F Inventory and Assessment of Resources

Table of Contents

Figures

Tables

F Inventory and Assessment of Resources

This section provides information on the nature and occurrence of water resources in the State of Hawai‘i, as mandated by the State Water Code. It also includes discussions on the human impacts to those resources and the issues, challenges, and opportunities for improving management and protection practices. A "systems area" approach to water resource management is taken to recognize the connections between ground and surface water resources. CWRM encourages the exploration and application of this approach through the information presented herein and through State actions to support sustainable management of water resources. The remaining sections are generally organized as follows:

- **Evolving Issues in Water Resource Management**: This section highlights major issues that impact water resources in Hawai‘i. CWRM considers these issues when inventorying and assessing water resources for management purposes.

- **Managing Hawai‘i's Water Resources for Sustainability:** Human beings are constantly impacting the natural hydrologic cycle. To address climate change and increased populations and water needs, CWRM's "Systems Area" hydrologic unit approach and goals and objectives for water resource inventory efforts and tracking are described. Also listed are items specifically applicable to ground water and surface water inventory and assessment.

- **The Hydrologic Cycle:** A short overview of how water moves among the ocean, the atmosphere, and the Earth is provided to set the stage for the subsequent discussion on the nature and occurrence of ground and surface water.

- **Nature and Occurrence of Ground Water:** Information on ground water occurrence and aquifer settings is followed by an explanation of the ground water hydrologic units as delineated by CWRM and how ground water availability is quantified and assessed. Finally, an inventory of hydrologic unit aquifer system areas and their sustainable yields are presented with additional supporting information incorporated by reference.

- **Nature and Occurrence of Surface Water:** Similar to the previous section on ground water, surface water occurrence and settings are described and followed by an explanation of the surface water hydrologic units delineated by CWRM. Information on the quantification of stream flow is accompanied by a summary of issues associated with quantification and assessment of resources. The section on surface water concludes with an inventory of surface water hydrologic units with information on instream flow standards as determined thus far.

F.1 Evolving Issues in Water Resource Management

F.1.1 Ground and Surface Water Interaction

> *Traditionally, management of water resources has focused on surface water or ground water as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with ground water. These interactions take many forms. In many situations, surface-water bodies gain water and solutes from ground-water systems and in others the surface-water body is a source of ground-water recharge and causes changes in ground-water quality. As a result, withdrawal of water from streams can deplete ground water or conversely, pumpage of ground water can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of ground-water quality and conversely pollution of ground water can degrade surface water. Thus, effective land and water management requires a clear understanding of the linkages between ground water and surface water as it applies to any given hydrologic setting.*
>
> *– Robert M. Hirsch, Chief Hydrologist, USGS*[1]

In the above excerpt from the 1998 United States Geological Survey (USGS) Circular 1139, author Robert M. Hirsch summarizes the difficulties faced by scientists and water managers in understanding the integrated nature of ground and surface water systems. From a government perspective, the typical administrative separation of ground and surface water management creates additional challenges for most water managers, especially as research efforts constantly reveal new aspects, venues, and extent by which ground and surface water systems are interdependent. The intent of USGS Circular 1139 is to help Federal, State and local agencies construct a scientific base for the development of policies governing the management and protection of aquifers, streams, and watersheds.

The author further asserts that, "**Effective policies and management practices must be built on a foundation that recognizes that surface water and ground water are simply two manifestations of a single integrated resource**." The document emphasizes that management of one component of the hydrologic system, such as a stream or an aquifer, tends to be only partly effective because each hydrologic component is in continuous interaction with other components. Concerns related to water supply, water quality, and degradation of aquatic environments are frequently at the forefront of water management issues, and the interaction of ground water and surface water has been, and continues to be, a significant area of focus and deliberation. Hirsch provides an example where contaminated aquifers that discharge to streams can result in long-term contamination of surface water and, conversely, streams can be

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[1] *USGS Circular 1139: Ground Water and Surface Water: A Single Resource,* <http://water.usgs.gov/ogw/gwsw.html>.

a major source of contamination to aquifers. Although this scenario may be more common throughout the Continental US, this could also occur in Hawaiʻi, where the implications and impacts of cross-contamination may be devastating to our limited water resources, population, and environment.

Although surface water typically has a hydraulic connection to ground water, according to Hirsch, the interactions are difficult to observe and measure and “commonly have been ignored in water-management considerations and policies.” The limited understanding of ground and surface water interactions makes it difficult to characterize the processes.

In Hawaiʻi, water managers, government agencies, and hydrologists struggle with ground and surface water interactions, as most dramatically demonstrated by high-profile water disputes in East Maui, in the Wailuku area on Maui (ʻĪao Aquifer System Area), and in Windward Oʻahu (Waiāhole Ditch System). Due to the volcanically-formed aquifers, island topography, and tropical climate, surface water and ground water interactions are typically unique in comparison with the larger-scale river basin watersheds and expansive sedimentary aquifer systems typical of mainland US areas. Nevertheless, the large-scale concepts, themes, issues, and investigations related to ground and surface water interaction remain pertinent to Hawaiʻi in that they provide insight for consideration and adaptation for island systems. The following examples of common water-resource issues, as adapted from Hirsch, are provided to demonstrate how understanding the interconnections between ground water and surface water are “fundamental to development of effective water-resource management and policy.”

F.1.2 Water Supply

- It has become difficult in recent years to construct or even maintain reservoirs for surface storage of water because of environmental and safety concerns and because of the difficulty in locating suitable sites. An alternative, which can reduce or eliminate the necessity for surface storage, is to use an aquifer for temporary storage of water. For example, water stored underground during times of high streamflow can be withdrawn during times of low streamflow. The characteristics and extent of the interactions of ground water and surface water affects the success of such conjunctive-use projects.

- Decisions impacting instream flow standards should account for surface water diversions and ground water interaction, if applicable. These decisions should consider ground water withdrawals and changes to recharge from changes in irrigation source and end use patterns and other land-surface applications of water. However, accounting for these ground water components can be difficult and controversial.

- In some regions, the water released from reservoirs decreases in volume, or is delayed significantly, as it moves downstream because some of the released water seeps into the streambanks. These losses of water and delays in travel time can be significant, depending on antecedent ground water and stream flow conditions as well as on other factors such as the condition of the channel and the presence of aquatic and riparian vegetation.

- Ground water pumping impacts to stream flow and coastal leakage are becoming an increasing concern in regard to setting sustainable yields. Although the advantage of using aquifers for storage is clear when utilizing ground water for domestic public trust purposes, pumpage may change the shape and size of such storage, possibly changing the locations and outflows from the aquifer to streams and coastal leakage. These changes, in turn, are raising concerns regarding the protection of traditional and customary rights, even when the sustainable yield of the aquifer itself is protected. To address these concerns, studies are needed to identify and quantify the impacts of reducing aquifer discharge and to clarify the impacts on ecosystems and related traditional and customary rights. In turn, these impacts should be considered when setting sustainable yields for aquifer system areas. These will most likely be localized and site specific, even within individual hydrologic units. (i.e. aquifer system areas). This issue is discussed more fully in **Section F.2.1**.

F.1.3 Water Quality

Hawaii Department of Health is responsible for managing and regulating contamination and pollution of both surface and ground water. Their roles and responsibilities are further described in **Appendix M**.

- Much of the ground water contamination in the United States is in shallow aquifers that are directly connected to surface water. In some settings where this is the case, ground water can be a major and potentially long-term contributor to contamination of surface water. Determining the contributions of ground water to contamination of streams and lakes is a critical step in developing effective water management practices.

- A focus on watershed planning and management is increasing among government agencies responsible for managing water quality as well as broader aspects of the environment. The watershed approach recognizes the interactions between ground and surface water. Integrating ground water into this “systems” approach is essential but challenging because of limitations in knowledge of the interactions of ground water and surface water. These difficulties are further complicated because the boundaries between surface water watersheds and ground water aquifers may not coincide.

- To meet water quality standards and criteria, State and local agencies need to quantify the contaminants entering surface waters (wasteload) so they can issue permits and control discharges of waste. Typically, ground water inputs are not included in estimates of wasteload; yet, in some cases, water quality standards and criteria cannot be met without reducing contaminant loads from ground water discharges to streams. Even under natural conditions, ground water inputs may elevate the levels of some contaminants above water quality standards.

- It is generally assumed that Hawaiʻi's ground water is safe for consumption without treatment. However, there has been increasing concern about the quality of ground water from wells that may be impacted by contaminated surface water and increasing interest in identifying when filtration or treatment of ground water is needed.

- Wetlands, marshes, and wooded areas along streams (riparian zones) are protected in some areas to help maintain wildlife habitat and the quality of nearby surface water. Greater knowledge of the water-quality functions of riparian zones and of the pathways of exchange between shallow ground water and surface water bodies is necessary to properly evaluate the effects of riparian zones on water quality.

- More recent concerns have been raised concerning the impacts of ground water discharge to the water quality of anchialine ponds and submarine coastal leakage and its effects on nearshore ecology and traditional and customary rights.

F.1.4 Characteristics of Aquatic Environments

- Human activities that alter the acidity, nutrients, temperature, chlorides, and dissolved oxygen of either or both ground and surface water may have a significant effect on aquatic environments, particularly where ground and surface water mix, or where there are changes in the natural interaction of ground and surface water.

- The flow between surface water and ground water creates a dynamic habitat for aquatic fauna near the interface. These organisms are part of a food chain that sustains a unique ecological community. Studies indicate that these organisms may provide important indications of water quality changes.

- Many wetlands are dependent on a relatively stable influx of ground water throughout changing seasonal and annual weather patterns. Wetlands can be highly sensitive to the effects of ground water development and to land use changes that modify the ground water flow regime of a wetland area. Understanding the interaction between wetlands and ground water flow is essential to assessing how wetlands impact water quality, ground water flow, and stream flow in large areas.

- The success of new wetlands constructed to replicate those that have been destroyed depends on the extent to which the replacement wetland is hydrologically similar to the destroyed wetland. For example, the replacement of a wetland that is dependent on ground water for its water and chemical input needs to be located in a similar ground water discharge area if the new wetland is to replicate the original. Although a replacement wetland may have a water depth similar to the original, the communities that populate the replacement wetland may be completely different from communities that were present in the original wetland because of differences in hydrogeologic setting.

F.2 Managing Hawai‘i’s Water Resources for Sustainability

The movement of water between the atmosphere, the land, and the ocean is described by the hydrologic cycle. In Hawai‘i, solar energy and other factors cause the evaporation of water from the ocean. Clouds form and render their moisture over the islands. This rainfall supports stream flow and replenishes ground water, while a portion returns to the atmosphere.

Human settlement has changed the land-related components of the hydrologic cycle. For example, early Hawaiians diverted the natural flow patterns of streams through ‘auwai (a ditch or canal) to provide water for agriculture, but much of the water was eventually returned to downstream segments of the stream. Later, as the sugar industry became established in Hawai‘i, large-scale stream diversions and wells were constructed and exported water to out-of-basin areas to support the plantations and the needs of the growing population. Most recently, the decline of plantation agriculture and increasing urbanization have significantly altered drainage and ground water recharge patterns. The cumulative effects of land use changes and other human activities can shift the natural balance of the hydrologic cycle. Such changes can have profound social, environmental, and economic impacts within our island communities.

F.2.1 Ground Water Dependent Ecosystems and Sustainable Yield

Ground water supplies about 90% of the drinking water in Hawai‘i and demands for this water resource are expected to grow as population increases. An issue that is of growing concern is the impact of ground water development on near shore ecosystems dependent on ground water to meet some or all of their water requirements. Known as ground water dependent ecosystems (GDEs), these biological communities should be assessed in greater detail with respect to their relationship with ground water discharge. In Hawaii, GDEs support a variety of valuable ecosystem services, such as flood control, water supply, water purification, recreational opportunities, biodiversity, and traditional and customary rights. However, the current approach for managing ground water in Hawaii does not explicitly account for the ground water discharge needs of GDEs.

The current management approach involves the establishment of sustainable yields for delineated aquifer system areas. For most aquifers, CWRM uses a Robust Analytical Model (RAM) to derive sustainable yield estimates. RAM is a simple tank model based on fundamentally accepted hydraulic principles that can be applied quickly and easily to any aquifer for which estimates of recharge, original head, and equilibrium head are available with the purpose of protecting optimally placed wells and the aquifer itself. While RAM limits ground water development to roughly half the recharge for most basal aquifers - allowing the other half to continue to discharge at the coast - no analysis of the actual needs of GDEs is conducted. In addition, the actual amount of discharge at any given point along the coast is influenced by the location of wells, the distribution of pumpage, and localized coastal discharge points such as springs. There are a number of other assumptions and limitations associated with RAM. RAM was developed for unconfined basal aquifers and assumes a sharp interface between freshwater and saltwater, homogenous and isotropic aquifer conditions, and uniform, laminar ground water flow. RAM also assumes optimal well spacing and an even pumpage distribution, which is not the case for most aquifers. Please refer to **Section F.4.3.3** for a more detailed discussion of RAM.

