
| **PPERCO** | Varies | 10 to 17.5 | Phosphorus percolation coefficient |
| **PHOSKD** | Varies | 100 to 200 | Phosphorus soil partitioning coefficient |

## Appendix 2A

### *Atmospheric $CO_2$ Projections*

Atmospheric concentration of $CO_2$ is expected to increase between 550 (B1 emission scenario) and 970 ppm (A1FI emission scenario) from its observed concentration of 330 ppm in 2003-04 (IPCC TAR, 2001). The two extreme scenarios represent a future world of a very rapid economic growth (A1FI) or a future world with low economic growth and fossil fuel independency (B1) as shown in (**Table 7**).

Out of the four IPCC families of emission scenarios (A1, A2, B1, and B2), the A1 scenario family describes a projected world of very fast economic growth as well as new and more efficient technological advances. The subcategory, A1FI describes alternative directions of technological change in the energy system with intensive use of fossil fuel. On the other hand, the B1 scenario describes an economy with material intensity reductions as well as the introduction of clean energy technologies, but no additional climate initiatives. Both A1 and B1 define a world with the global population that peaks in midcentury followed by a decline (IPCC SRES, 2001).

### *Temperature*

As the atmospheric $CO_2$ concentration increases, global temperature increases as one of the negative impacts. All temperatures are relative to the period 1980-1999 (Table 2A - 1). The model simulations were based on the extreme values of the “Likely” range (1.1° C and 6.4° C) (IPCC AR4, 2007).

*Table 2A - 1. Projected global average surface warming at the end of the 21st century (Adapted from IPCC AR4).*

| **Case** | **Temperature change (°C at 2090-2099 relative to 1980-1999)** | |
|---|---|---|
| | Best estimate | Likely range |
| **B1 scenario** | 1.8 | 1.1 – 2.9 |
| **A1T scenario** | 2.4 | 1.4 – 3.8 |
| **B2 scenario** | 2.4 | 1.4 – 3.8 |
| **A1B scenario** | 2.8 | 1.7 – 4.4 |
| **A2 scenario** | 3.4 | 2.0 – 5.4 |
| **A1FI scenario** | 4.0 | 2.4 – 6.4 |

### *Digital Elevation Model (DEM)*

Digital Elevation Model was obtained from USGS with a resolution of a 10-meter in 7.5-minute quadrangle maps named after a local physiographic feature (i.e. name of a city). Each quadrangle map came compressed into 18 Spatial Data Transfer Standard (SDTS) files stored in a zip folder. DEM was preprocessed by: converting into an ArcGIS compatible DEM file using SDTS Translator program; combining quadrangle files by mosaicking if the desired watershed is spread across more than one file; and removing negative elevation values (under mean sea level in the bay area) as the entire elevation dataset is raised by a constant value (10 m).

AnnAGNPS delineated watershed boundaries based upon the DEM. Then, the model divided the watershed into subwatersheds or cells and generates associated stream network. The density of the cell network was determined by specifying the values of critical source area (CSA; the minimum area for which a channel can be created) and minimal source channel length (MSCL; the threshold for the shortest channel segment). The study area was delineated using the default CSA value of 8 ha and MSCL value of 130 m.

### ***Climate Input File***

Temperature (daily max, min and dew-point temperature values), precipitation, sky cover, wind speed/direction, solar radiation, and evapotranspiration data were required for compiling the climate input file (DayClim.inp) for executing AnnAGNPS. Except the weather stations in the airports, current land surface stations did not provide dew-point temperature, sky cover, and wind speed/direction data. Therefore, these particular data for the watershed were acquired from the nearest airport weather station (Lihue Airport, Kauaʻi) and assumed to be the same within the watershed as well. In cases where dew-point temperature was unavailable, it was assumed to be the same as minimum temperature.

#### *Precipitation*

Precipitation input data were based on historical data from 20 weather stations within and around the Hanalei watershed (Figure 2A - 1). For spatial rainfall variation, observed daily point rainfall data was distributed using Kriging method in ArcGIS at 30m resolution. Next, using annual rainfall isohyets (UH Mānoa’s Geography Department, Rainfall Atlas of Hawaiʻi), 14 “secondary climate” are created. Precipitation data for these “secondary climate” files were created using the Model Builder within ArcGIS (Figure 2A - 2).

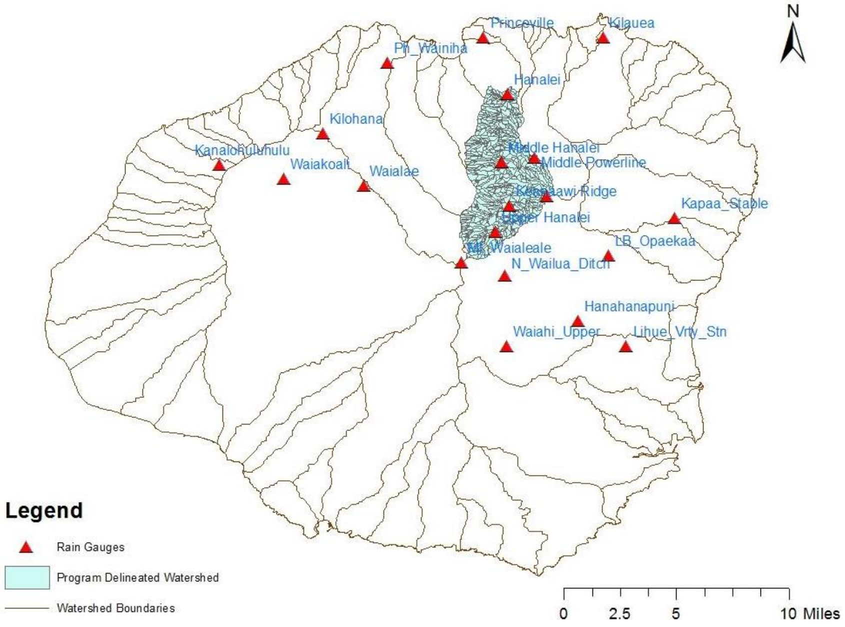


*Figure 2A - 1. Rain guage network.*

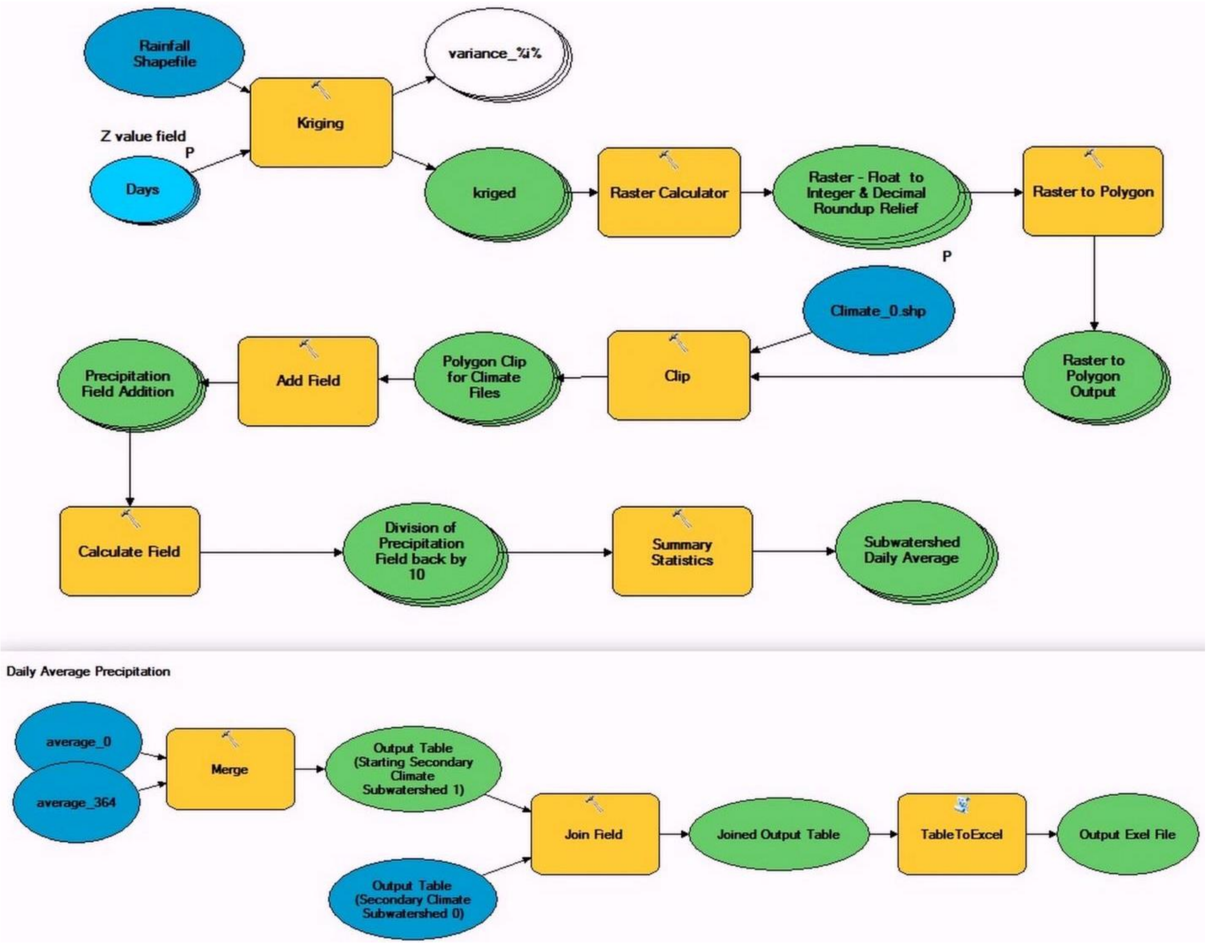


*Figure 2A - 2. Rainfall distribution calculation process using ArcGIS Model Builder.*

*Evapotranspiration*

I calculated evapotranspiration potential (ETP) using the FAO Penman-Monteith equation (Allen *et al.*, 1998) with some modification.

$$r_s = \frac{r_l}{LAI_{active}} \tag{1}$$

where $r_s$ is bulk surface resistance [s m-1], $r_l$ bulk stomatal resistance of the well-illuminated leaf [s $m^{-1}$] and $LAI_{active}$ active (sunlit) leaf area index [$m^2$ (leaf area) $m^{-2}$ (soil surface)].

$$r_l = \frac{1}{g_{CO_2}} = \frac{1}{g * \left[1.4 - 0.4 * \left(\frac{CO_2}{330}\right)\right]} \tag{2}$$

where $g_{CO2}$ is modified leaf conductance from SWAT model (Arnold *et al.*, 1994) and g is conductance without the effect of $CO_2$ for reference crop, grass, 0.01 m $s^{-1}$.

Assuming 7% increase of LAI,

$$LAI_{CO_2} = LAI * \left[1 + \frac{7}{100} * \left(\frac{CO_2 - 330}{330}\right)\right] \tag{3}$$

$$LAI = 24 * h \tag{4}$$

where LAI is leaf area index for the reference crop, grass and h is reference crop, grass, height, 0.12 m.

$$LAI_{CO_2} = 2.88 * \left[1 + \frac{7}{100} * \left(\frac{CO_2 - 330}{330}\right)\right] \tag{5}$$

For reference crop, grass,

$$LAI_{active} = 0.5 * LAI_{CO_2} \tag{6}$$

$$r_a = \frac{208}{u_2} \tag{7}$$

where $r_a$ is aerodynamic resistance [s m-1] and $u_2$ is wind speed at 2 m height [kPa].