Our precautionary approach to management warrants a review of other management tools. A review of global policy initiatives for the protection and management of GDEs undertaken by Rohde et al[2] in 2017 reveals that specific reference to ecosystems dependent on ground water has only been incorporated into a handful of legislation in the United States, the European Union, South Africa, and Australia. Of these, Australia was found to have the most comprehensive framework to manage and protect GDEs. Following is a summary of Australia's approach, as presented by Rohde, et al.

Australia has embraced an adaptive management approach to protecting GDEs as required under its National Water Initiative of 2004[3]. The adaptive management strategy utilizes ongoing monitoring and targeted research to determine ecological water requirements and thresholds of GDEs and uses best available information to inform management decisions. Due to the diversity of GDEs, thresholds must be ***locally*** [emphasis added] determined. Choosing appropriate indicators and developing monitoring protocols are a key part of implementation. Due to the large degree of uncertainty and knowledge gaps at the onset, Australia has taken a precautionary approach by incorporating risk management to help to minimize adverse consequences to vulnerable GDEs of high ecological value in the interim.

California also utilizes an adaptive management approach to protect GDEs. Recognizing that "environmental uses of groundwater" is a beneficial use,[4] local ground water sustainability agencies must identify and consider impacts on all beneficial uses and users in their ground water sustainability plans by setting measurable objectives to avoid undesirable outcomes. A 2015 review of literature and existing ground water management plans by the Union of Concerned Scientists[5] indicates that effective measurable objectives achieve the following:

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[2] Rohde, M.M., Froend, R., and Howard, J., 2017 May, A Global Synthesis of Managing Groundwater Dependent Ecosystems Under Sustainable Groundwater Policy, *Ground Water*, 55(3):293-301.

[3] *Intergovernmental Agreement on a National Water Initiative*, http://www.agriculture.gov.au/SiteCollectionDocuments/water/Intergovernmental-Agreement-on-a-national-water-initiative.pdf

[4] 2014 Sustainable Groundwater Management Act (with 2015 amendments). <http://groundwater.ca.gov/docs/2014%20Sustainable%20Groundwater%20Management%20Legislation%20with%202015%20amends%201-15-2016.pdf>

[5] Union of Concerned Scientists. September 2015, *Measuring What Matters.* <http://www.ucsusa.org/sites/default/files/attach/2015/09/measuring-what-matters-california-sustainable-groundwater-report.pdf>

- define a clear baseline;
- set quantitative thresholds
- develop protective triggers that require action before reaching a threshold;
- incorporate regular measurement and monitoring;
- account for uncertainty; and
- adapt to changing conditions and new information.

Each local ground water sustainability agency must set interim milestones in five-year increments and achieve the sustainability goal for each basin within 20 years of plan implementation. Each agency's plan must also summarize the type of monitoring sites, measurements, and frequency, as well as protocols to detect changes in ground water conditions.

In Hawaii, concerns over GDE impacts due to ground water withdrawals have been raised in several water cases over the years. Most recently, this was the central issue in a petition to designate the Keauhou Aquifer System Area on Hawaii Island as a ground water management area. (Please refer to **Appendix I CWRM Regulatory Programs** for more information on water management areas and associated regulatory controls.) The National Park Service (NPS) filed the petition in 2013 to preserve and protect the underground fresh water flows that support cultural and natural resources along the Kona coast, including the Kaloko-Honokōhau National Historical Park. Through its adjudication of the case, CWRM recognized the need to refine its management approach to ground water and requested that its staff study ways to refine the estimation of sustainable yields to account for the needs of GDEs. For more up-to-date information on this issue, please visit our website at <http://dlnr.hawaii.gov/cwrm/groundwater/activities/keauhou/> (accessed June 24, 2019)

Based on the best available information, CWRM staff should propose action triggers and develop a suite of possible management actions for consideration by CWRM. It is recommended that CWRM build on the work done by NPS to establish an adaptive management approach for the Kaloko-Honokōhau National Historical Park as a priority pilot project. This approach can then be applied to other areas in the State where concerns over the impacts of ground water withdrawals on GDEs have been raised.

F.2.2 Applying the "Systems Area" Approach to Water Resource Management

The WRPP encourages effective ground and surface water management through the application of a hydrologic unit systems approach that focuses on the interaction and feedback that occurs between ground and surface water systems and management decisions. Imposed stresses impact the physical ground water system (geologic framework, hydraulic properties, and boundary conditions); with changes observed to ground water levels, discharge rates, and water-quality conditions.

F.2.3 Goals for Water Resource Inventory and Assessment

It is evident that short- and long-term climate change is shifting the natural balance of the hydrologic cycle. Measured long- and short- term declines in Hawaiʻi's rainfall and streamflow are well documented. These can also produce profound social, environmental, and economic impacts within our island communities.

To sustainably manage water resources, it is critical to apply an organized program for measuring, assessing, and communicating water-related information to decision makers and to the public. Government agencies, resource managers, private purveyors, and the general public benefit from the continued investigation and study of water resources. The best information available should be applied to explore the processes and resource interdependencies implicit in the water cycle. With increasing insight, better resource management strategies can be developed and implemented to achieve sustainability. The following CWRM goals are intended to guide and influence water resource inventory and assessment efforts in support of sustainable water planning and management activities.

- Continually study and update the inventory the water resources of the State (occurrence, location, extent, and behavior) to support resource management, policy and regulatory decisions, and planning efforts, and to protect and sustain resource viability and to provide for the maximum beneficial use of water by present and future generations.

- Promote the administrative use of management boundaries designated by CWRM to define the extent of ground water and surface water hydrologic units and ensure the consistent application of these boundaries throughout the State and across State and county jurisdictions.

- Commit to long-term, reliable, and collaborative data collection programs and use of improved methods of analyses.

- Seek the advice of other professional hydrologists in assessing, monitoring, analyzing, and reviewing the resource inventory defined in this plan.

- Apply inventory and assessment information to manage the conservation, protection, and use of the State's water resources for social, economic, and environmental needs as mandated by the State Water Code.

- Apply inventory and assessment information toward managed conjunctive use of ground water and surface water supplies and the artificial recharge of ground water systems.

- Apply best science practices, improved understanding of resources, and informed consensus of stakeholders toward addressing both challenges and opportunities.

- Establish measurable interim instream flow standards on a stream-by-stream basis whenever necessary to protect the public interest in waters of the State.
- Utilize the best available information on the potential impacts of climate change in the setting of instream flow standards and the calculation of ground water sustainable yield.
- Incorporate provisions for management and protection of ground water dependent ecosystems in the establishment of ground water sustainable yield.

F.3 The Hydrologic Cycle

The hydrologic cycle (**Figure F-1**) refers to the constant movement of water between the ocean, the atmosphere, and the Earth. A continuous cycle of water can be easily observed on small oceanic islands like Hawai‘i. Solar energy drives the hydrologic cycle by causing **evapotranspiration (ET).** Evapotranspiration is the loss of water from soils, canopy, and open water bodies through evaporation and the transfer of water from plants to the air through transpiration. Moisture in the air is carried by trade winds up mountain sides, where it cools and condenses, and finally falls to the land surface as rain or fog drip. Plants immediately absorb and use some of the rain and fog drip, but the remaining volume of water infiltrates through the ground surface, runs off to the ocean or streams, evaporates into the atmosphere, or ends up recharging the ground water aquifers.

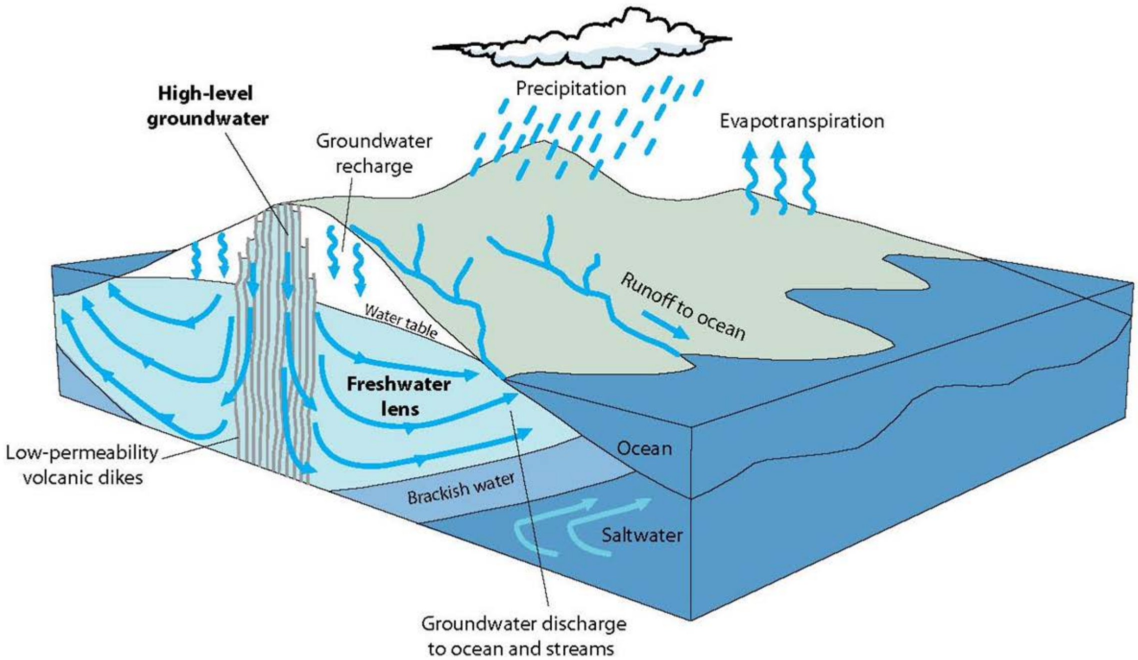
The four main elements of the hydrologic cycle are: 1) precipitation; 2) infiltration and recharge; 3) runoff; and 4) evapotranspiration. These can be summarized in the equation:

$$R = P - RO - ET$$

where “R” is natural recharge due to infiltration and subsequent deep percolation, “P” is precipitation, “RO” is runoff, and “ET” is evapotranspiration.

Infiltration is key to sustaining ground water resources. Human activities, especially agricultural and urban activities, alter infiltration and runoff patterns, affecting the components of the hydrologic cycle. As rainwater wets the land surface, shallow infiltration saturates the uppermost soil layer and replaces soil moisture used by plants. Thereafter, excess water percolates slowly downward to recharge ground water bodies and support stream flow in perennial sections. One factor that affects the rate of infiltration is the permeability of the ground surface. Permeability describes the ease with which water travels through a material. Ground surfaces with high permeability allow rapid infiltration of rainfall. Conversely, low-permeability surfaces like concrete and asphalt inhibit infiltration, causing water to pond or flow across the surface as runoff. Therefore, different land uses can encourage or inhibit infiltration.

Figure F-1 Hydrology of Ocean Islands



Source: USGS Pacific Islands Water Science Center.
<http://hi.water.usgs.gov/studies/GWRP/islhydro.html> (accessed June 24, 2019)

F.4 Nature and Occurrence of Ground Water

Much research and study has been devoted to the nature and occurrence of ground water in Hawai‘i. Over the past century, various private, federal, State, county, and university ground water investigations have helped scientists understand the unique and complex nature of Hawai‘i’s ground water resources. An internet search for ground water hydrology of the Hawaiian Islands will return over 314,000 articles related to this subject.

To help communicate Hawai‘i ground water concepts to the public, the USGS and CWRM cooperatively developed and published in 2000 the reference brochure entitled *Ground Water in Hawai‘i*. The document contains descriptions of Hawai‘i’s hydrologic settings and hydrogeology. The Honolulu Board of Water Supply (BWS), in consultation with CWRM, has also developed descriptions of Hawai‘i’s ground water settings for inclusion in the BWS’s *Ko‘olau Loa Watershed Management Plan* and *Waianae Watershed Management Plan*. The information in the following sections adapts CWRM’s collaborative work with the USGS and BWS to provide a basic overview of the nature and occurrence of ground water in the State.

F.4.1 Ground Water Occurrence

The State Water Code defines ground water as "any water found beneath the surface of the earth, whether in perched supply, dike-confined, flowing, or percolating in underground channels or streams, under artesian pressure or not, or otherwise." Water beneath the ground surface occurs in two principle zones: the unsaturated zone and the saturated zone. In the unsaturated zone, the pore spaces in soils and rocks contain both air and water, whereas in the saturated zone, the pore spaces are entirely filled with water. The saturated zone of ground water is what is known as an aquifer.