Then the modification $r_s/r_a$ is computed by:

$$\frac{r_s}{r_a} = \frac{u_2}{208 * 0.01 * \left[1.4 - 0.4 * \left(\frac{CO_2}{330}\right)\right] * 0.5 * 2.88 * \left[1 + 0.07 * \left(\frac{CO_2 - 330}{330}\right)\right]} \tag{8}$$

then the resulting table is given below (Table 2A - 2).

*Table 2A - 2. Calculated rs/ra factors for different CO2 emissions.*

| **$CO_2$ Emission (ppm)** | **$r_s/r_a$** |
|---|---|
| **550** | 0.435 $u_2$ |
| **710** | 0.573 $u_2$ |
| **970** | 1.311 $u_2$ |
| **330** | 0.340 $u_2$ |

### *Watershed Input File*

Once all the required data were collected (see **Table 8**) and prepared, AnnAGNPS combined information from soil, field and climate for each cell/subwatershed and produced preliminary watershed.inp input file. Detail information includes cell area, slope, perimeter, RUSLE LS factor, channel segment length and slopes, and the topology of the cell network.

Further refinement to the two input files, watershed.inp and DailyClim.inp, was made by using AnnAGNPS Input Editor. Land use/cover (or categorized as Non-Crop) data included annual root mass, annual cover ratio, annual rainfall height, and surface residue cover for each type of plant. It must be managed by: reclassifying into one of four groups namely cropland, forest, pasture, urban and rangeland; and specifying rock cover and inter-rill erosion code values using "Management Field Data". Then, Management Schedule Data section is used to specify residue cover change (e.g due to feral pigs or fertilizer applications) if there is any. Then, Management Operation Data section is used to specify the amount of residue cover change. Next, Runoff Curve Number Data section is used to specify runoff curve number for each type of land cover reclassified earlier. Next, Simulation Period Data option is used to specify simulation period, average annual RUSLE rainfall factor and 10-yr EI (RUSLE energy intensity for 10 year frequency rainfall). In addition to these basic input values, there are other optional data to further describe the watershed as well. Finally, AnnAGNPS save all these values into the final executable watershed data file, watershed.inp.

### *Surface Water Runoff and Sediment Routing*

Within AnnAGNPS, cell surface water runoff is computed from the cell Runoff Curve Number and precipitation using the SCS rainfall-runoff equation. Sediment due to erosion is calculated using RUSLE (Revised Universal Soil Loss Equation).

Runoff from any cell (excluding point sources) is routed along each reach using reach routing sequence ensuring all reaches upstream of a given reach are routed prior to its routing. Reaches with no water at the upstream end are ignored. For each reach, an equivalent runoff curve number (CN) and associated ratio of initial abstraction to 24-hour effective precipitation (Ia/P) are computed using upstream runoff volume and weighted rainfall. Then, Ia/P ratio and the user defined rainfall type (Type III for Hawai‘i in general) are used to determine a peak flow for the reach using the extended TR-55 method. All these parameters are then transferred to the downstream end of the reach.

Along each reach, sediment routing is done using the Bagnold equation (Bagnold, 1966). First, water runoff is separated into within bank flow and/or out of bank flow. Then, depending on the particle class (clay, silt, sand, small aggregate, and large aggregate) sediment is routed while considering three sources (sheet & rill, gully, and bed & bank).

### *Nutrient Routing*

For each reach, AnnAGNPS computes a daily mass balance for nitrogen (N), phosphorus (P), and organic carbon (OC) considering N and P by plant uptake, fertilizer application, residue decomposition, and soil N and P transformations. In addition, for each cell, daily sediment-bound N and P, soluble N and P in runoff, and sediment-bound OC are determined. N and P plant uptake are simulated through a simple crop growth stage index. The soil N and P transformation is computed using adapted EPIC equation (Sharpley & Williams, 1990). Decay of each nutrient is calculated based on the reach travel time, water temperature, and an appropriate decay constant.

## Appendix 2B

### *FCM Simulation*

Scenario simulation includes computing component vectors for Steady State and Scenario State in four similar steps. First, the steady state vector is developed by placing a value of 1 for each of the elements in the vector. Second, the steady state vector is then subject to matrix multiplication with the adjacency structural matrix of the desired cognitive map and a new vector is created. Third, each of the elements within this vector is subjected to a logistic function (f(x) = (1/(1 + eˆ(−x))) to keep the values in the interval [0,1]. Fourth, the new vector is applied to matrix multiplication with the adjacency matrix and the elements are again subjected to a logistic function. Step four is iterated until the vectors of FCM map component converge. Scenario State vectors are produced in a similar procedure except that desired increased/decreased scenario values (see Table 11) take the place of steady state values in the first step. Finally, the relative differences of Scenario State vectors from Steady State vectors are computed as the relative impact of different FCM (e.g., climate change) scenarios (Gray *et al.*, 2012).

### *FCM Structural Metrics*

Using matrix algebra tools of graph theory, I can calculate structural metrics on FCM adjacency matrix. These measures estimate the degree of shared knowledge across individuals or groups, and determine exogenous system forcings as well as characteristics (i.e., hierarchical or democratic) (Gray *et al.*, 2014; Ozesmi & Ozesmi, 2004).

Metrics include: density, indegree, outdegree, centrality, transmitter, receiver and ordinary components, complexity, and hierarchy index. Density is the ratio of the number of relationships and components squared. The higher the density, the more potential management policies exist (Hage & Harary, 1983). Next, outdegree and indegree are the row sum and column sum of absolute values of a variable in the adjacency matrix. They show the cumulative strength of connections and components outgoing and entering a variable. Centrality, the sum of outdegree and indegree of a variable, indicates the importance of the individual weight of a variable. Then, transmitter components have a positive outdegree (i.e., zero indegree), while receiver components have only positive indegree. Ordinary components have both non-zero indegree and outdegree (Bougon *et al.*, 1977). Furthermore, ratios of receiver to transmitter components (R/T), complexity, are used to compare FCMs. A complex FCM has a larger ratio with more outputs and less controlling forcing components. Finally, hierarchy index is calculated using,

$$Hierarchy\ Index, h = \frac{12}{(N-1)N(N+1)} \sum_i \left[ od(v_i) - \frac{\sum od(v_i)}{N} \right]^2 \qquad (9)$$

where h is hierarchy index, N is the total number of components in an FCM, and od($v_i$) is outdegree for each variable i. Hierarchy index indicates a hierarchical (i.e., top-down system with score 1) or democratic system (with score 0) (MacDonald, 1983). Democratic FCMs represent systems with high level of integration, dependent components, and more adaptive capacity to local environmental changes (Sandell, 1996).

### *Monte Carlo Simulation*

For each of the 16 ordinary components for the wetland birds, random function was used to simulate 10,000 FCM scenarios in the Monte Carlo simulation. State vectors for the ordinary variables were altered, between 1 and -1, one at a time to see changes in Chicks and Adult Abundance (see FCM Simulation above). Statistics (i.e., minimum, maximum, average standard deviation) of change in abundance were recorded, for plotting histogram (not shown here) as well as bar graph (see Figure 2B - 1).

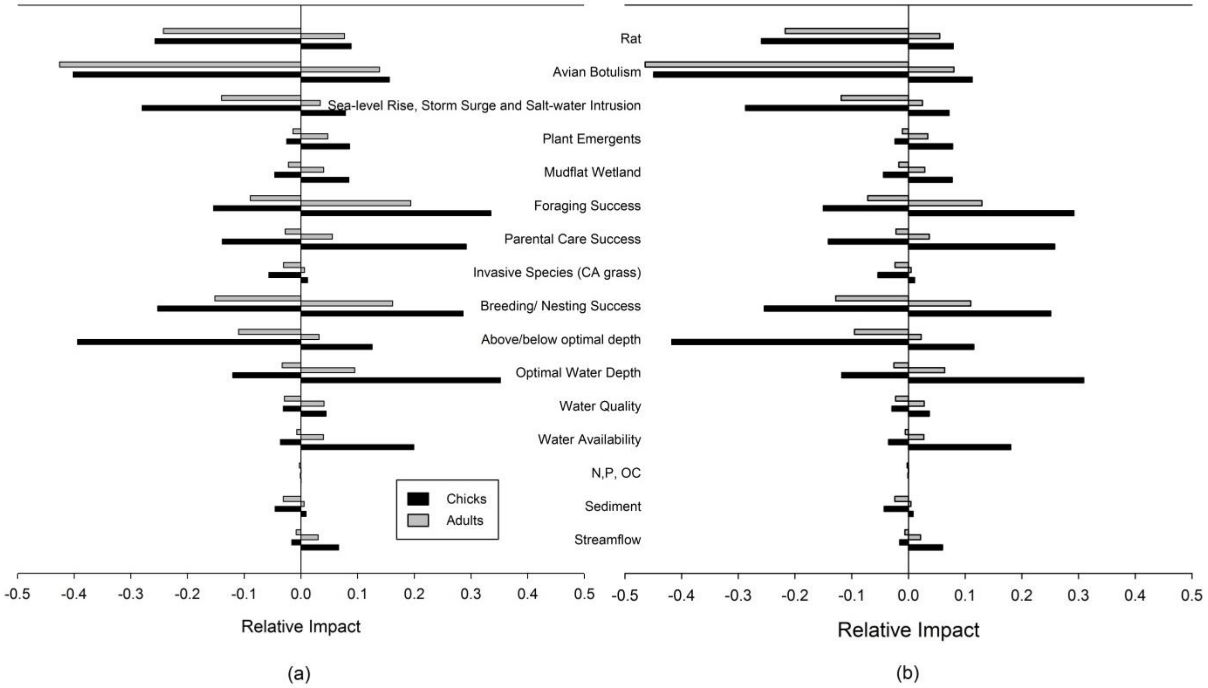


*Figure 2B - 1. Monte Carlo simulation results for a) Hawaiian Stilt, and b) Hawaiian Coot/Moorhen.*

## Appendix 2C

### *FCM interviewees and affiliations*

The four local ecologists participated in FCM model building are Dr. Christopher Lepczyk, Dr. Sheila Conant, Andrew Titmus, and Michael Mitchell. Except Dr. Conant and Mr. Mitchell, the rest of the interviewees are co-authors in this paper. Dr. Lepczyk is a professor at the School of Forestry and Wildlife Sciences, Auburn University, and an affiliate professor at University of Hawai‘i at Mānoa. Dr. Conant is a professor emeritus professor of the Biology Department at the University of Hawai‘i at Mānoa. Mr. Titmus is a PhD candidate at the University of Hawai‘i at Mānoa, and Mr. Mitchell is the deputy director of the Hanalei National Wildlife Refuge on the island of Kaua‘i.

# Appendix 3A

## ***SWAT Model***

### *Watershed Delineation*

Though the whole island of Maui was included in SWAT model simulation for calibration against observed direct runoff from USGS stream gauges, I would report model outputs for the study watersheds in this study (Figure 17). Watershed delineation led to 12 sectors (Figure 3A - 1) for ease of post-processing, and 2976 subbasins (Figure 3A - 2) for more agreement between simulated and observed water budget components. Detailed subbasin delineation was necessary for representing of high spatial variation for the island. For study watersheds, 168 subbasins were in leeward study watersheds, and 100 were in windward, ‘Iao, watersheds.

Then, to model highly complex terrain, soil and land use, I further divided the subbasins of the whole island into hydrologic response units. Slope analysis of digital elevation model indicated that it was prudent to classify the island into three categories of slope percentages: 0 to 50, 50 to 100, and above 100. Majority of 100% and above fell in the conservation zone, while 100 to 50% were in the mid-plains and 0 to 50% in the coastal regions including urban areas. Using lower-bound threshold levels of 20% for land use/cover, 10% for soil, and 20% and slope percentage with each subbasin (Winchell *et al.*, 2007), a total of 10,472 hydrologic response units were created for simulation.

Seven USGS stream gauges (Figure 18) and their records were found to be within the spatial and temporal (1990 to 2009) scale. They were used to calibrate streamflow, sediment, and nutrients. Though all of them were in the windward, other watersheds would be calibrated using previously published data and estimates.

Water quality calibration included comparing model outputs (sediment, nitrogen, and phosphorus) against observed values (sediment, nutrient, and phosphorus) at USGS stream gauges as well as turbidity, total nitrogen, phosphorus, and suspended solids at water quality sampling sites (Figure 3A - 3). Though sediment load from the model was similar to total suspended solids at the sampling sites, these datasets were assumed to be the same for this study.

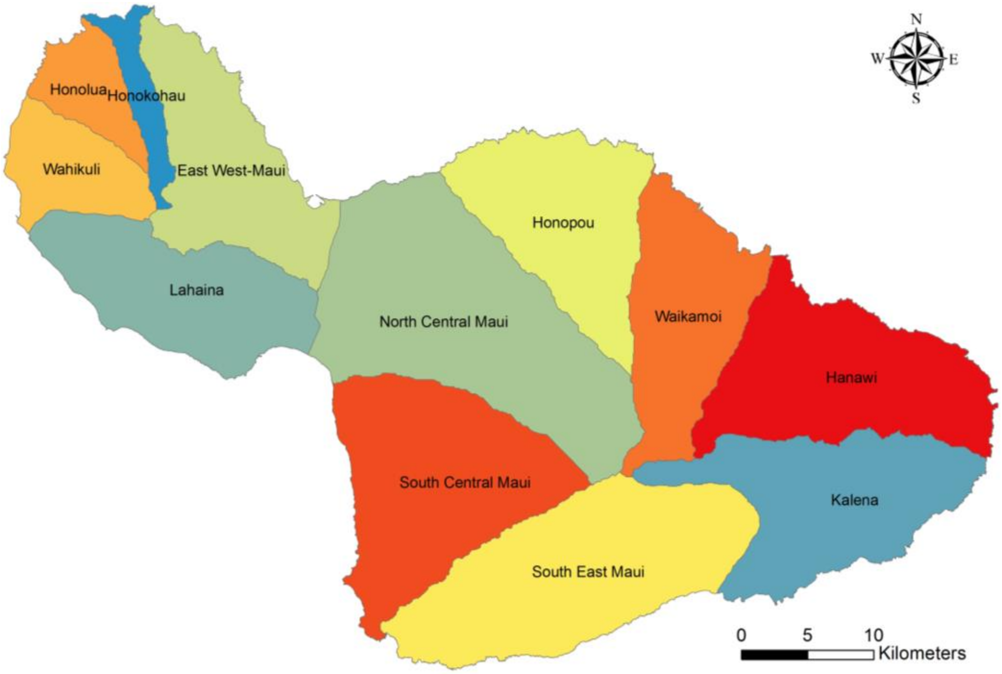


*Figure 3A - 1. Sectors for subsequent watershed delineation to ease post-processing and calibration.*

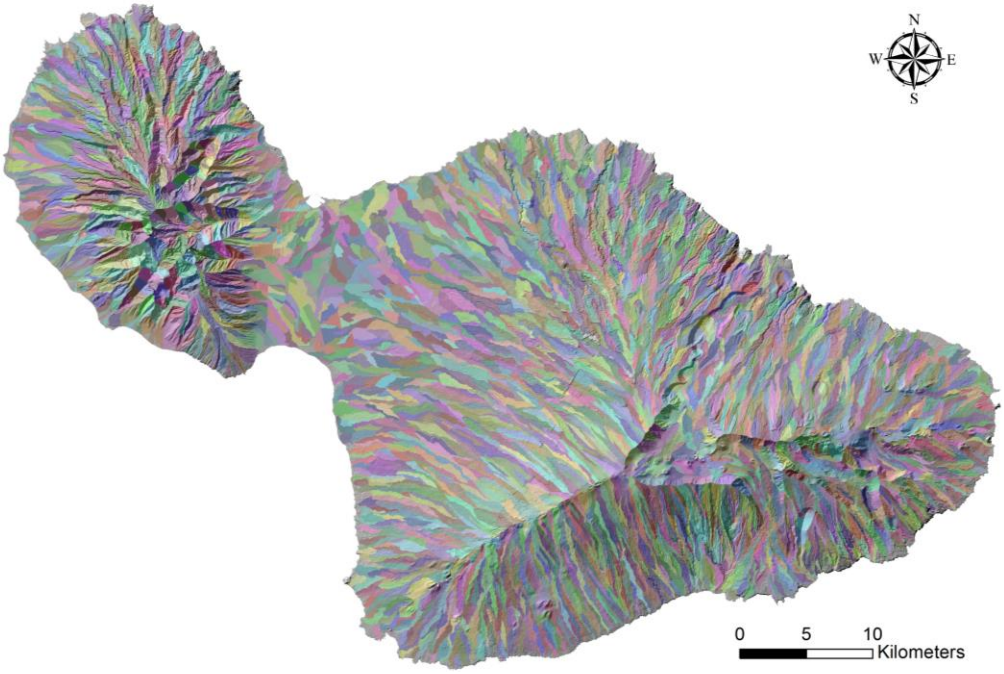


*Figure 3A - 2. SWAT-delineated subbasins (n = 2976).*

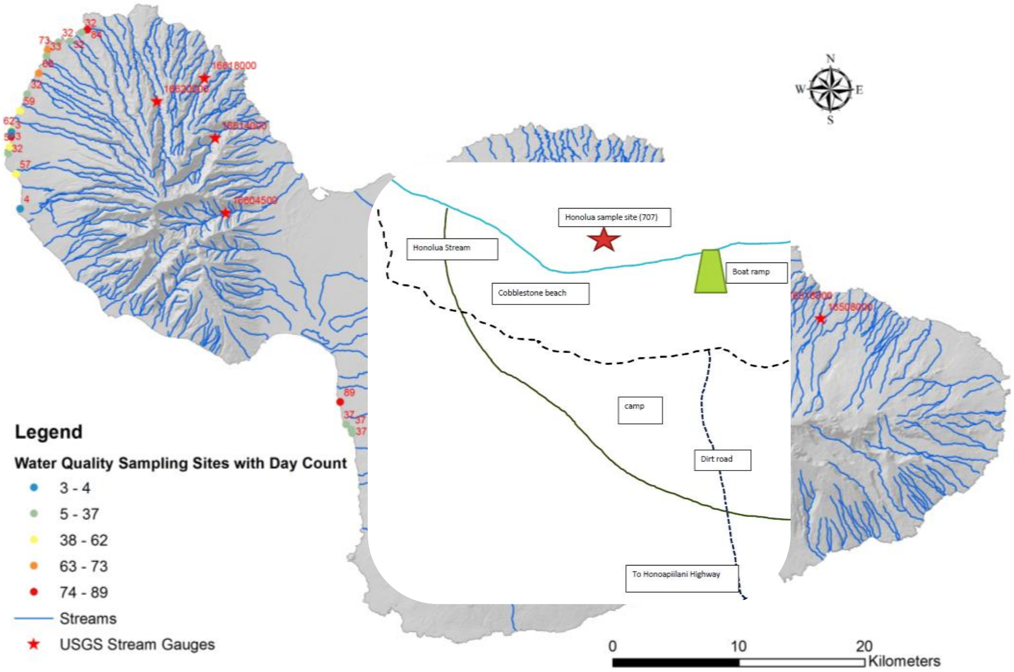


*Figure 3A - 3. Water quality sampling sites with day count and USGS stream gauges available for calibration. Inset figure for Honolua Bay shows a typical offshore water quality sampling site (HI DOH - CWB, 2017).*

*First-Order Uncertainty Analysis (FOUA)*

In FOUA, the expected model output and variance of the performance function are approximated by,

$$E[C] \approx f(X_m) \tag{15}$$

So, the variance for all the parameters can be estimated using,

$$Var[C] \cong \sum_{i=1}^{n} \left(\frac{\partial f}{\partial X}\right)_{X_m}^{2} * Var[X_i] \tag{16}$$

Or, the variance for each parameter (with uniform distribution) can be estimated using,

$$SC_i \cong \left(\frac{\partial f}{\partial X_i}\right)^2 Var[X_i] \tag{17}$$

$$Var[X_i] = \sigma^2 = \frac{(b-a)^2}{12} \tag{18}$$

where a = minimum and b = maximum value.