Ground water occurs within portions of geologic formations that are favorable for receiving, storing, and transporting water. Subsurface formations that are saturated are called aquifers. The USGS defines an aquifer as follows:

> "Aquifer - *a geologic formation(s) that is water bearing. A geological formation or structure that stores and/or transmits water, such as to wells and springs. Use of the term is usually restricted to those water-bearing formations capable of yielding water in sufficient quantity to constitute a usable supply for people's uses".*
>
> - USGS Dictionary of Water Terms <https://www.usgs.gov/special-topic/water-science-school/science/dictionary-water-terms?qt-science_center_objects=0#qt-science_center_objects> (accessed June 24, 2019)

Lava erupted during the principal growth stage, or shield building stage, of a volcano tends to form the most extensive and productive aquifers throughout the Hawaiian Islands. Lava from the shield building stage consists of basalts that characteristically form thin flows ranging in thickness from a few feet to a few tens of feet. The shield stage is the most voluminous phase of eruptive activity during which 95 to 98 percent of the volcano is formed. Lava flows erupt from the central caldera and rift zones. Intrusive dikes fed by rising magma extend down the rift zones and may erupt if they reach the surface. Some volcanoes have a postshield-stage during which younger lava flows form over the shield-stage basalts. The postshield-stage lava flows are marked by a change in lava chemistry and character that commonly leads to the formation of massive lava flows that can be many tens of feet thick. After a period of volcanic inactivity, lava might issue from isolated vents on the volcano during a final rejuvenated stage.

Permeability refers to the ease with which fluids can move through rock. The permeability of volcanic rocks is variable and depends of the mode of emplacement, amount of weathering, and thickness of the rocks. The three main groups of volcanic rocks (lava flows, intrusive dikes, and pyroclastic deposits) are formed by different modes of emplacement. Weathering reduces the permeability of all types of volcanic rocks. The thickness of a lava flow can depend of the lava chemistry and the topography over which it cooled. Thicker flows generally are less permeable and form from lava accumulating on flat topography or in depressions.

Lava flows are mainly composed of two lava morphologies: pāhoehoe and ʻaʻā. Pāhoehoe flows are thinner and form from more fluid lava. Pāhoehoe flows have smooth, undulating surfaces, and commonly exhibit ropy textures. ʻAʻā flows have coarse surfaces of rubble, or clinker, and thick interior sections composed of massive rock. A typical geologic profile will show a sequence of both ʻaʻā and pāhoehoe flows. The interconnected void spaces in a sequence of pāhoehoe flows may lead to high permeability. The layers of clinker at the top and bottom of ʻaʻā flows also impart high permeability (similar to that of coarse-grained gravel) to volcanic-rock aquifers. However, the lava in the core of an ʻaʻā flow typically cools as a massive body of rock with much lower permeability. The most productive and most widespread aquifers consist of thick sequences of numerous thin lava flows; however, ground water occurs in a variety of geologic settings in Hawaiʻi, as described in the sections below.

F.4.1.1 Basal Water

The freshwater lenses in basal aquifers occur in dike-free volcanic rocks and in sedimentary deposits and are the most important sources of freshwater supply in Hawaiʻi. Basal waters can be either confined or unconfined. Unconfined aquifers are where the upper surface of the saturated aquifer is the water table itself. Confined aquifers are where the aquifer is overlain by low or poorly permeable formation boundaries that cause the ground water under the formation to be pressurized. Water levels in a confined aquifer will rise above the confining formation through breaches in the formation such as wells or natural flowing springs.

In some coastal areas there is a sediment sequence of low permeability commonly called "caprock." This caprock barrier tends to confine and restrict the seaward flow of freshwater and causes the thickness of the freshwater lens to be greater than it would if the caprock was absent. Depending upon the effectiveness of the caprock, the resulting lens could range from local thickening of a relatively thin lens of a hundred feet to over 1800 feet. Therefore, the amount of water stored in a basal lens bounded by caprock is significant. Water is withdrawn from the basal aquifer for various uses; basal aquifers provide the primary source for municipal water in Hawaiʻi.

The thickness of the freshwater basal lens can be estimated using the Ghyben-Herzberg formula, which assumes a hypothetical sharp interface between freshwater and seawater, and states that every foot of freshwater above mean sea level indicates 40 feet of freshwater below mean sea level. For example, if freshwater is known to occur at an elevation 20 feet above mean sea level, it can be reasonably estimated that the hypothetical sharp interface would be approximately 800 feet below sea level.

The Ghyben-Herzberg formula provides a reasonable estimate of the freshwater basal lens thickness; however, in actuality, the interface between freshwater and seawater occurs as a brackish transition zone, rather than a sharp interface, with salinity gradually increasing with depth. Therefore, the Ghyben-Herzberg formula is used to estimate the midpoint of the transition zone, which is 50% seawater and 50% freshwater. The thickness of transition zone depends on various chemical and physical parameters including, but not limited to geology, advection and dispersion, mechanical mixing, physical properties of the aquifer, tidal fluctuation, and atmospheric pressure variation. The movement of the brackish transition zone, both horizontally inland from the seacoast and vertically upward, presents a constant potential danger of saline contamination to the freshwater portion of the system. Surface water and ground water interactions in these areas predominantly occur near coastal areas in streams, wetlands, and achialine ponds.

F.4.1.2 Dike Water

Ground water impounded behind dikes in the mountains is often called "dike-impounded water," or "high-level water." Dikes are low permeability magmatic intrusions, usually wihin rift zones or calderas, that typically consist of nearly vertical slabs of dense, massive rock, generally a few feet thick, which can extend for considerable distances and cut across existing older lava flows. High-level water impounded in permeable lavas occurring between dikes in the interior portions of the islands is usually of excellent quality due to the elevation of dike impounded aquifers, the low permeability of dike structures, and the distance from the ocean, which prevents sea water intrusion. Tunnels and shafts have been drilled through multiple dike compartments to develop this water source. Dike water can occur in low elevation rift or caldera zones such as Windward Oahu.

Some water leakage occurs across dike boundaries, and this water flows to down-gradient dike compartments or to the basal aquifer. However, the interaction between these dike-confined and basal aquifers is not well understood and is difficult to quantify. In fact, recent discoveries of deep freshwater aquifers beneath saltwater underlying basal aquifers on the Big Island are modifying the conceptual models of ground water, at least on the Big Island. These may be related to dike water impounded geology. Also, additional discoveries of very high-level water on the Big Island may also modify the current conceptual models for ground water.

Dike-impounded water may overflow directly to a stream at the ground surface where stream erosion has breached dike compartments. Once breached to the water table, the percentage of overall contribution to total stream flow depends on the head of the stored water, how deep the stream has cut into the high-level reservoir, the permeability of the lavas between dikes, the size of the compartments as well as connections to other compartments, and the amount of recharge into the breached compartment. Surface water and ground water interactions in these aquifers are assumed to have a one to one relationship for management purposes.

F.4.1.3 Perched Water

Water in perched aquifers is also classified as high-level water. In this type of system, water is "perched" on top of layers of low permeability material such as dense volcanic rock, weathered and solidified ash, or clay-bearing sediments that may overlie basal or dike aquifers. Discharge of perched water sometimes occurs as springs where the water table breaches the land surface by erosion. Perched water supplies can be developed by tunnels or by constructing masonry chambers around spring orifices to collect flow and to prevent surface contamination. This type of water is of excellent mineral quality, and like most dike water, is free from seawater encroachment.

Perched water can also be found in alluvial deposits. Alluvial water is found in the more recent alluvial layers in valley fills and remains perched because of older compacted alluvial layers below. Sometimes small wells can be productive in this area but generally the alluvium provides small amounts of water.

Related to dike water, recent discoveries of very high-level water on the Big Island may also modify the current conceptual models for ground water if they are shown to effectively be perched water. Surface water and ground water interactions in these aquifers depend on the local conditions and physical construction of wells.

F.4.1.4 Caprock Water

Caprock units found in Hawaiian aquifer systems are generally composed of sedimentary formations and are commonly seen in oceanic islands with emergent shorelines. They show a dominant presence of reefal limestone, consisting of fringing coralline build-up and associated calcareous sediments interlayered by fine-grained alluvial sedimentation. This suggests sedimentation in shallow marine and littoral environments. Having formed in submarine conditions and with high clay content, young calcareous sedimentary units may preserve the brackish or saline caprock water as interstitial fluid or as perched water within the formation. Moreover, intertidal fluctuation and sea-level rise allows sea water intrusion into the caprock units, creating a broad transition zone of brackish water along coastal areas. Recharge from surface flows, local rainfall, return irrigation water, and leakage from unconfined or confined basal water could result into a potential resource of caprock water, but may be of limited direct use due to its saline quality. Caprock water occurs, and perhaps is fairly common, around older, emergent Hawaiian Islands, such as Oʻahu. A good example of an extensive caprock formation is the ʻEwa and Honolulu Caprock, where brackish water has been pumped and utilized. Surface water and ground water interactions in these aquifers predominantely occur near coastal areas in streams, wetlands, and achialine ponds. Sustainble yields for caprock aquifers are not counted against sustainable as is basal, dike, perched, and alluvial aquifers.

F.4.1.5 Brackish Water

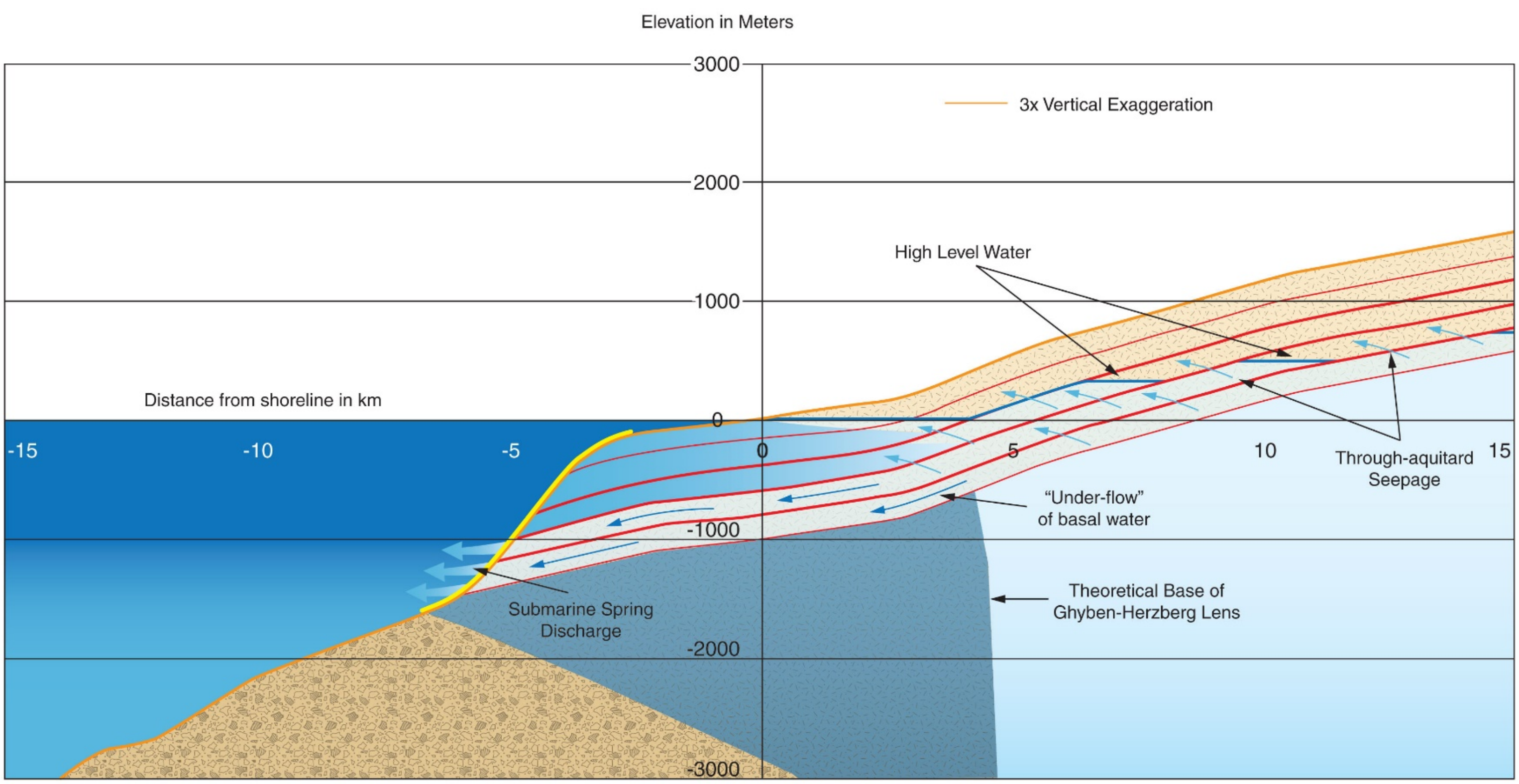
Water occurring in the caprock, in a transition zone, and in near-shore basal springs comprises a large resource that is presently unused for municipal supplies due to excessive chlorides (salt) content. Chlorides range from just above recommended drinking water guidelines to that nearly of seawater. With respect to its potential as an alternative source of water supply, brackish water desalination is generally more cost-effective and environmental-friendly than seawater desalination.

While slightly brackish water can be used for irrigation purposes, utilization of brackish water sources for municipal supplies requires the reduction of chloride concentration through blending and/or demineralization. Water exhibiting chloride concentrations greater than 250 milligrams per liter (mg/L or part per million - ppm) is generally considered unacceptable for drinking purposes. The county water departments generally limit chloride levels of water within their municipal system to less than 160 milligrams per liter (mg/L or parts per million – ppm).

F.4.1.6 Deep Confined Freshwater

On Hawaiʻi Island, there are at least four deep monitor wells that have penetrated through basal aquifers and underlying saltwater and have encountered freshwater in confined artesian aquifers. Two such wells are in each of the Hilo and Keauhou Aquifer System Areas. These discoveries have altered the traditional island conceptual model of freshwater completely floating on top of higher density saltwater. More study is necessary to better understand the extent and nature of this ground water occurrence.

Figure F-2 Deep Confined Freshwater



Source: Donald Thomas, June 21, 2014, *Revised Conceptual Model of Hawaii's Hydrology and Implications for the Keauhou Aquifer*, Public testimony received at the December 10, 2014 CWRM meeting <http://files.hawaii.gov/dlnr/cwrm/submittal/2014/sb20141210E2.pdf> (accessed June 24, 2019).

Future updates of this plan may include discussions of other geologic settings where ground water occurs.

F.4.2 Ground Water Hydrologic Units

Ground water hydrologic units have been established by CWRM to provide a consistent basis for managing ground water resources. An aquifer coding system is used to reference and describe the ground water hydrologic units delineated by CWRM. This section describes the aquifer coding system and lists all ground water hydrologic units by island. Maps illustrating the hydrologic unit boundaries are included in **Section F.4.2.3**.

F.4.2.1 Purpose of Aquifer Coding

As described earlier in **Section F.4.1**, ground water occurs in variable settings throughout the State of Hawaiʻi. The aquifer coding system described herein was established to provide a consistent method by which to reference and describe ground water resources and to assist in various water planning efforts. The coding system encourages public understanding of ground water hydrology by delineating areas that are related and exhibit similar characteristics.

The primary objective of the coding system is to provide standard aquifer delineations and framework for the coordination of data, information, and resource management practices. The aquifer coding system provides the following benefits:

- Establishment of a consistent and uniform aquifer coding system and a reference for statewide planning, surveying, and regulatory purposes.
- Facilitation of consistent collection and sharing of ground water information amongst CWRM, community organizations, private and public entities, and other agencies;
- Facilitation of public and private implementation of resource protection measures. Such measures include, but are not limited to, permitting, monitoring, best management practices, and ground water availability;
- Effective coordination of monitoring, data collection, and data interpretation.

F.4.2.2 Basis for Ground Water Hydrologic Unit Delineations

In general, each island is divided into regions that reflect broad hydrogeological similarities while maintaining hydrographic, topographic, and historical boundaries where possible. These divisions are known as Aquifer Sector Areas. Smaller sub-regions are then delineated within Aquifer Sector Areas based on hydraulic continuity and related characteristics. These sub-regions are called Aquifer System Areas, which are the basic ground water hydrologic unit. In general, these units allow for optimized spreading of island-wide pumpage on an aquifer-system-area scale.

It is important to recognize that Aquifer Sector Area and Aquifer System Area boundary lines were based largely on observable surface conditions (i.e. topography, drainage basins and streams, and surface geology) and limited subsurface geological data such as water level characteristics. In general, only limited subsurface information (i.e. well logs and well cores) is available. Hydrogeologic features and conditions at the surface may not adequately or accurately reflect subsurface conditions that directly affect ground water flow. As a result, the Aquifer Sector Area and Aquifer System Area boundary lines should be recognized as management lines and not strict hydrologic boundaries where ground water flow does not cross. Communication of ground water between Aquifer Sector Areas and between Aquifer System Areas is known to occur.

The aquifer coding system was first initiated by the State Department of Health in response to directives from the U.S. Environmental Protection Agency. Since then, boundary delineations of ground water hydrologic units were manually drawn or re-traced by the DLNR Division of Water and Land Development (DOWALD) General Flood Control Plan of Hawaii (1983), the State Department of Health (1987), and the Commission on Water Resource Management (1990).

The naming convention for ground water hydrologic units indicates regional and sub-regional divisions as follows:

Island division	= Island
Regional division	= Aquifer Sector Area
Sub-regional division	= Aquifer System Area

F.4.2.3 Aquifer Coding System

The aquifer coding system is based on a hierarchy in which the island is the largest component, followed by the Aquifer Sector Area as the regional component, and the Aquifer System Area as the sub-regional component. The island is identified by a single-digit number in conformance with the first digit of the Hawaiʻi State well numbering system, derived from the U.S. Geological Survey (1976). Each Aquifer Sector Area is identified by a two-digit number and a Hawaiian geographic name or a geographic term such as Windward. Finally, the Aquifer System Area is identified by a two-digit number. Therefore, ground water hydrologic units are assigned a unique code in the five-digit format as follows:

0	**00**	**00**
Island	Aquifer Sector Area	Aquifer System Area

The individual components of the aquifer system area code are described below.

Island **<u>0</u>**0000

The island code component identifies the major Hawaiian island by a unique number assigned by USGS and DLNR. Each island is considered by the USGS to be a distinctive hydrologic unit.

Aquifer Sector Area 0**<u>00</u>**00

The Aquifer Sector Area code component identifies regional hydrologic units within each island. These Aquifer Sector Areas represent large regions with hydrogeological similarities.

Aquifer System Area 000**<u>00</u>**

The Aquifer System Area code component identifies sub-regional hydrologic units within each Aquifer Sector Area. Aquifer System Areas represent aquifers that exhibit hydrogeological continuity.

There is a total of 114 Ground Water Hydrologic Units delineated across the islands of Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, Maui, and Hawaiʻi. **Table F-1 to Table F-6** below list all units by island and are accompanied by **Figure F-2 to Figure F-7** showing the unit boundaries.

Table F-1 Kauaʻi (2) Ground Water 13 Hydrologic Units

Līhuʻe Aquifer Sector Area (01)	
20101	Kōloa
20102	Hanamāʻulu
20103	Wailua
20104	Anahola
20105	Kīlauea
Hanalei Aquifer Sector Area (02)	
20201	Kalihiwai
20202	Hanalei
20203	Wainiha
20204	Nāpali
Waimea Aquifer Sector Area (03)	
20301	Kekaha
20302	Waimea
20303	Makaweli
20304	Hanapēpē

Table F-2 Oʻahu (3) Ground Water 27 Hydrologic Units

Honolulu Aquifer Sector Area (01)	
30101	Pālolo
30102	Nuʻuanu
30103	Kalihi
30104	Moanalua
30105	Waiʻalae-West
30106	Waiʻalae-East
Pearl Harbor Aquifer Sector Area (02)	
30201	Waimalu
30203	Waipahu-Waiawa
30204	ʻEwa-Kunia
30205	Makaiwa
30207	ʻEwa Caprock - Malakole
30208	ʻEwa Caprock - Kapolei
30209	ʻEwa Caprock - Puʻuloa
Waiʻanae Aquifer Sector Area (03)	
30301	Nānākuli
30302	Lualualei
30303	Waiʻanae
30304	Mākaha
30305	Keaʻau
North Aquifer Sector Area (04)	
30401	Mokulēʻia
30402	Waialua
30403	Kawailoa
Central Aquifer Sector Area (05)	
30501	Wahiawā
Windward Aquifer Sector Area (06)	
30601	Koʻolauloa
30602	Kahana
30603	Koʻolaupoko
30604	Waimānalo
Waiāhole Ditch Area (07)	
30701	Waiāhole Ditch

Table F-3 Molokaʻi (4) Ground Water 16 Hydrologic Units

West Aquifer Sector Area (01)	
40101	Kaluakoʻi
40102	Punakou
Central Aquifer Sector Area (01)	
40201	Hoʻolehua
40202	Pālāʻau (formerly Manawainui)
40203	Kualapuʻu
Southeast Aquifer Sector Area (01)	
40301	Kamiloloa
40302	Kawela
40303	ʻUalapuʻe
40304	Waialua
Northeast Aquifer Sector Area (01)	
40401	Kalaupapa
40402	Kahanui
40403	Waikolu
40404	Hāʻupu
40405	Pelekunu
40406	Wailau
40407	Hālawa

Table F-4 Lānaʻi (5) Ground Water 9 Hydrologic Units

Central Aquifer Sector Area (01)	
50101	Windward
50102	Leeward
Mahana Aquifer Sector Area (02)	
50201	Hauola
50202	Maunalei
50203	Paomaʻi
Kaʻā Aquifer Sector Area (03)	
50301	Honopū
50302	Kaumalapau
Kanao Aquifer Sector Area (04)	
50401	Keālia
50402	Mānele

Table F-5 Maui (6) Ground Water 25 Hydrologic Units

Wailuku Aquifer Sector Area (01)	
60101	Waikapū
60102	ʻĪao
60103	Waiheʻe
60104	Kahakuloa
Lahaina Aquifer Sector Area (02)	
60201	Honokōhau
60202	Honolua
60203	Honokōwai
60204	Launiupoko
60205	Olowalu
60206	Ukumehame
Central Aquifer Sector Area (03)	
60301	Kahului
60302	Pāʻia
60303	Makawao
60304	Kamaʻole
Koʻolau Aquifer Sector Area (04)	
60401	Haʻikū
60402	Honopou
60403	Waikamoi
60404	Keʻanae
Hana Aquifer Sector Area (05)	
60501	Kūhiwa
60502	Kawaipapa
60503	Waihoʻi
60504	Kīpahulu
Kahikinui Aquifer Sector Area (06)	
60601	Kaupō
60602	Nakula
60603	Lualaʻilua

Table F-6 Hawai‘i (8) 24 Ground Water Hydrologic Units

Kohala Aquifer Sector Area (01)	
80101	Hāwī
80102	Waimanu
80103	Māhukona
East Mauna Kea Aquifer Sector Area (02)	
80201	Honoka‘a
80202	Pa‘auilo
80203	Hakalau
80204	Onomea
West Mauna Kea Aquifer Sector Area (03)	
80301	Waimea
Northeast Mauna Loa Aquifer Sector Area (04)	
80401	Hilo
80402	Kea‘au
Southeast Mauna Loa Aquifer Sector Area (05)	
80501	‘Ōla‘a
80502	Kapāpala
80503	Nā‘ālehu
80504	Ka Lae
Southwest Mauna Loa Aquifer Sector Area (06)	
80601	Manuka
80602	Ka‘apuna
80603	Kealakekua
Northwest Mauna Loa Aquifer Sector Area (07)	
80701	‘Anaeho‘omalu
Kīlauea Aquifer Sector Area (08)	
80801	Pāhoa
80802	Kalapana
80803	Hilina
80804	Keaīwa
Hualālai Aquifer Sector Area (09)	
80901	Keauhou
80902	Kīholo