Total uncertainty (OR) standard deviation (SD),

$$SD = \sqrt{Var[C]} \tag{19}$$

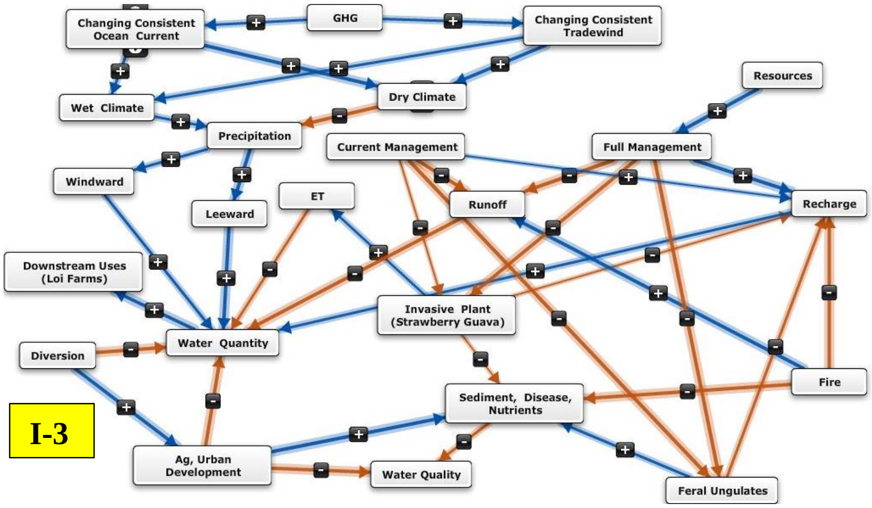
Coefficient of Variation (CV),

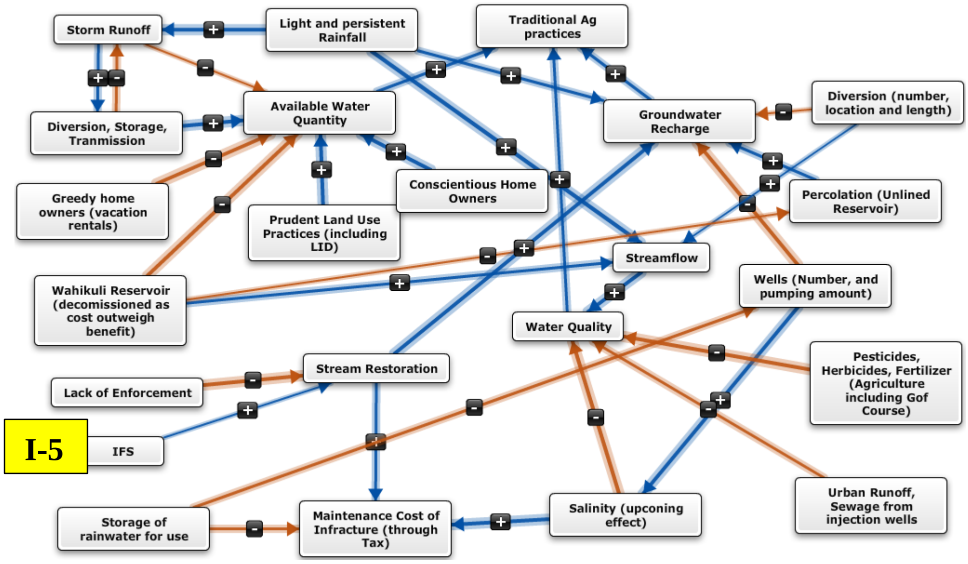
$$CV = \frac{SD}{mean} \tag{20}$$

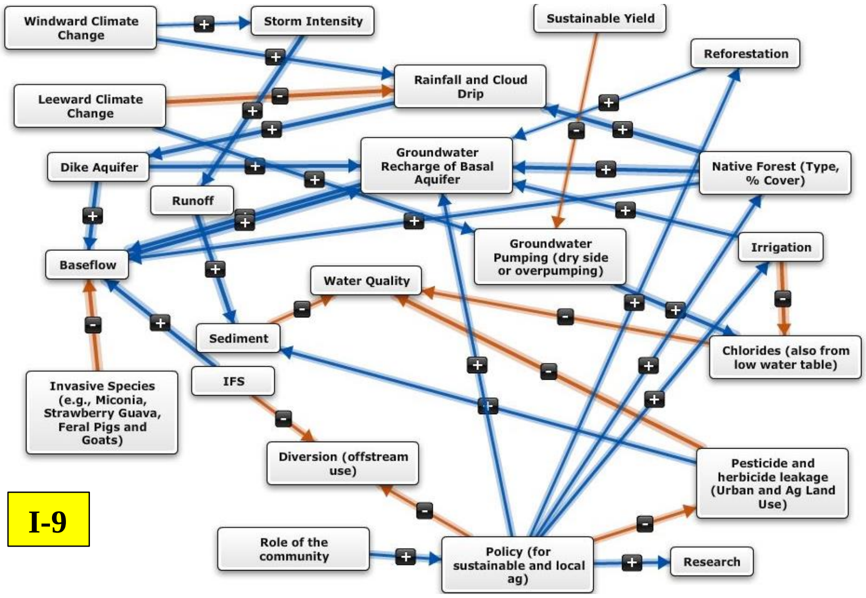
The variability of each parameter in interest was propagated to the overall variance of SWAT and MentalModeler outputs. Then, parameters were ranked according to their uncertainty contribution.

### *FCM Models*

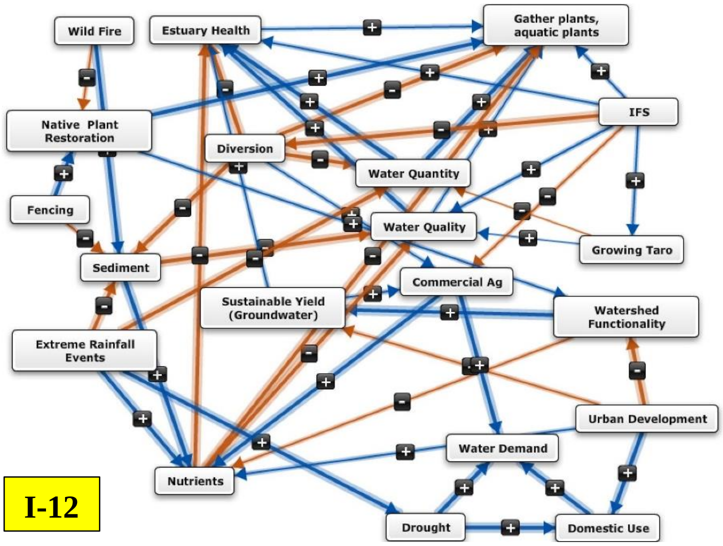
#### *Water Resources Manager*



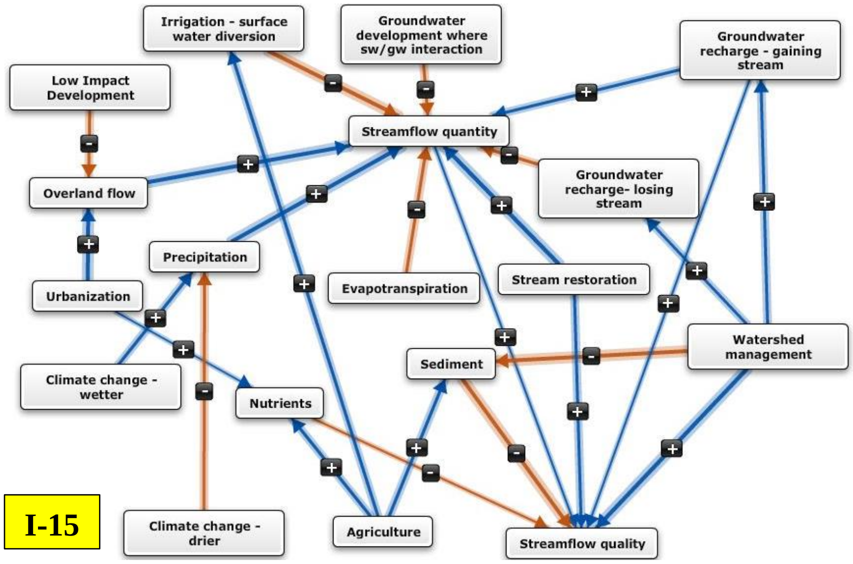



Windward Climate Change
Storm Intensity
Sustainable Yield
Reforestation
Leeward Climate Change
Rainfall and Cloud Drip
Dike Aquifer
Groundwater Recharge of Basal Aquifer
Native Forest (Type, % Cover)
Runoff
Baseflow
Groundwater Pumping (dry side or overpumping)
Irrigation
Water Quality
Sediment
Chlorides (also from low water table)
IFS
Invasive Species (e.g., Miconia, Strawberry Guava, Feral Pigs and Goats)
Diversion (offstream use)
Pesticide and herbicide leakage (Urban and Ag Land Use)
Role of the community
Policy (for sustainable and local ag)
Research

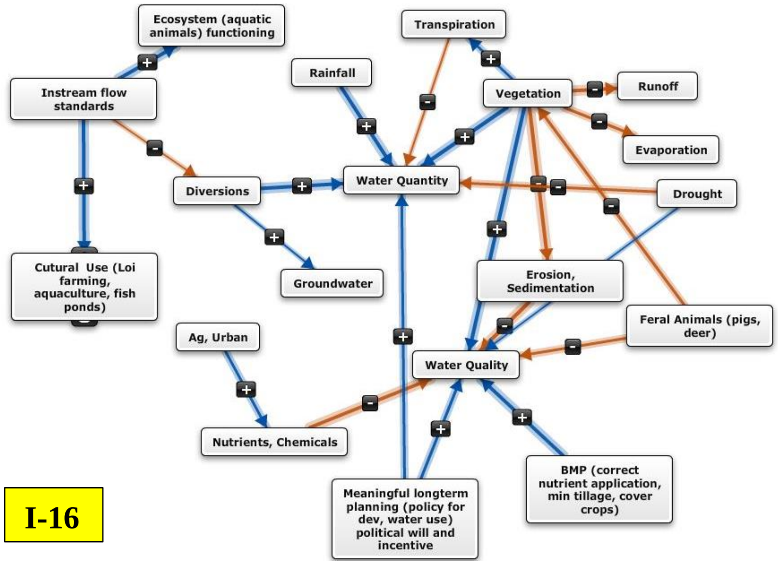
**I-9**


Wild Fire
Estuary Health
Gather plants, aquatic plants
IFS
Native Plant Restoration
Diversion
Water Quantity
Fencing
Water Quality
Growing Taro
Sediment
Sustainable Yield (Groundwater)
Commercial Ag
Watershed Functionality
Extreme Rainfall Events
Urban Development
Water Demand
Nutrients
Drought
Domestic Use

**I-12**

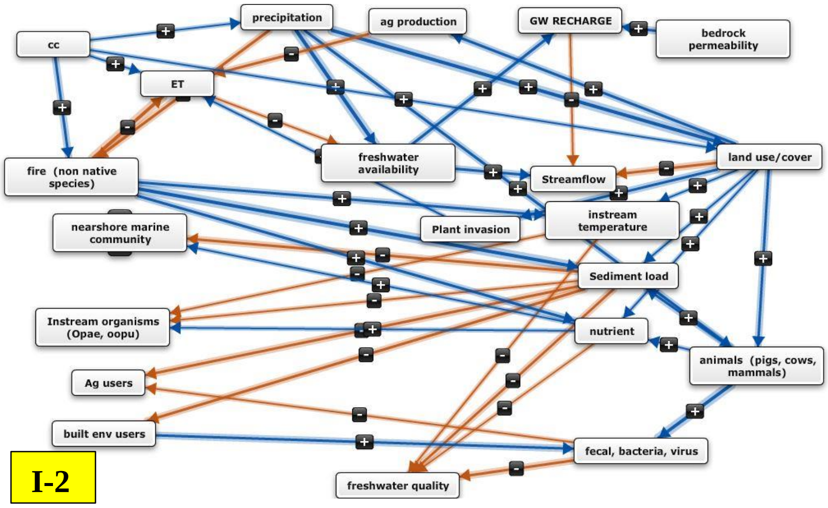

Irrigation - surface water diversion
Groundwater development where sw/gw interaction
Groundwater recharge - gaining stream
Low Impact Development
Streamflow quantity
Overland flow
Groundwater recharge- losing stream
Precipitation
Evapotranspiration
Stream restoration
Urbanization
Watershed management
Sediment
Climate change - wetter
Nutrients
Climate change - drier
Agriculture
Streamflow quality