Figure F-3 Island of Kauaʻi Ground Water Hydrologic Units

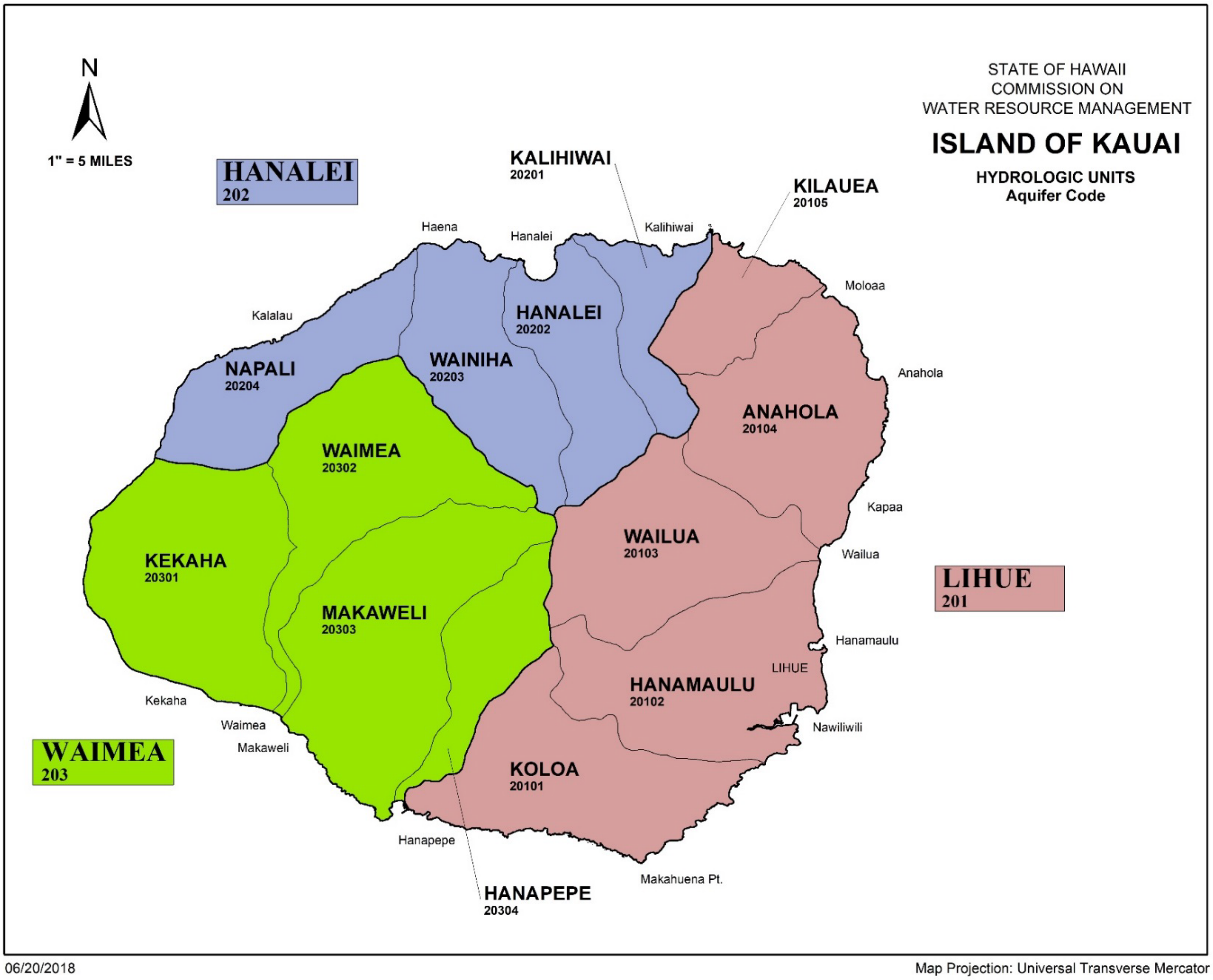


Figure F-4 Island of O'ahu Ground Water Hydrologic Units

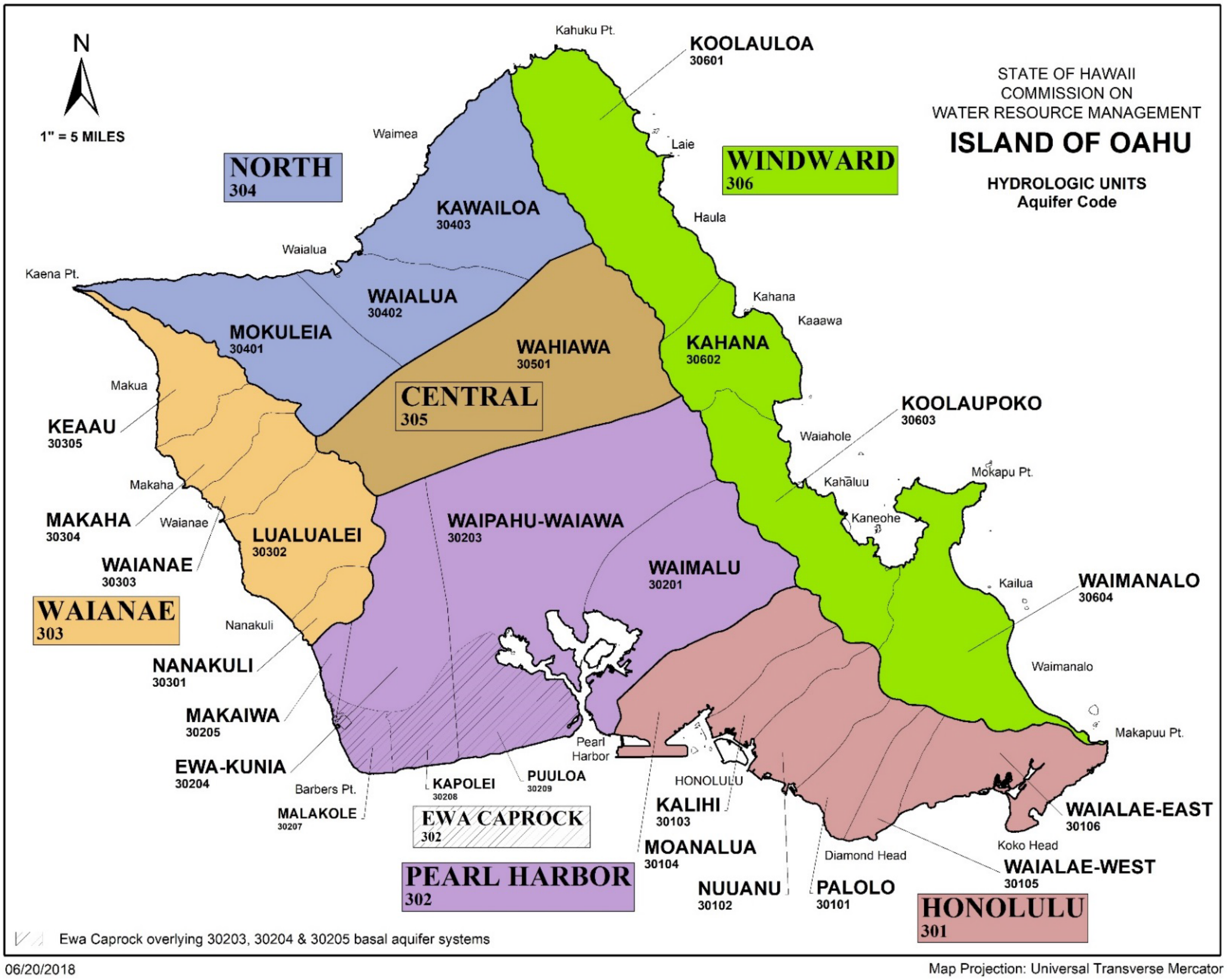
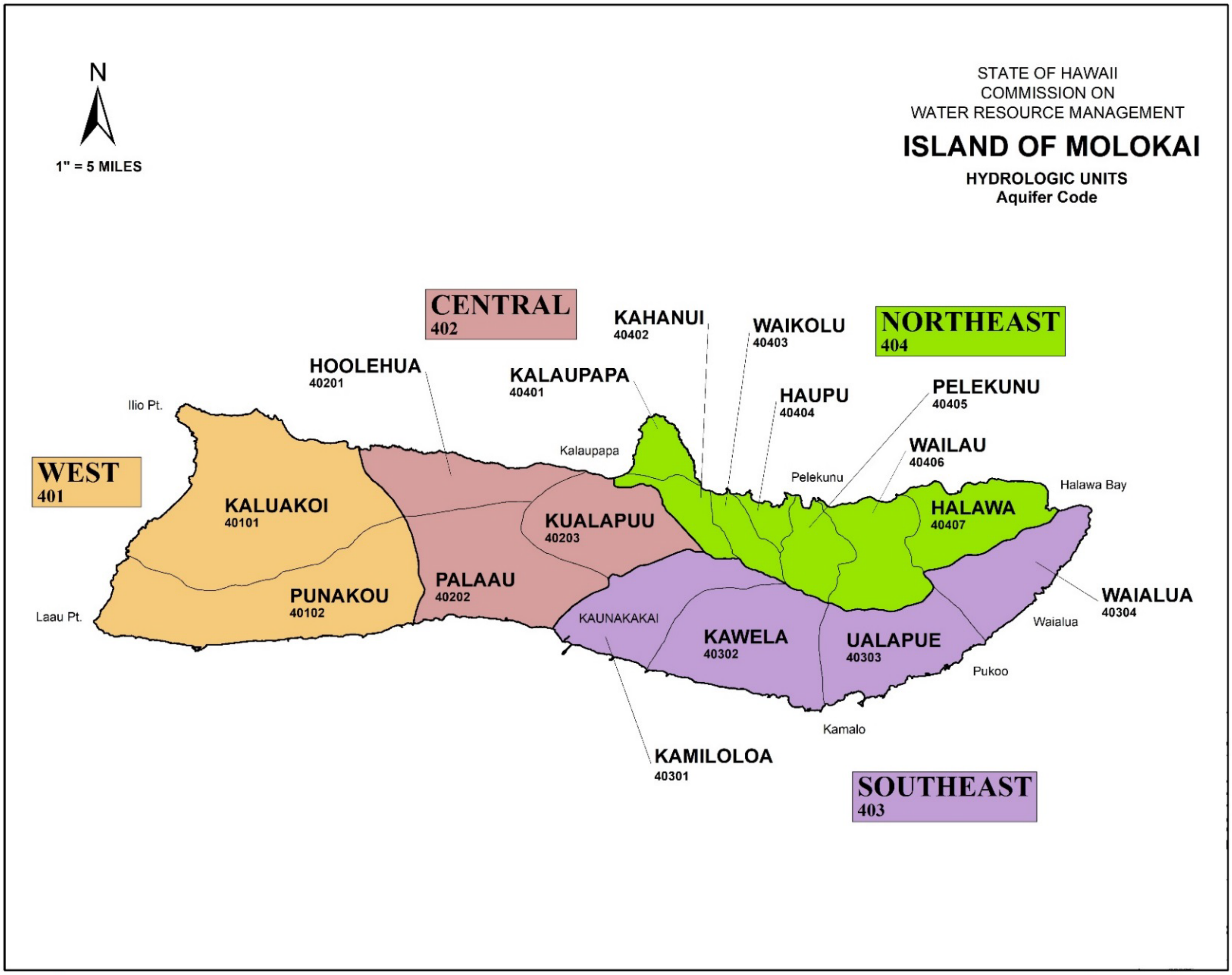