**I-15**

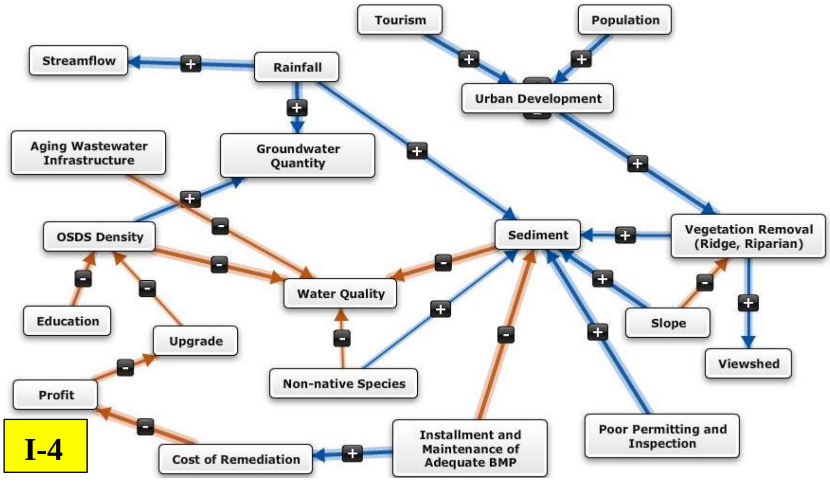


**I-16**

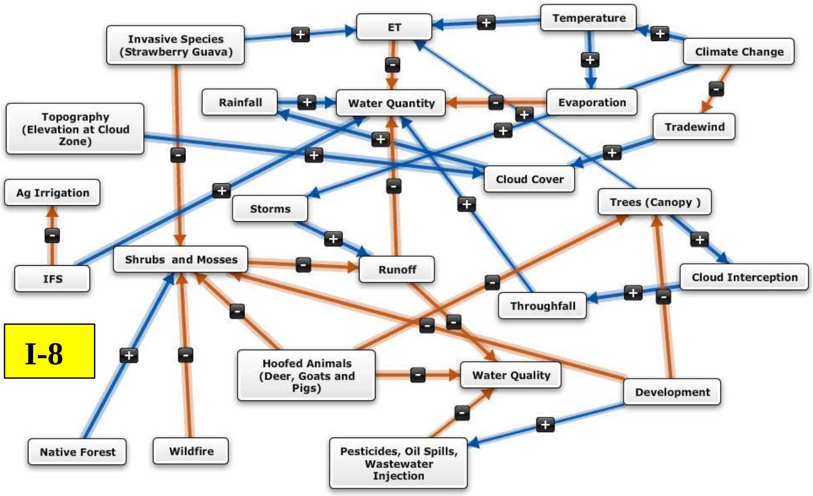
*Conservationist*



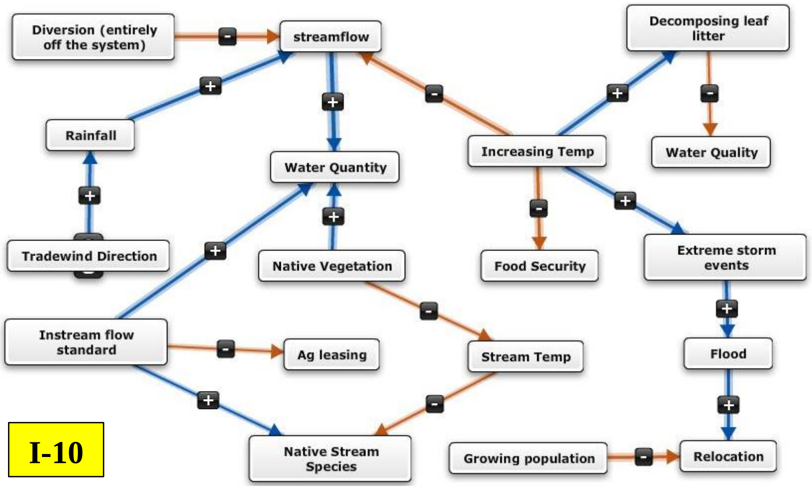
**I-2**



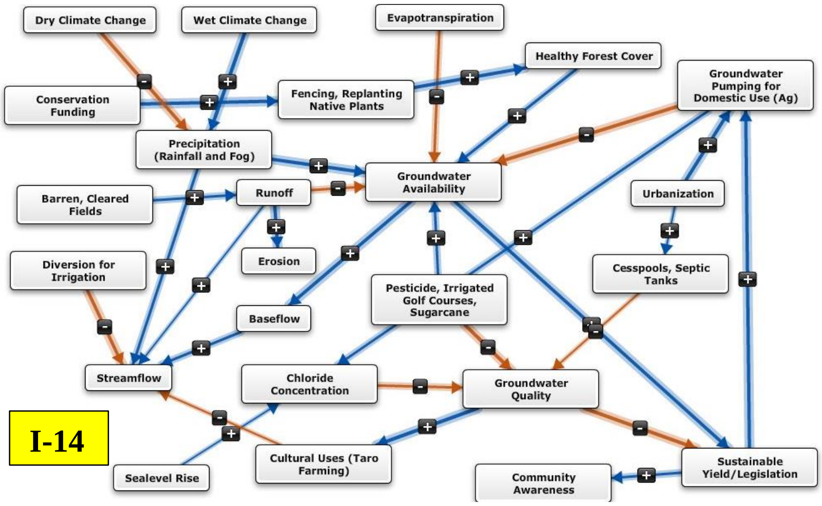
**I-4**


Invasive Species (Strawberry Guava)
ET
Temperature
Climate Change
Topography (Elevation at Cloud Zone)
Rainfall
Water Quantity
Evaporation
Tradewind
Ag Irrigation
Cloud Cover
Storms
Trees (Canopy )
IFS
Shrubs and Mosses
Runoff
Cloud Interception
Throughfall
Hoofed Animals (Deer, Goats and Pigs)
Water Quality
Development
Native Forest
Wildfire
Pesticides, Oil Spills, Wastewater Injection

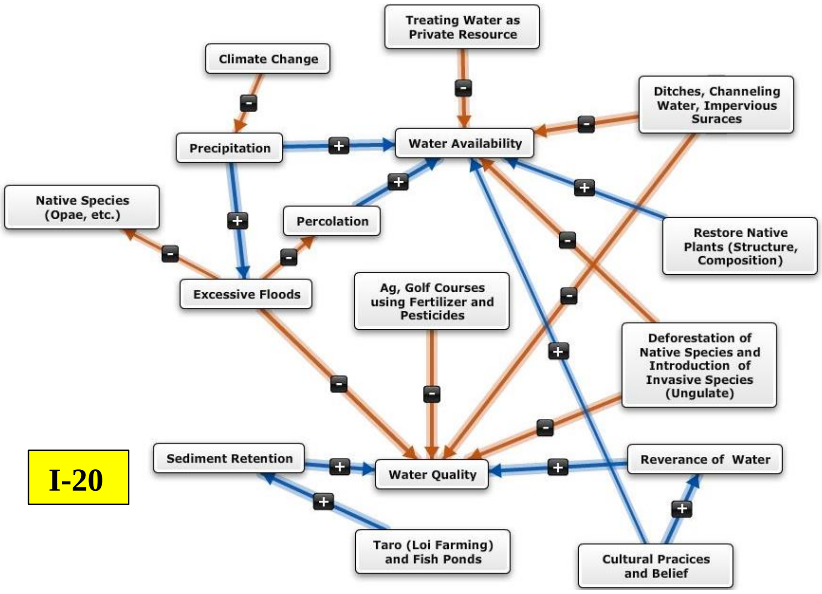
I-8


Diversion (entirely off the system)
streamflow
Decomposing leaf litter
Rainfall
Water Quantity
Increasing Temp
Water Quality
Tradewind Direction
Native Vegetation
Food Security
Extreme storm events
Instream flow standard
Ag leasing
Stream Temp
Flood
Native Stream Species
Growing population
Relocation

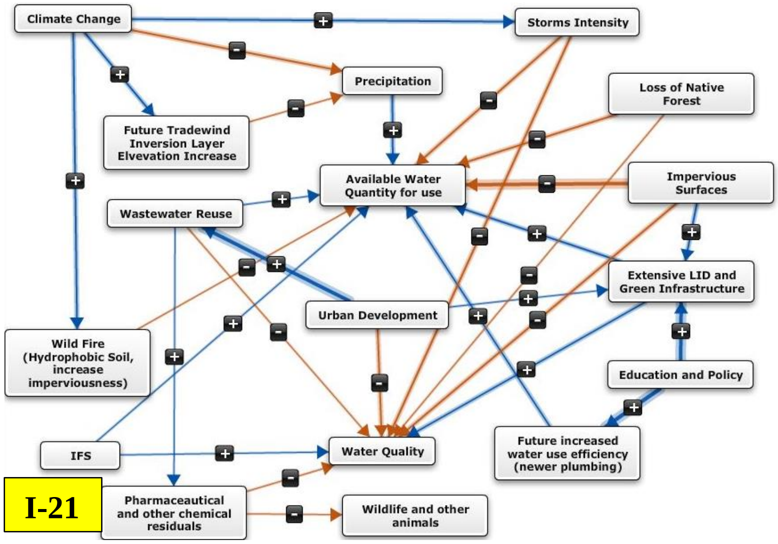
I-10


Dry Climate Change
Wet Climate Change
Evapotranspiration
Healthy Forest Cover
Conservation Funding
Fencing, Replanting Native Plants
Groundwater Pumping for Domestic Use (Ag)
Precipitation (Rainfall and Fog)
Groundwater Availability
Barren, Cleared Fields
Runoff
Urbanization
Erosion
Diversion for Irrigation
Cesspools, Septic Tanks
Baseflow
Pesticide, Irrigated Golf Courses, Sugarcane
Streamflow
Chloride Concentration
Groundwater Quality
Cultural Uses (Taro Farming)
Sealevel Rise
Community Awareness
Sustainable Yield/Legislation

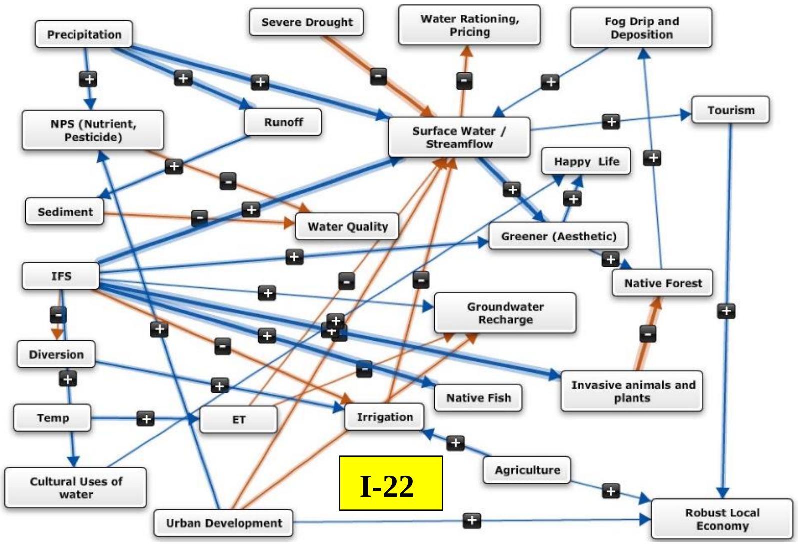
I-14


Treating Water as Private Resource
Climate Change
Ditches, Channeling Water, Impervious Suraces
Precipitation
Water Availability
Native Species (Opae, etc.)
Percolation
Restore Native Plants (Structure, Composition)
Excessive Floods
Ag, Golf Courses using Fertilizer and Pesticides
Deforestation of Native Species and Introduction of Invasive Species (Ungulate)
Sediment Retention
Water Quality
Reverance of Water
Taro (Loi Farming) and Fish Ponds
Cultural Pracices and Belief

**I-20**

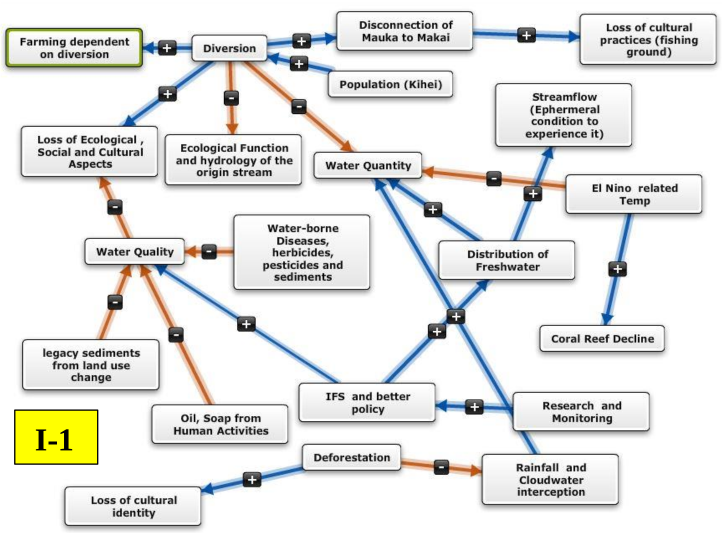

Climate Change
Storms Intensity
Precipitation
Loss of Native Forest
Future Tradewind Inversion Layer Elevation Increase
Available Water Quantity for use
Impervious Surfaces
Wastewater Reuse
Extensive LID and Green Infrastructure
Urban Development
Wild Fire (Hydrophobic Soil, increase imperviousness)
Education and Policy
IFS
Water Quality
Future increased water use efficiency (newer plumbing)
Pharmaceautical and other chemical residuals
Wildlife and other animals