Figure F-5 Island of Moloka‘i Ground Water Hydrologic Units



06/20/2018 Map Projection: Universal Transverse Mercator

Figure F-6 Island of Lānaʻi Ground Water Hydrologic Units

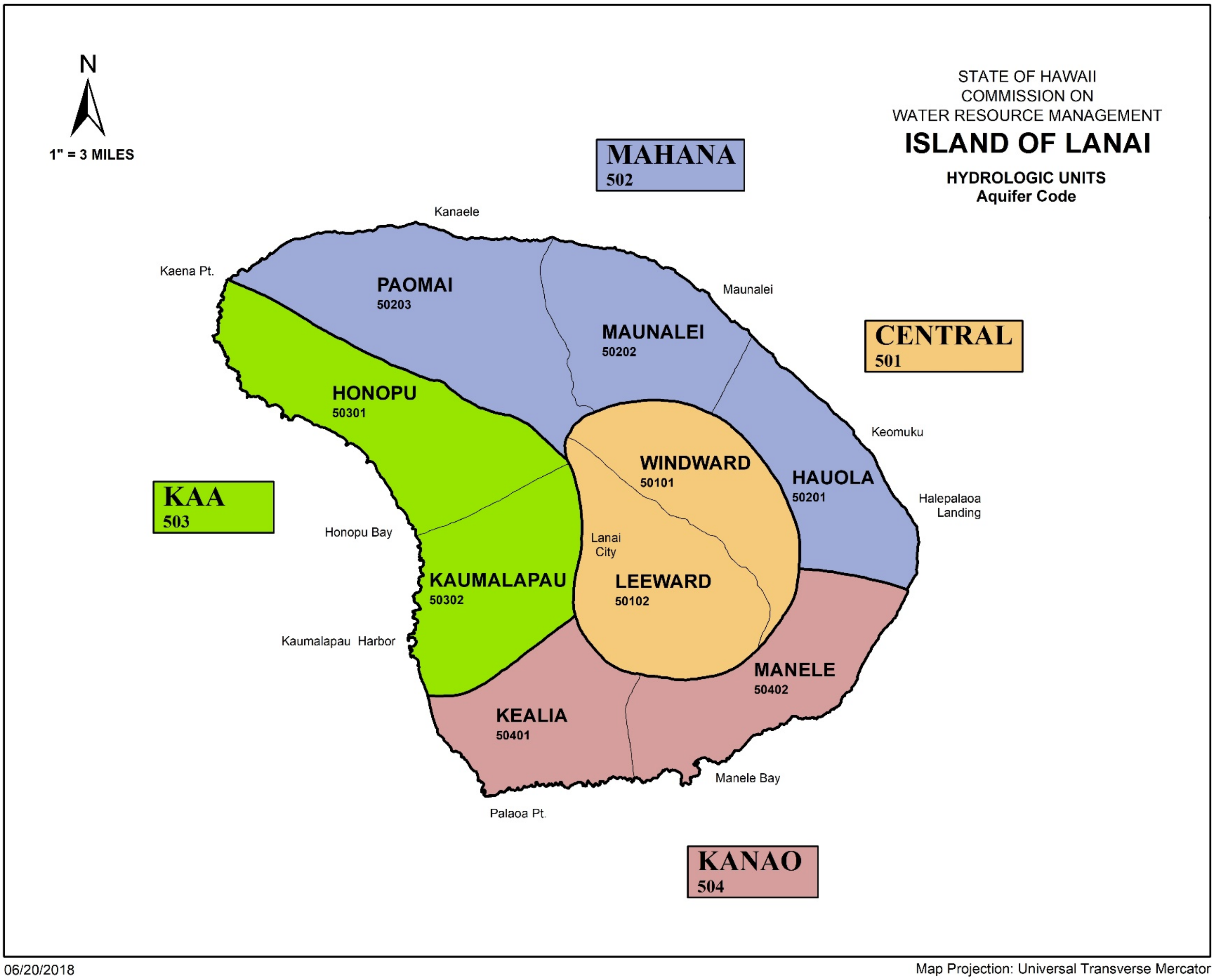


Figure F-7 Island of Maui Ground Water Hydrologic Units

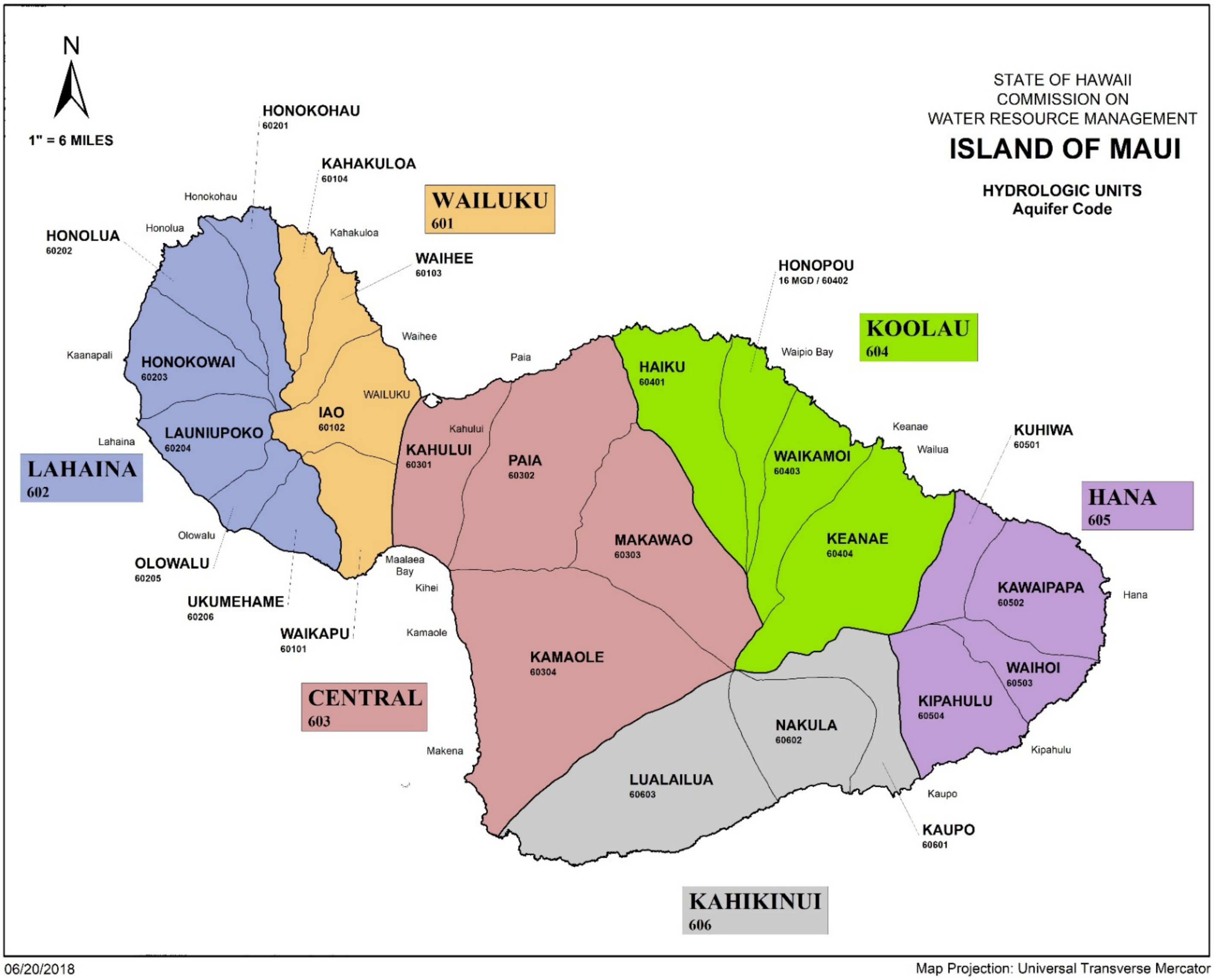
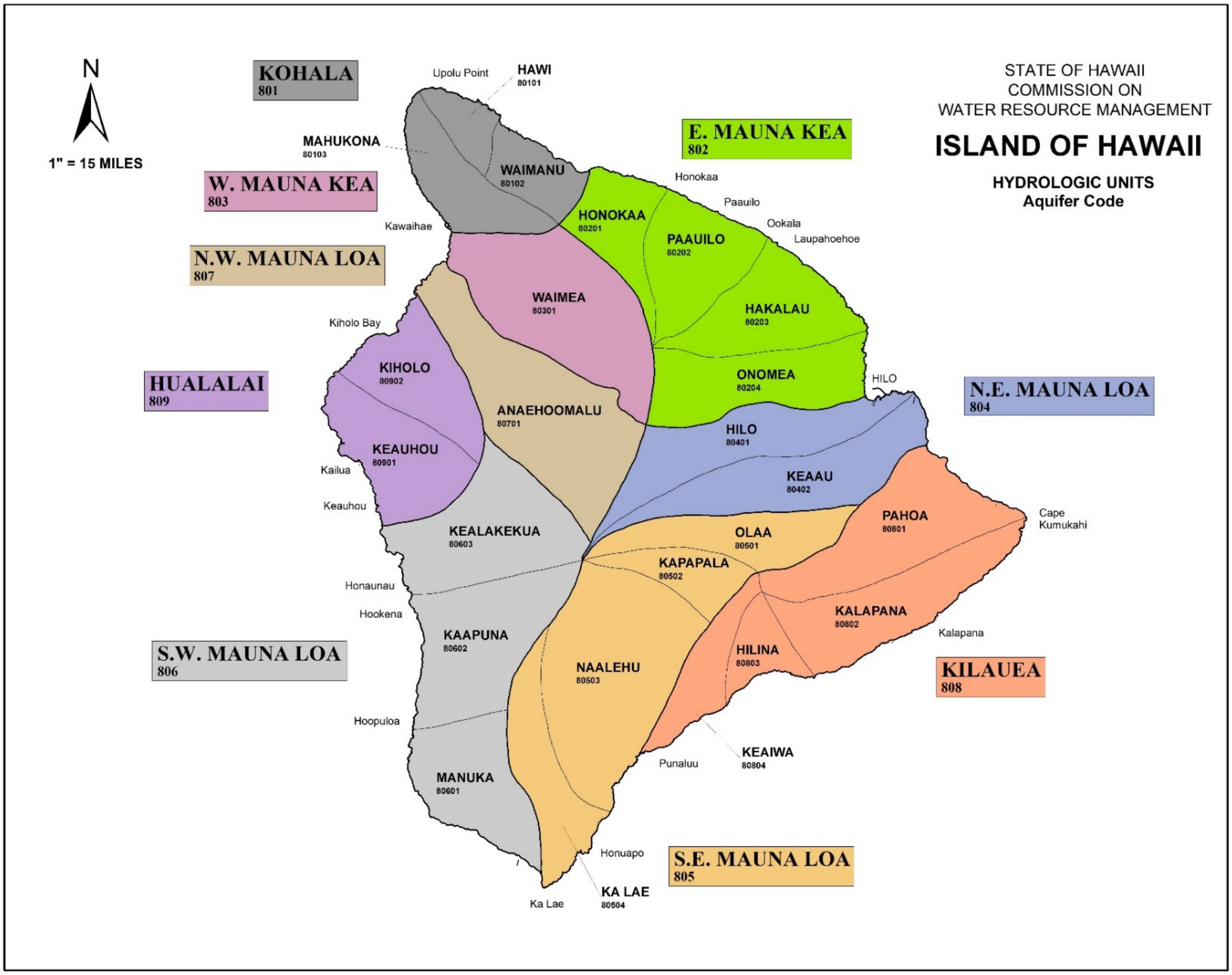


Figure F-8 Island of Hawai‘i Ground Water Hydrologic Units



06/20/2018

Map Projection: Universal Transverse Mercator

F.4.3 Determining the Availability of Ground Water Resources: Assessing Recharge, Ground Water/Surface Water Interactions, and Sustainable Yields

Ground water flow patterns and chemical transport processes within that flow can be difficult to understand and predict because they occur below the ground surface. Therefore, scientists must often infer and interpolate the status and characteristics of ground water resources from limited data and modeling tools. Use of these tools requires the establishment of certain assumptions and inputs, which inherently possess varying degrees of uncertainty. The following sections provide an overview of the primary issues related to the quantification of recharge, ground and surface water interaction, and sustainable yield. These issues contribute to uncertainties in the estimation of available ground water resources.

F.4.3.1 Assessing Ground Water Recharge

Ground water recharge is the replenishment of fresh ground water and depends on many natural and human-related factors. Recharge can change over time and in response to changes and events in climatological trends and land use. Ultimately, the goal of water-budget and recharge analysis is to quantify how much and where freshwater eventually reaches and becomes part of a saturated ground water aquifer.

Estimating Recharge

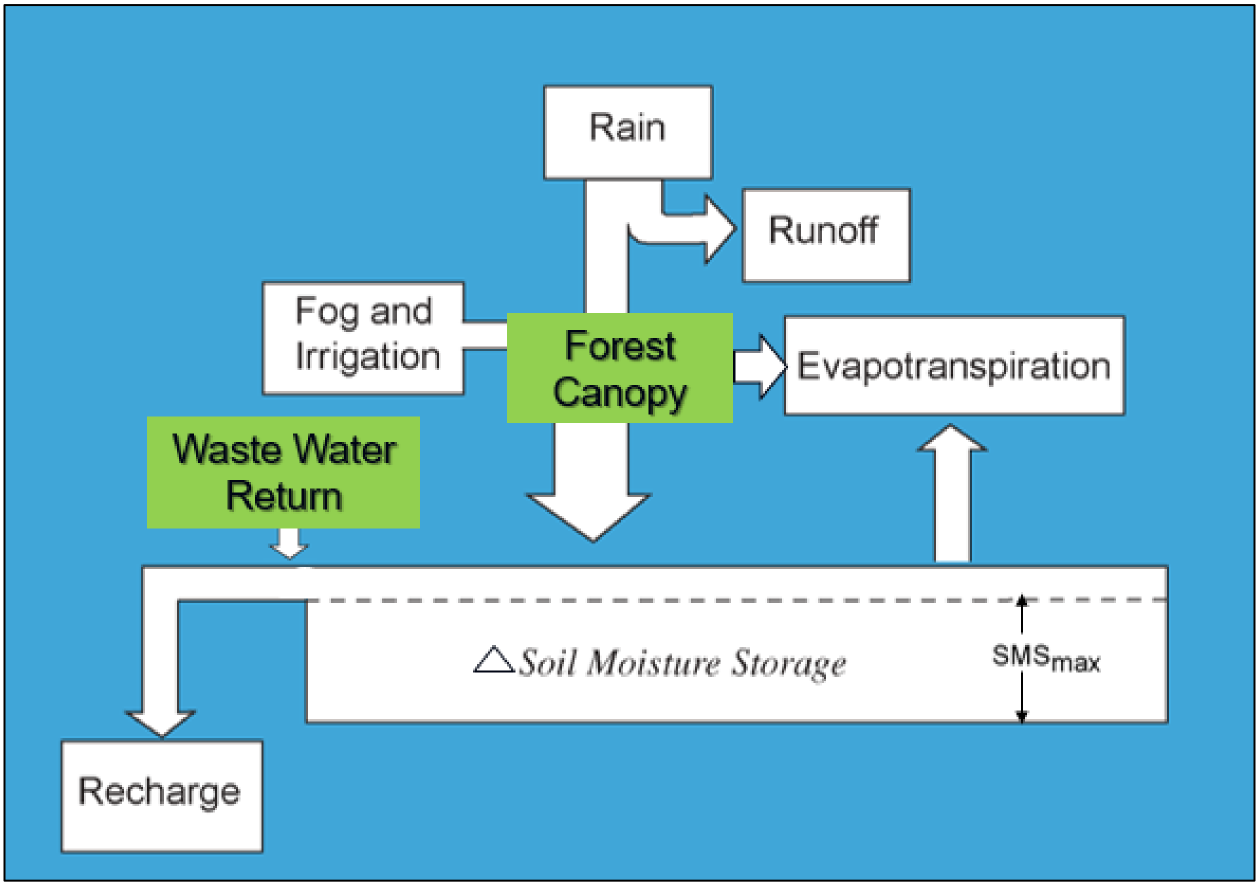
The ground water recharge equation (or ‘soil-moisture water-budget’ or ‘mass-balance’ equation) considered in this plan to estimate ground water recharge over a specified area is:

$$R = RF + FD + IR + WWR - DRO - \Delta SMS - ET - FCIE \quad \text{(equation 1)}$$

where:

R = Recharge
RF = Rainfall
FD = Fog drip
IR = Irrigation return
WWR = Waste-water return (e.g. cesspools, injection well, etc.)
DRO = Direct surface runoff
ΔSMS = Change in soil-moisture storage
ET = Evapotranspiration
FCIE = Forest canopy interception-evaporation

Figure F-9 Factors Contributing to Ground Water Recharge



Various methods have been derived using the above equation in varying levels of complexity and analysis to estimate ground water recharge. Each of the components within this equation have their own 'best estimate' quantification issues. Some of these major issues regarding the application of this equation are:

- Spatial Data Coverage
- Time Steps
- Direct Runoff Estimation; and
- Soil-Moisture & Forest Canopy Storage/ Evapotranspiration Interaction

These are discussed in more detail in the subsections below.

Spatial Data Coverage. The number and location of rainfall, fog-drip, evaporation, streamflow, irrigation return flow, soils, and land use cover data collection and analysis affect the estimation of recharge. There are three entities that maintain major climatological networks: the USGS; the U.S. Department of Commerce, National Oceanic & Atmospheric Administration (NOAA), National Weather Service (NWS); and the University of Hawai'i - State Climate Office (SCO). The SCO is currently updating the statewide rainfall station index.

Many investigations relied on the DLNR's *Rainfall Atlas*, R76, 1986, which has been used as the standard long-term baseline monthly rainfall average and median throughout the state. This has been updated with CWRM's *The Rainfall Atlas of Hawai'i 2011*, for the 30-year base period of 1978-2007. Likewise, the DLNR *Pan Evaporation: State of Hawai'i 1894-1983*, R74, 1986 provided the best long-term statewide annual estimate of pan evaporation. This has also been updated with CWRM's *Evapotranspiration of Hawai'i 2014*, for the approximate 10-year base period of 2001-2011. The best spatial soil coverage is the United States Department of Agriculture (U.S. DOA) Soil Conservation Service's *Soil Survey of Islands of Kaua'i, O'ahu, Maui, Moloka'i, and Lāna'i, State of Hawai'i*, 1972-73 has been updated by U.S. DOA with the Natural Resources Conservation Service, Soil survey geographic (SSURGO) database to: U.S. Department of Agriculture, Natural Resources Conservation Service, at https://sdmdataaccess.nrcs.usda.gov/. Another source of significant historic and spatial climactic and irrigation data is the Hawai'i Agricultural Research Center (formerly the Hawai'i Sugar Planters Association and the Pineapple Research Institute of Hawai'i), which compiles data collected by sugar plantations for irrigation activities.

Spatial data coverage density varies for both rainfall and streamflow data collection and return irrigation areas such that some areas will have higher density of data compared to others. The most current land cover data is compiled through the Gap Analysis Program (GAP) run by the U.S. Geological Survey that maps, in part, the land cover of the dominant plant species. This mapping of land use cover will greatly enhance potential evapotranspiration spatial coverage data. Lastly, spatial data coverage differences can be best represented in recharge analysis through the use of Geographic Information Systems (GIS) and preferably on a basin wide scale, coincident with aquifer system area boundaries.

Time Steps. Time steps are periods over which data is available and comparable to each other. Time steps can be annual, monthly, daily, or even hourly. In ground water management, annual recharge is the most conservative approach (monthly or daily recharge data is only needed for detailed modeling analysis). Usually, annual time-step water budget averages are more conservative estimates than monthly, daily, or hourly water budget averages because 'spikes' in precipitation and evaporation intensities and effects of soil-moisture storage are attenuated and significant inputs to recharge can be lost. Another way to phrase this is that annual averages tend to overestimate actual evaporation; thus, underestimates recharge.

Annual water budgets were used in the 1990 WRPP assessment of recharge and are therefore considered reasonably conservative. However, the recharge water budget equation above works best with shorter time steps, with daily time-steps being the most realistically achievable data set. Unfortunately, it is also difficult for all data points to have daily time-steps over the same period of analysis. For example, daily readings for rainfall are readily available whereas pan evaporation daily data is much more limited.

Precipitation and evaporation intensities as well as soil-moisture storage vary significantly between and during the wet and dry seasons and have a significant effect on seasonal recharge rates. For numerical ground water modeling, monthly and daily time-steps provide a better way to look at transitory behavior of an aquifer and should provide a better calibration opportunity than annual time-steps. Further, if sufficient data is available, daily time-steps is preferable to monthly time steps.

Total Direct Runoff Estimation. Total direct runoff for an entire drainage basin is difficult to measure. Estimates of total direct runoff do not account for the amount of overland flow to the ocean (which does not contribute to stream flow). Soil properties and land use also change and affect this component. If adequate rainfall and streamflow data is available, direct runoff-to-rainfall ratios can be computed on a basin-wide scale. There is also a recent issue whether baseflow from streams should be subtracted from the recharge budget; however, the baseflow is considered comparable to coastal leakage, which is a discharge of ground water after recharge has taken place and is not subtracted from recharge. Also, baseflow is often not uniform throughout an entire stream reach where some are gaining while others are losing (returning to the ground water) in the same stream.

Soil-Moisture & Forest Canopy Storage/Evapotranspiration Interaction. Another critical consideration is when to subtract ET in the water budget. Past recharge studies using the above recharge equation, which includes soil-moisture storage considerations, have used the following two methods:

1. ET is subtracted before soil-moisture storage capacity considerations. Any water left over then goes to soil storage and any water in excess of soil storage then goes to recharge.

2. ET is subtracted only after soil-moisture storage capacity considerations and any recharge has occurred. In other words, ET potential is limited by soil-moisture storage capacities.

Method 1 is considered to be more realistic and conservative than method 2, especially for daily recharge calculations. Method 2 has been used for monthly recharge estimates when daily calculations are not possible, or Method 1 seemed to unreasonably underestimate monthly recharge. The best GIS based soil datasets are available from the U.S. Department of Agriculture's Natural Resources Conservation Service, Soil Survey Geographic Database.

Also, the lastest ET studies have added the forest canopy capture in heavily forested areas as another storage reservoir where additional evaporation can occur prior to reaching the soil reservoir. This provides an additional conservative element to the more recent recharge estimations from the USGS.

Simplified Ground Water Recharge Calculation: The 1990 WRPP

The June 1990 WRPP used a simplified version of the recharge calculation to determine recharge and is the statewide standard under that portion of the HWP. It can be generally represented as follows:

$$R = RF - DRO - ET \quad \text{(equation 2)}$$

where:

R = Recharge
RF = Rainfall
DRO = Direct runoff (surface water flows)
ET = Evapotranspiration

all values are in average annual values (inches/year)

Fog drip, irrigation, and changes in soil-moisture storage, were generally not considered. In some well-studied areas, such as the Pearl Harbor area on Oʻahu, irrigation return contributions were considered in calculating net draft or pumping rate, which is the actual pumping rate minus the rate of irrigation return flow. In general, though, the 1990 WRPP plainly states that no adjustments to the statewide water budgets were made to account for return irrigation and sought to reflect pre-agricultural and pre-urbanization conditions.

Estimates for rainfall, direct runoff, and evapotranspiration were based on simple but reasonable methods for estimating these recharge parameters at the time. Weighted annual averages for rainfall, direct runoff and evapotranspiration in inches per year (in/yr) over aquifer system areas, based on DLNR rainfall maps,[6] were used. Direct runoff calculations were based on empirical correlations between annual average rainfall and runoff based on the following empirical equation:

[6] Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall Atlas of Hawaii, Report R76, Deptartment of Land and Natural Resources, Division of Water and Land Development, State of Hawaii, 267 p.

$$DRO = aRF^n$$

where:

DRO = Direct runoff (surface water flows)
RF = Rainfall
a = empirical constant
n = empirical constant

The 1990 WRPP states these are not very good estimators for direct runoff compared to actual streamflow data but are reasonable estimators at the system area scale where actual data is lacking and provide a simple consistent method for statewide application. Lastly, pan evaporation maps from DLNR pan evaporation maps[7] were not used directly to estimate evapotranspiration. Instead, where rainfall exceeded 55 in/yr, evapotranspiration was assigned as 40 in/yr, while in areas where rainfall was less than 55 in/yr, evapotranspiration was assigned to be 73% of rainfall.

The differences imparted by seasonal variations and the order in which to subtract evapotranspiration from its relationship with soil-moisture storage were not addressed in the 1990 WRPP. Other soil characteristics available in terms of direct runoff/rainfall ratios available were not considered in detail either.

Though the 1990 WRPP did not consider all of the generally accepted recharge considerations (it did not recognize soil-moisture storage for example), it was a reasonably conservative first cut that could be quickly applied statewide to estimate recharge, especially in areas with little or no data. This was based on the fact that using annual averages overestimated the effect of annual evaporationtranspiration.

Ground Water Recharge Studies in Hawaiʻi since the 1990 WRPP

Since the publication of the June 1990 WRPP, there have been many ground water recharge related studies published for various locations within the state that use the more generalized recharge calculation rather than the 1990 WRPP simplified version. There have also been unpublished private reports that are purported to use the more generalized ground water recharge calculation recognized as the minimal standard by this update of the WRPP.

Further investigation is needed to refine estimates of natural recharge rates. At this time, there are significant variations between reported values of natural recharge to Hawaiʻi basal aquifers. For example, the rate of natural recharge in the Iao Aquifer System Area on Maui was estimated by CWRM in 1990 at 15 MGD (based on a 17.81 square mile recharge area) and by Engott in

[7] Ekern, P.C., and Chang, J.H., 1985, Pan Evaporation: State of Hawaii, 1894-1983, Report R74, Deptartment of Land and Natural Resources, Division of Water and Land Development, State of Hawaii, 172 p.

2007 at 42 MGD[8] (based on an 18.12 square mile recharge area). These reported values were both derived by hydrologic balance analysis, but Engott's method also included fog drip, daily (instead of annual) time steps, and areal issues with valley fill, caprock, and irrigation return scenarios. According to the principle of hydrology balance, natural recharge equals precipitation minus the total of surface runoff and evapotranspiration. Therefore, more accurate estimation of the rate of natural recharge can only be achieved with an improved understanding of precipitation, including fog drip and rainwater, surface runoff, and evapotranspiration.

The most recent recharge estimates by the USGS have been for the islands of Hawaiʻi (2011), Maui (2014), and Oʻahu (2015) that are based on approximately the most recent 30 years of data using more updated form of the water budget.

Recommendations for Recharge Assessment

- Achieve more accurate estimation of the rate of natural recharge through further study of relevant hydrologic processes such as precipitation (including canopy throughfall of fog water and rainwater), surface runoff, and evapotranspiration.
- Identify the rainfall isohyets described in CWRM's *Rainfall Atlas of Hawaii*, 2011 as the minimum standard to be used in estimating ground water recharge.
- Incorporate the Evapotranspiration of Hawaii 2014 data for recharge estimates.
- Update recharge estimates statewide for complete island coverage using the general ground water recharge equation (equation 1) in its entirety.
- Review ground water recharge components with other state and federal agencies and produce GIS coverage formats for various time-steps (annual, monthly, and if feasible, daily) and update where feasible.
- Consider current and future land use (urban vs. rural vs. agriculture) impacts to water budget component processes.
- Provide recharge updates in GIS coverage format to be placed on the State GIS system.

[8] Engott, John A., and Vana, Thomas T. 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in central and west Maui, Hawaii, 1926-2004: U.S. Geological Survey Scientific Investigations Report 2007-5103, 56 p. Available online at http://pubs.usgs.gov/sir/2007/5103 .

F.4.3.2 Assessing Ground and Surface Water Interactions

In Hawaiʻi, ground water and surface water interactions may occur under the following conditions:

- High-level water seeps into stream channels to provide baseflow to streams;
- Basal water in coastal areas flows into stream channels to provide baseflow;
- Stream water between marginal dike zones and coastal areas infiltrates into ground water, as evidenced by losing stream reaches in these areas; and/or
- Basal water also discharges through basal and/or caprock springs to provide water to wetlands and ponds.

Author Gordon A. Macdonald and Agatin T. Abbott, in their 1970 book entitled *Volcanoes in the Sea, The Geology of Hawaii*, describe the close interrelationship between surface water and ground water in many of Hawaiʻi's watersheds. The discharge of excess water stored in high-level aquifers provides "a significant portion of the low water flow of many Hawaiian streams." In the following statement, the authors accurately anticipate that controversy over ground water development impacts to streamflow would soon manifest:

> *"This is certain to become a source of major conflict in future years, not only on Oahu but also on the neighbor islands, because increasing groundwater development from the headwater areas of the stream basins will surely reduce down-stream supplies for irrigation as well as water for other instream uses such as wildlife habitats and recreation and aesthetic enjoyment."*

In more recent publications, ground and surface water interactions are discussed in the context of the contested case hearing over the Waiāhole Ditch irrigation system, located in Windward Oʻahu. The system provides an example of how the development of water tunnels and stream diversions can impact the base flow (flow supplied by ground water discharge to the stream) of diverted streams as well as the recharge of the basal lens. In his 2002 book Hawaiian Natural History, Ecology, and Evolution, Alan C. Ziegler wrote of the Waiāhole Ditch System and its water resource impacts as follows:

"The entire Waiāhole Ditch System is approximately 43.5 km (27 miles) long, and since its opening in 1916 has had an average water flow of over 1.4 m^3/s (32 mg/d). Of the average flow over the life of the project, 1.2 m^3/s (27 mg/d) is estimated to have been groundwater. The average amount of surface water the system collected from streams and perched springs might thus seem to be 0.2 m^3/s (4.5 mg/d). Because the withdrawal of high-level groundwater caused less to seep out to these surface water sources, however, the reduction from predevelopment Windward surface water flow was substantially greater than this amount, conceivably at least twice as much, although no exact figures are available." [9]

Surface and ground water relationships are further complicated by human impacts and infrastructure installed to transport water between different hydrologic units. The built environment can create artificial relationships between surface and ground water resources, and these situations can be difficult to manage. In his book Water and the Law in Hawaiʻi, published in 2004, Lawrence H. Miike notes that the laws regulating surface and ground water resources have developed separately, although natural and man-made interaction exists. An example of this is the artificial relationship between Windward Oʻahu surface water and Leeward ground water created by the Waiāhole Ditch System. Miike further notes that, as a result of the 2000 Waiāhole Ditch Contested Case, where there exists an undisputed interrelationship between surface and ground water, the State's water use permitting authority extends to both ground and surface water withdrawals if there is a designation of either a ground or surface water management area (see **Appendix I CWRM Regulatory Programs** for discussion on water management areas and CWRM's regulatory programs).