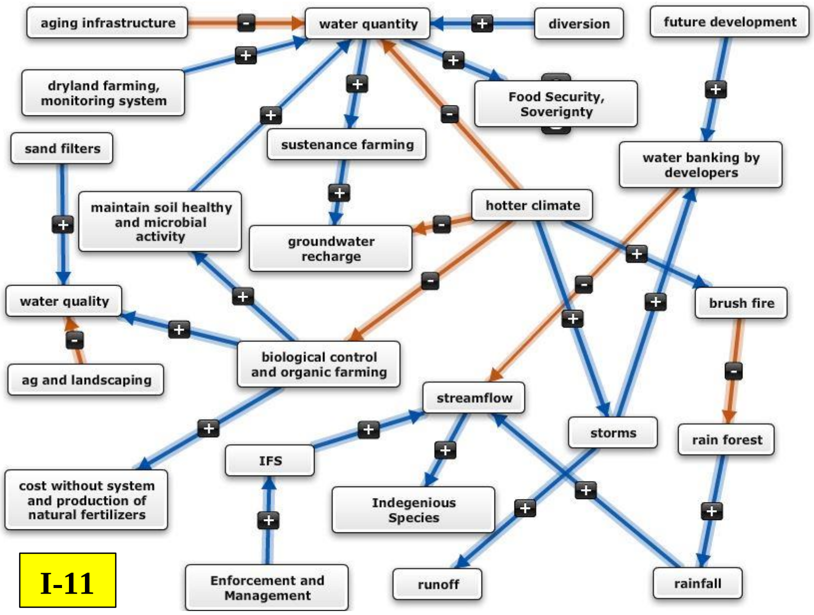
**I-21**

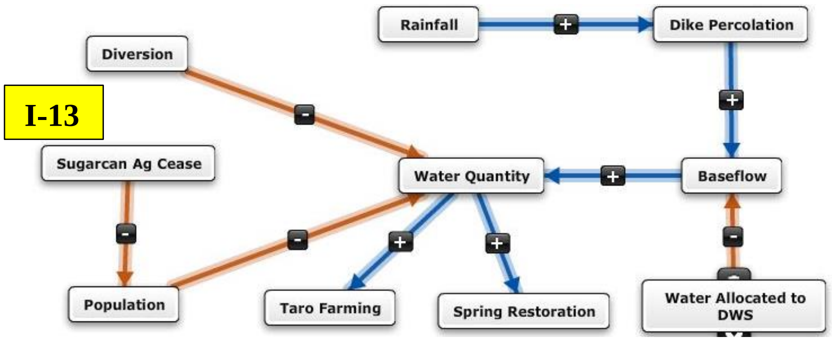

Precipitation
Severe Drought
Water Rationing, Pricing
Fog Drip and Deposition
Tourism
NPS (Nutrient, Pesticide)
Runoff
Surface Water / Streamflow
Happy Life
Sediment
Water Quality
Greener (Aesthetic)
IFS
Native Forest
Groundwater Recharge
Diversion
Native Fish
Invasive animals and plants
Temp
ET
Irrigation
Agriculture
Cultural Uses of water
Urban Development
Robust Local Economy

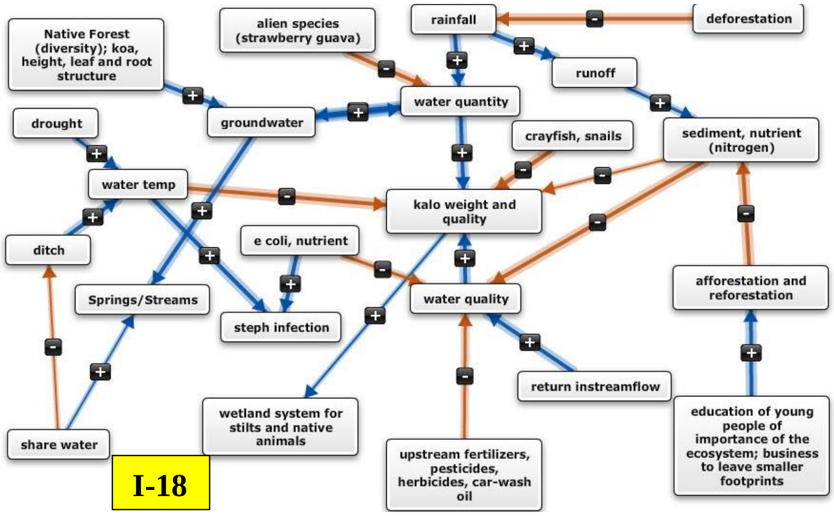
**I-22**

*Agriculturalist*


I-1

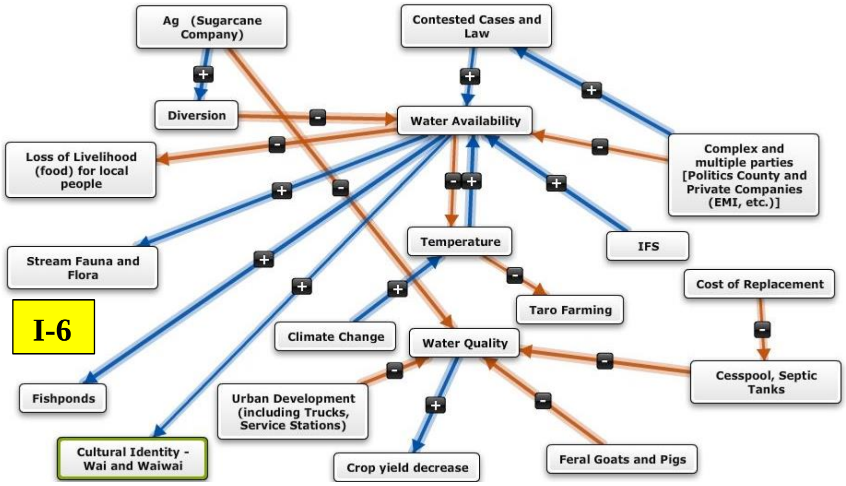

I-11


I-13

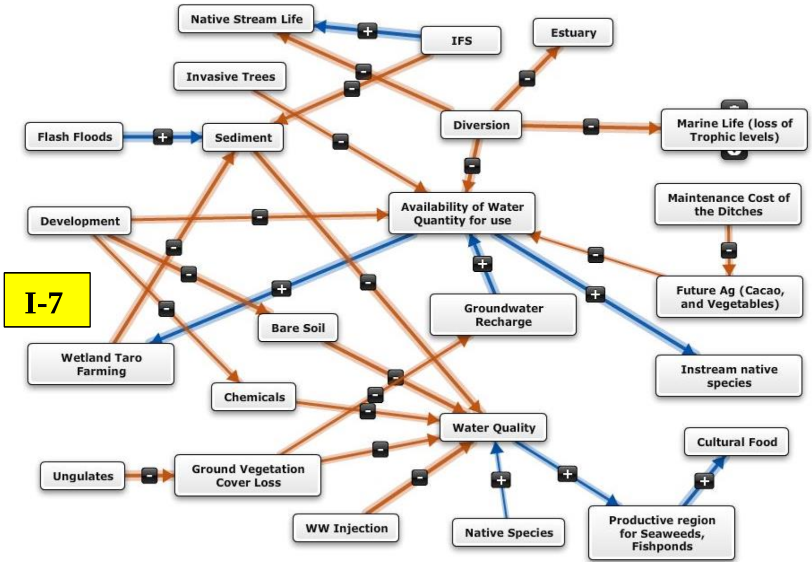


**I-18**

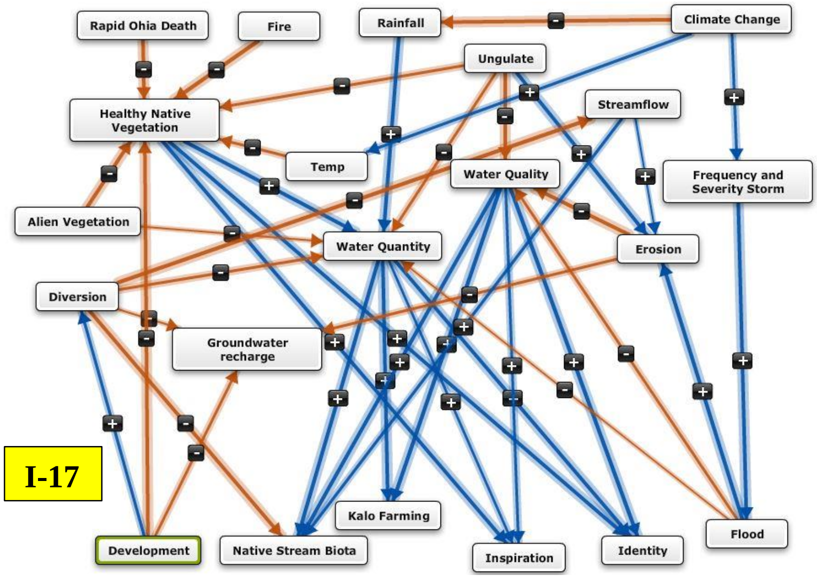
*Cultural Practitioner*



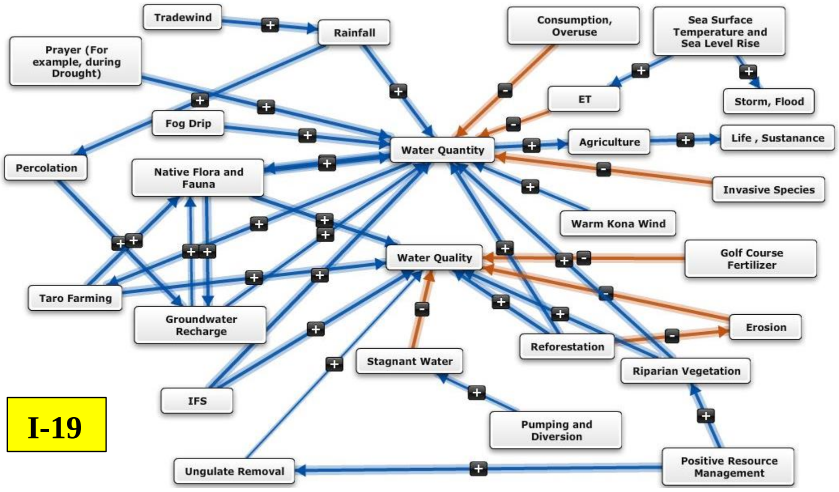
**I-6**


Native Stream Life
IFS
Estuary
Invasive Trees
Flash Floods
Sediment
Diversion
Marine Life (loss of Trophic levels)
Development
Availability of Water Quantity for use
Maintenance Cost of the Ditches
Groundwater Recharge
Future Ag (Cacao, and Vegetables)
Wetland Taro Farming
Bare Soil
Instream native species
Chemicals
Water Quality
Cultural Food
Ungulates
Ground Vegetation Cover Loss
WW Injection
Native Species
Productive region for Seaweeds, Fishponds

I-7


Rapid Ohia Death
Fire
Rainfall
Climate Change
Ungulate
Healthy Native Vegetation
Streamflow
Temp
Water Quality
Frequency and Severity Storm
Alien Vegetation
Water Quantity
Erosion
Diversion
Groundwater recharge
Kalo Farming
Development
Native Stream Biota
Inspiration
Identity
Flood

I-17


Tradewind
Rainfall
Consumption, Overuse
Sea Surface Temperature and Sea Level Rise
Prayer (For example, during Drought)
ET
Storm, Flood
Fog Drip
Water Quantity
Agriculture
Life , Sustanance
Percolation
Native Flora and Fauna
Invasive Species
Warm Kona Wind
Water Quality
Golf Course Fertilizer
Taro Farming
Groundwater Recharge
Erosion
Reforestation
Stagnant Water
Riparian Vegetation
IFS
Pumping and Diversion
Ungulate Removal
Positive Resource Management

I-19

***FCM Sensitivity Analysis***

*Table 3A - 1.Sensitive parameters for SWAT modeling in Maui.*

| **Parameter** | **Selected Value** | **Acceptable Range** | **Definition** |
|---|---|---|---|
| | | **Water Quantity** | |
| **ESCO** | 1 | 0.01 to 1 | Soil evaporation compensation factor |
| **EPCO** | 0.01 | 0.01 to 2 | Plant uptake compensation factor |
| **ICN** | 1 | 0 or 1 | Daily curve number calculation method |
| **CNCOEF** | 0.5 | 0.5 to 2 | Plant evapotranspiration curve number coefficient |
| **DEP_IMP** | 6000 | 0 to 6000 (mm) | Depth to impervious layer in soil profile |
| **SHALLST** | 1000 | 0 to 5000 | Initial depth of water in the shallow aquifer (mm) |
| **DEEPST** | 2000 | 0 to 10000 | Initial depth of water in the deep aquifer (mm) |
| **ALPHA_BF** | 0.5 | 0 to 1 | Baseflow alpha factor |
| **ALPHA_BF_D** | 1 | 0 to 1 | Baseflow alpha factor for deep aquifer |
| **GWQMN** | 0 | 0 to 5000 | Threshold depth of water in the shallow aquifer for return flow to occur |
| **GW_REVAP** | 0.02 | 0.02 to 0.2 | Groundwater "revap" coefficient |
| **REVAPMN** | 1000 | 0 to 1000 | Threshold depth of water in the shallow aquifer for "revap" to occur |
| **RCHRG_DP** | 0.05 | 0 to 1 | Deep aquifer percolation fraction |
| **SOL_AWC** | | 0 to 1 | Soil available water content |
| | | **Water Quality** | |
| **USLE_K** | Varies | 0 to 0.65 | Soil erodibility factor |
| **USLE_P** | Varies | 0 to 1 | Support practice factor |
| **SOL_CBN** | Varies | 0.05 to 10 | Organic carbon content |
| **NPERCO** | Varies | 0 to 1 | Nitrogen percolation coefficient |
| **PPERCO** | Varies | 10 to 17.5 | Phosphorus percolation coefficient |
| **PHOSKD** | Varies | 100 to 200 | Phosphorus soil partitioning coefficient |

*Table 3A - 2. Structural metrics for the four representative stakeholders (top to bottom): I-5 as the water resources manager, I-2 as the conservationist), I-18 as the agriculturalist, and I-6 as the cultural practitioner.*

| **I-5 (Water Resources Manager)** | **Indegree** | **Outdegree** | **Centrality** | **Transmitter** | **Receiver** | **Ordinary** |
|---|---|---|---|---|---|---|
| Available Water Quantity | 5.25 | 0 | 5.25 | 0 | 1 | 0 |
| Light and Persistent Rainfall | 0 | 2.5 | 2.5 | 1 | 0 | 0 |
| Streamflow | 1.75 | 1 | 2.75 | 0 | 0 | 1 |
| Storm Runoff | 1.5 | 0.75 | 2.25 | 0 | 0 | 1 |
| Groundwater Recharge | 3.25 | 0.5 | 3.75 | 0 | 0 | 1 |
| Wells (Number and Pumping Amount) | 0.5 | 2 | 2.5 | 0 | 0 | 1 |
| Percolation | 0.25 | 0.5 | 0.75 | 0 | 0 | 1 |
| Diversion | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| Wahikuli Reservoir | 0 | 1.75 | 1.75 | 1 | 0 | 0 |
| Water Quality | 3.5 | 0 | 3.5 | 0 | 1 | 0 |
| Diversion, Storage, Transmission | 0.5 | 1.5 | 2 | 0 | 0 | 1 |
| Maintenance Cost of Infrastructure | 2 | 0 | 2 | 0 | 1 | 0 |
| Stream Restoration | 1.25 | 1.5 | 2.75 | 0 | 0 | 1 |
| IFS | 0 | 0.25 | 0.25 | 1 | 0 | 0 |
| Lack of Enforcement | 0 | 1 | 1 | 1 | 0 | 0 |
| Pesticides Herbicides Fertilizer | 0 | 1 | 1 | 1 | 0 | 0 |
| Urban Runoff Injection Sewage | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| Salinity | 1 | 2 | 3 | 0 | 0 | 1 |
| Storage of Rainwater for Use | 0 | 1 | 1 | 1 | 0 | 0 |
| Traditional Ag Practices | 0.5 | 0 | 0.5 | 0 | 1 | 0 |
| Prudent Land Use Practices | 0 | 1 | 1 | 1 | 0 | 0 |
| Greedy home owners (Vacation Rentals | 0 | 1 | 1 | 1 | 0 | 0 |
| Conscientious Home Owners | 0 | 1 | 1 | 1 | 0 | 0 |
| **Total Count** | | | | 11 | 4 | 18 |
| **Density** | 0.056710775 | | | | | |
| **Hierarchy Index** | 0.010676233 | | | | | |

| **I-2 (Conservationist)** | **Indegree** | **Outdegree** | **Centrality** | **Transmitter** | **Receiver** | **Ordinary** |
|---|---|---|---|---|---|---|
| Precipitation | 0.25 | 3 | 3.25 | 0 | 0 | 1 |
| ET | 2 | 0.25 | 2.25 | 0 | 0 | 1 |
| Groundwater Recharge | 1 | 0.25 | 1.25 | 0 | 0 | 1 |
| Streamflow | 1.25 | 0 | 1.25 | 0 | 1 | 0 |
| Bedrock Permeability | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| Freshwater quality | 1.5 | 0 | 1.5 | 0 | 1 | 0 |
| Sediment Load | 1.75 | 2.25 | 4 | 0 | 0 | 1 |
| Fecal Bacteria Virus | 1.5 | 0.75 | 2.25 | 0 | 0 | 1 |
| Instream Temperature | 0.75 | 0.5 | 1.25 | 0 | 0 | 1 |
| Instream organisms | 0.75 | 0 | 0.75 | 0 | 1 | 0 |
| Nutrient | 1 | 0.75 | 1.75 | 0 | 0 | 1 |
| Freshwater Availability | 1.25 | 1 | 2.25 | 0 | 0 | 1 |
| Nearshore Marine community | 0.75 | 0 | 0.75 | 0 | 1 | 0 |
| Ag Users | 0.75 | 0 | 0.75 | 0 | 1 | 0 |
| Built Env Users | 0.5 | 0.5 | 1 | 0 | 0 | 1 |
| Animals | 1 | 1.75 | 2.75 | 0 | 0 | 1 |
| Land Use Cover | 1.25 | 2.75 | 4 | 0 | 0 | 1 |
| Fire | 1 | 3 | 4 | 1 | 0 | 1 |
| Plant Invasion | 0.5 | 0.25 | 0.75 | 0 | 0 | 1 |
| Ag production | 0.5 | 0.5 | 1 | 0 | 0 | 1 |
| Climate Change | 0 | 1.25 | 1.25 | 1 | 0 | 0 |
| **Total Count** | | | | 3 | 5 | 15 |
| **Density** | 0.095238095 | | | | | |
| **Hierarchy Index** | 0.027164502 | | | | | |

| **I-18 (Agriculturalist)** | **Indegree** | **Outdegree** | **Centrality** | **Transmitter** | **Receiver** | **Ordinary** |
|---|---|---|---|---|---|---|
| Water quantity | 3 | 2 | 5 | 0 | 0 | 1 |
| Drought | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| Rainfall | 1 | 2 | 3 | 0 | 0 | 1 |
| Ditch | 0.25 | 1 | 1.25 | 0 | 0 | 1 |
| Water temp | 1.5 | 2 | 3.5 | 0 | 0 | 1 |
| Kalo weight and quality | 4.25 | 0.25 | 4.5 | 0 | 0 | 1 |
| Deforestation | 0 | 1 | 1 | 1 | 0 | 0 |
| Groundwater | 2 | 2 | 4 | 0 | 0 | 1 |
| Alien species (e.g., strawberry guava) | 0 | 1 | 1 | 1 | 0 | 0 |
| Native forest diversity | 0 | 1 | 1 | 1 | 0 | 0 |
| Crayfish snails | 0 | 1 | 1 | 1 | 0 | 0 |
| Water quality | 3 | 1 | 4 | 0 | 0 | 1 |
| Share water | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| Upstream nutrients (e.g., fertilizers) | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| E coli nutrient | 0 | 1.5 | 1.5 | 1 | 0 | 0 |
| Runoff | 1 | 0.5 | 1.5 | 0 | 0 | 1 |
| Steph infection | 2 | 0 | 2 | 0 | 1 | 0 |
| Return instream flow | 0 | 1 | 1 | 1 | 0 | 0 |
| Afforestation and reforestation | 1 | 1 | 2 | 0 | 0 | 1 |
| Education | 0 | 1 | 1 | 1 | 0 | 0 |
| Wetland system for native species | 0.25 | 0 | 0.25 | 0 | 1 | 0 |
| Springs, Streams | 1.25 | 0 | 1.25 | 0 | 1 | 0 |
| Sediment and nutrient | 1.5 | 1.25 | 2.75 | 0 | 0 | 1 |
| **Total Count** | | | | 10 | 3 | 19 |
| **Density** | 0.051039698 | | | | | |
| **Hierarchy Index** | 0.0087268 | | | | | |

| **I-6 (Cultural Practitioner)** | **Indegree** | **Outdegree** | **Centrality** | **Transmitter** | **Receiver** | **Ordinary** |
|---|---|---|---|---|---|---|
| Ag  Sugarcane Company | 0 | 2 | 2 | 1 | 0 | 0 |
| Water Availability | 4 | 4 | 8 | 0 | 0 | 1 |
| Contested Cases and Law | 1 | 0.5 | 1.5 | 0 | 0 | 1 |
| Historical Owner | 0 | 0 | 0 | 1 | 1 | 0 |
| Loss of Livelihood | 1 | 0 | 1 | 0 | 1 | 0 |
| Diversion | 1 | 1 | 2 | 0 | 0 | 1 |
| Complex and multiple parties (Politics, County and Private Companies such as EMI etc.) | 0 | 1.5 | 1.5 | 1 | 0 | 0 |
| Law | 0 | 0 | 0 | 1 | 1 | 0 |
| Climate Change | 0 | 1 | 1 | 1 | 0 | 0 |
| Temperature | 1.5 | 1.5 | 3 | 0 | 0 | 1 |
| Water Quality | 4 | 1 | 5 | 0 | 0 | 1 |
| Urban Development  including Trucks, Service Stations | 0 | 1 | 1 | 1 | 0 | 0 |
| Cesspool and Septic Tanks | 0.5 | 1 | 1.5 | 0 | 0 | 1 |
| Taro Farming | 0.5 | 0 | 0.5 | 0 | 1 | 0 |
| Cost of Replacement | 0 | 0.5 | 0.5 | 1 | 0 | 0 |
| IFS | 0 | 1 | 1 | 1 | 0 | 0 |
| Crop yield decrease | 1 | 0 | 1 | 0 | 1 | 0 |
| Feral Goats and Pigs | 0 | 1 | 1 | 1 | 0 | 0 |
| Stream Fauna and Flora | 1 | 0 | 1 | 0 | 1 | 0 |
| Fishponds | 1 | 0 | 1 | 0 | 1 | 0 |
| Cultural Identity | 0.5 | 0 | 0.5 | 0 | 1 | 0 |
| **Total Count** | | | | 9 | 8 | 12 |
| **Density** | 0.045351474 | | | | | |
| **Hierarchy Index** | 0.023685838 | | | | | |

## Appendix 3B

### *Interview Consent Form*

My name is Hla Htun, a graduate student at the University of Hawai‘i at Manoa in the Department of Natural Resources and Environmental Management. As part of the requirements for earning my graduate degree, I am doing a research project which is a collaboration between UH Manoa (NREM-CTAHR) and UH Sea Grant College Program. Two Principal Investigators, an Academic Advisor and a Research Assistant (PhD student) constitute the research team.

**Project Description – Activities and Time Commitment**:
The researchers seek to understand how watershed-based ecosystem services, either historically or contemporarily valuable to stakeholders, will be impacted in the future under a range of climate and land use/cover change scenarios.

Stakeholders in the study area will be interviewed preferably in groups. During the session, theory will be presented, and then the participants will be asked to relate concepts and/or draw concept maps. The session will last approximately 30 minutes.

**Benefits and Risks:**
The results of the group or individual interviews will be further refined, input into a computer model and outcomes will be produced and presented. In addition, best management practices based on these results will also be suggested. These will also be published in one or more papers in greater detail. They will be available to the public as well as policy makers and stakeholders. As a result, the participants (stakeholders) will have a more informed, scientifically proven knowledge on preservation and protection of the associated ecosystems for their optimal services against increasing climate and land use/cover changes.

We do not foresee any associated real risks or discomforts, either physical or psychological, to the participant, his/her family and coworkers.

**Confidentiality and Privacy:**
None of the participants will be identified in any way. Strict confidentiality will be maintained throughout the research and beyond.

**Voluntary Participation:**
Participation in this research is entirely voluntary. You will not be penalized in any way should you decide not to participate in the research. In addition, we recognize that it is your right to withdraw from the study at any time without any consequences.

**Contact Info:**
If you have any questions or concerns, please contact.

**Pincipal Inestigator:** Lepczyk, Christopher
Associate Professor, University of Hawai‘i at Manoa

Email: lepczyk@hawaii.edu

**Co-Principal Investigator:** Gray, Steven
Assistant Professor, University of Massachusetts, Boston
Email: stevenallangray@gmail.com

**Academic Advisor**: Oleson, Kirsten
Assistant Professor of Ecological Economics,University of Hawai'i Manoa
Email: koleson@hawaii.edu

**Research Assistant**: Htun, Hla
PhD Student/Research Assistant
Email: hlahtun@hawaii.edu

**Office of Research Compliance**: UH Human Studies Program
Phone: 808.956.5007
Email: uhirb@hawaii.edu

**Signature for Consent**:
I agree to participate in the interview for the research project, **Forecasting climate change impacts on coastal ecosystem services in Hawai‘i through integration of ecological and social participatory models**.

**Name of Participant (Print): ____________________________________________________**

**Participant’s Signature: ______________________________________________**

**Signature of the Person Obtaining Consent: ____________________________________**

**Date: ____________________________**

Please initial next to either “Yes” or “No” to the following:

_____ Yes _____ No I consent to be audio-recorded for the interview portion of this research.

***Interview Script***

Thanks for agreeing to an interview.

My **research focuses** on understanding how freshwater resources, specifically **water quantity and quality**, **are affected by environmental change, human impacts, and management**.

**Objective** today is to:

- <u>Create a "mental map"</u> of your <u>perceptions of the main features of the freshwater system and relationships</u> between those features.
- You can <u>mention anything you feel is</u> important that is related to your view of the freshwater system.

Our focus is on freshwater resources in Central and West Maui.

Did you have a chance to look over the mental mapping background material?
Give intro to mechanism of mental mapping…do an example

Ready to start?

- Describe the freshwater resources in West Maui — Hla draw nodes and ask "what are the linkages" and draw arrows/score

- What is your biggest concern related to freshwater? What changes have you seen? What changes do you expect?
- What is driving that concern/change?
- What impact does this have on freshwater?
- How does that impact you? Your community?

- Any other features/components/relationships?
- … pause

** Transition to environmental impacts **

- How does land use change, things like change from ag land to fallow or conversion of ag land to residential development, impact the freshwater resources?
- Can you add in to your mental model impacts from land use change?
- How have land use change impacts been managed in the past? Did it have positive impacts on freshwater? Through what factors (of the mental model)? How are they being managed now? How will they be managed in the future?

** Transition to climate change impacts **

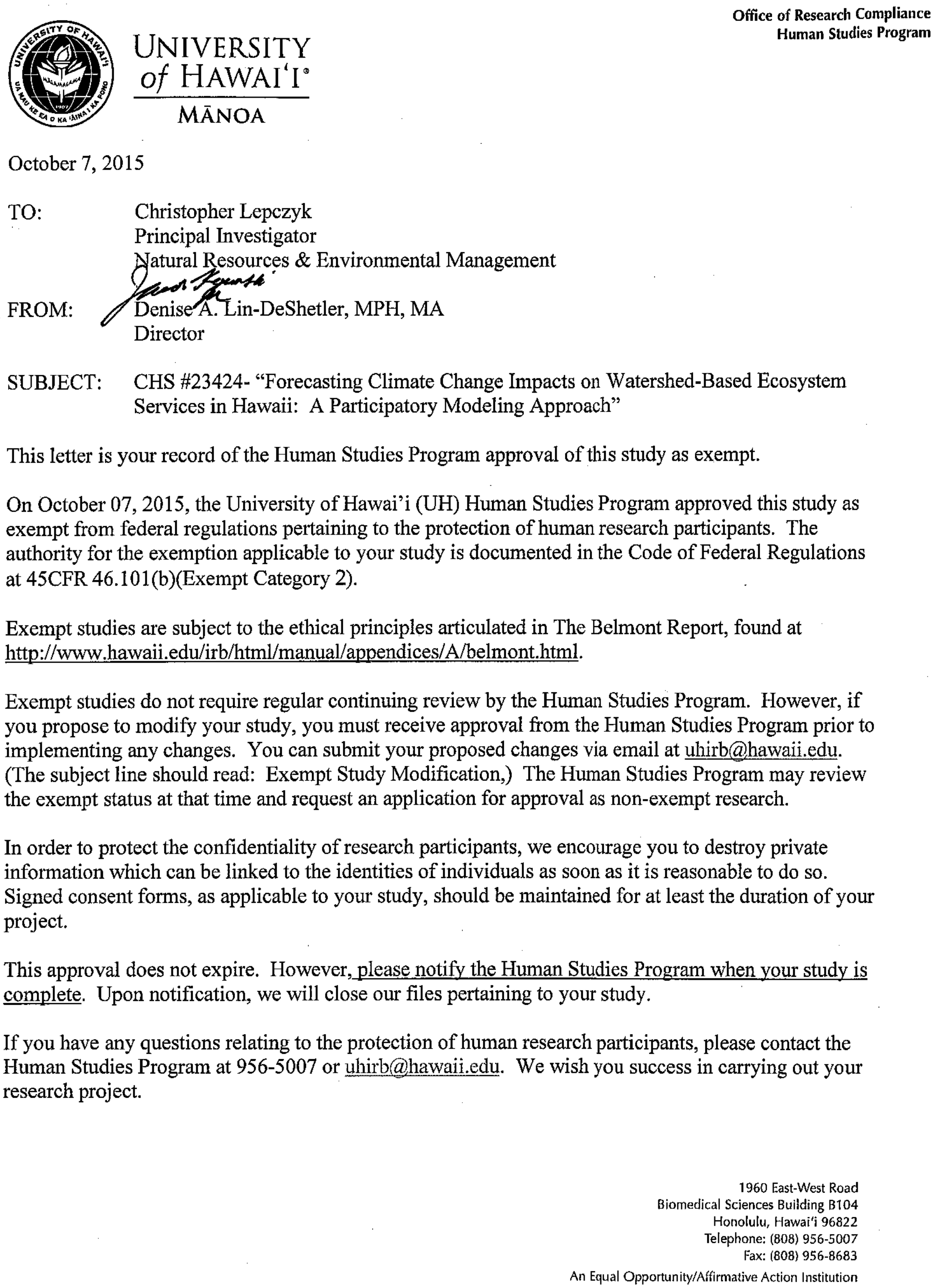
- Same thing for climate change - how has climate change impacted the system? How will it impact the system?

- How is climate change being managed? What adaptation measures have been put in place? What impact do/will these have? How do you think climate change will be managed in the future?

** Transition to Water Resources Policy **

- neutrally into policy, quote or paraphrase the language
- How does this policy affect components in your system? If not yet implemented, how will it affect components?

## *Human Subject Program Approval Letter*



UNIVERSITY
of HAWAIʻI®
MĀNOA

Office of Research Compliance
Human Studies Program

October 7, 2015

TO: Christopher Lepczyk
Principal Investigator
Natural Resources & Environmental Management

FROM: Denise A. Lin-DeShetler, MPH, MA
Director

SUBJECT: CHS #23424- “Forecasting Climate Change Impacts on Watershed-Based Ecosystem Services in Hawaii: A Participatory Modeling Approach”

This letter is your record of the Human Studies Program approval of this study as exempt.

On October 07, 2015, the University of Hawai’i (UH) Human Studies Program approved this study as exempt from federal regulations pertaining to the protection of human research participants. The authority for the exemption applicable to your study is documented in the Code of Federal Regulations at 45CFR 46.101(b)(Exempt Category 2).

Exempt studies are subject to the ethical principles articulated in The Belmont Report, found at http://www.hawaii.edu/irb/html/manual/appendices/A/belmont.html.

Exempt studies do not require regular continuing review by the Human Studies Program. However, if you propose to modify your study, you must receive approval from the Human Studies Program prior to implementing any changes. You can submit your proposed changes via email at uhirb@hawaii.edu. (The subject line should read: Exempt Study Modification,) The Human Studies Program may review the exempt status at that time and request an application for approval as non-exempt research.

In order to protect the confidentiality of research participants, we encourage you to destroy private information which can be linked to the identities of individuals as soon as it is reasonable to do so. Signed consent forms, as applicable to your study, should be maintained for at least the duration of your project.

This approval does not expire. However, please notify the Human Studies Program when your study is complete. Upon notification, we will close our files pertaining to your study.

If you have any questions relating to the protection of human research participants, please contact the Human Studies Program at 956-5007 or uhirb@hawaii.edu. We wish you success in carrying out your research project.

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