From a regulatory perspective, CWRM is primarily concerned with ground and surface water interaction issues as they affect surface water resources and estimates of ground water availability. Where ground water aquifers contribute to streamflow, well withdrawals from the contributing aquifer may cause depletion in stream base flow. This is a concern, as adequate stream flow must be maintained to support instream uses. In the interest of responsible management and protection of surface water resources, CWRM assesses ground and surface water relationships during staff evaluations of well permit applications. CWRM also must consider such relationships in the evaluation of sustainable yield estimates where aquifers are hydraulically connected to streams. The following sections provide examples of different types of interactions, information on methods for assessing ground and surface water interaction, and recommendations for improving monitoring and assessment.

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[9] Estimates for natural flow in streams affected by the Waiahole Ditch System can be found in the USGS Scientific Investigations Report 2006-5285, available online at http://pubs.usgs.gov/sir/2006/5285. (Yeung, C.W., and Fontaine, R.A., 2007, Natural and diverted low-flow duration discharges for streams affected by the Waiahole Ditch System, windward Oahu, Hawaii: U.S. Geological Survey Scientific Investigations Report 2006-5285.)

Ground Water Contributions to Stream Flow

Ground water can provide a significant contribution to stream flow. Most perennial stream segments in Hawaiʻi rely on input from dike-impounded ground water or basal water contributions at the coast. **Figure F-10** provides a schematic cross section of a dike-impounded ground water system along the length of a stream.

The upper reaches of many Hawaiian streams are within or near the area where volcanic dikes (near-vertical sheets of massive, low-permeability rock that cut through older rocks) impound ground water to high levels. Streams that intersect the water table of the dike-impounded ground water body are commonly perennial because they are continually recharged by the ground water body.[10] A stream that receives ground water discharge is called a "gaining" stream. In general, the flow increases as one moves downstream within dike zones. The development of a system to capture dike-impounded ground water can affect natural springs and reduce the amount of springflow that feeds the perennial streams in the upper reaches, resulting in diminished streamflows. An example of where such streamflow impacts have occurred is in the Windward Oʻahu watersheds affected by the Waiāhole Ditch system of tunnels and ditches.[11]

At low altitudes, water levels in streams and ground water bodies may be affected by ocean tides. Thus, streams in coastal areas may either gain or lose water during the day depending on the relative effects of the ocean tide on streams and ground water levels. Streams may also flow perennially in areas where dikes are not present. For example, in southern Oʻahu, ground water discharges to streams from a thin freshwater-lens system in permeable rocks at altitudes less than a few tens of feet.[12] Another example can be seen in eastern Kauai, where ground water discharges to streams from a vertically extensive freshwater-lens system in low-permeability rocks at altitudes of several hundred feet.[13]

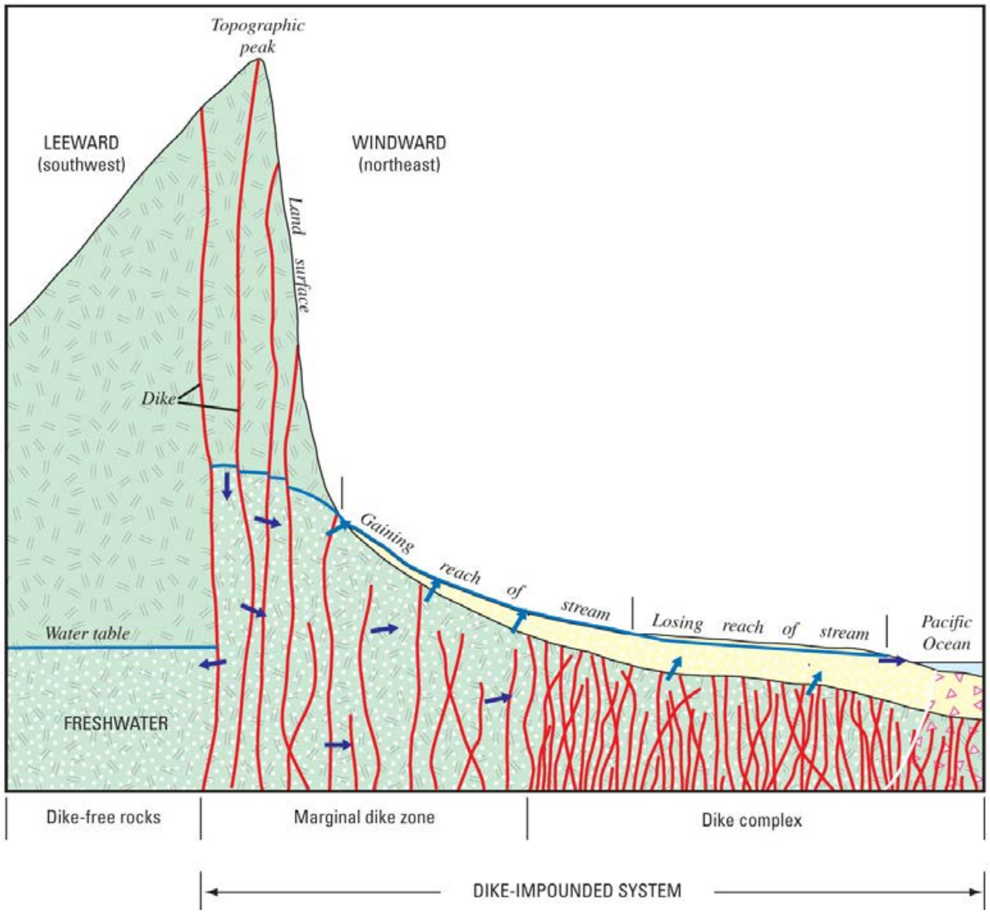
[10] Oki, D.S., 2003, Surface Water in Hawaii: U.S. Geological Survey Fact Sheet 045-03, 6 p.

[11] Hirashima, G.T., 1971, Tunnels and dikes of the Koolau Range, Oahu, Hawaii, and their effect on storage depletion and movement of ground water: U.S. Geological Survey Water-Supply Paper 1999-M, 21 p.

[12] Oki, D.S., 2003, Surface Water in Hawaii: U.S. Geological Survey Fact Sheet 045-03, 6 p.

[13] Izuka, S.K., and Gingerich, S.B., 1998, Ground water in the southern Lihue Basin, Kauai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 98-4031, 71 p.

Figure F-10 Schematic cross section showing a dike-impounded system (adapted from Oki and Brasher, 2003[14])



Stream Flow Contributions to Ground Water

Some streams run dry at lower reaches because water infiltrates into the streambed before reaching the coast. Depending on the local geology and soils, there are stream segments, or reaches, where water seeps down through the stream bed into ground water bodies. These reaches are referred to as "losing" stream reaches because stream flow is lost to ground water recharge. **Figure F-10** illustrates both gaining and losing stream reaches.

[14] Oki, Delwyn S. and Anne M.D. Brasher, 2003, Environmental Setting and the Effects of Natural and Human-Related Factors on Water Quality and Aquatic Biota, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigatons Report 03-4156, 98 p. Available online at http://pubs.usgs.gov/wri/wri034156.

Where ground water development has occurred in areas known to be subject to ground water/surface water interaction, the volume of surface water loss attributable to well pumping is usually not equal to the volume of ground water withdrawal. In rare cases, there is a direct and equal relationship between ground water withdrawals and stream flow depletion. However, this type of relationship depends on many factors, such as a well's proximity to a stream, well depth, and surrounding geology. **Figure F-11** illustrates how well pumping can affect the interaction between a ground water system and a stream. Therefore, it is important to have methods to assess the extent of ground and surface water interaction and the degree to which water development may influence stream discharge.

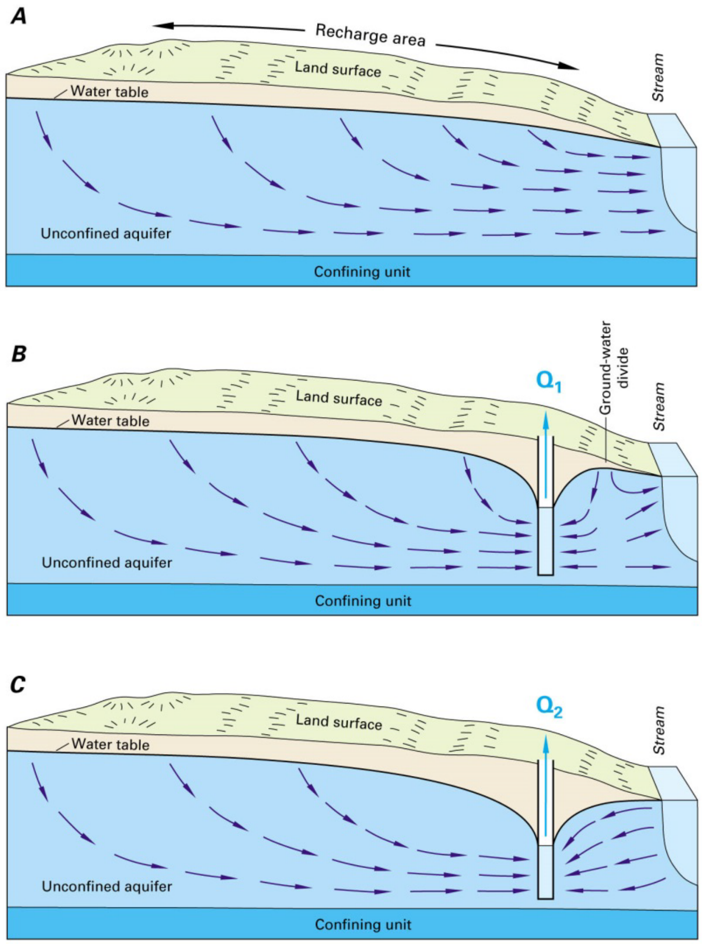
Water can move from the stream into the ground if the water table is at a lower elevation than the streamflow level. Losing stream conditions can occur if a rainfall event in the upper reaches, or a water diversion causes an increased stream discharge, bulking up the flow to a height above the water table, and subsequently forcing the stream water into the ground water system. Another example of losing stream conditions is where an active water supply well lowers the local water table and attracts the stream water towards the pumping well.

Methods to Assess Ground Water/Surface Water Interaction

Direct Measurement Within the Stream Channel. Base flow is the volume of water in a stream due solely to ground water input. It may be possible to directly measure the interaction of ground and surface water within a stream channel, although such efforts may not be feasible across the vast majority of the State because the investigations are field intensive, time consuming, and very costly. According to the USGS, "Future goals associated with the issue of ground water/surface water interaction can only be minimally addressed with the existing surface water data-collection program (continuous recording, low-flow partial record stations, and crest-stage gages). The current program is structured primarily to provide streamflow data at specific points. Streamflow data that describe the magnitude of changes in base flow (flow supplied by ground water discharge to the stream) or data from seepage runs along stream reaches are required to address the issue of ground water/surface water interaction."[15] Data sets that indicate changes in base-flow characteristics (e.g. changes in low-flow discharge) are generally not available for most areas of the State. Therefore, the wide application of these investigations may not be practicably implemented.

[15] Fontaine, R. A., 1996, Evaluation of the surface-water quantity, surface-water quality, and rainfall data-collection programs in Hawaii, 1994: U. S. Geological Survey, Water-Resources Investigations Report 95-4212, prepared in cooperation with the Commission on Water Resource Management, Dept. of Land and Natural Resources, State of Hawaii, 125 p.

Figure F-11 Effects of pumping from a hypothetical ground water system that discharges to a stream (Adapted from Alley and others, 1999[16]).



Under natural conditions (A), recharge at the water table is equal to ground-water discharge to the stream. Assume a well is installed and is pumped continuously at a rate, Q_1, as in (B). After a new state of dynamic equilibrium is achieved, inflow to the ground-water system from recharge will equal outflow to the stream plus the withdrawal from the well. In this new equilibrium, some of the ground water that would have discharged to the stream is intercepted by the well, and a ground-water divide, which is a line separating directions of flow, is established locally between the well and the stream. If the well is pumped at a higher rate, Q_2, a different equilibrium is reached, as shown in (C). Under this condition, the ground-water divide between the well and the stream is no longer present, and withdrawals from the well induce movement of water from the stream into the aquifer. Thus, pumping reverses the hydrologic condition of the stream in this reach from ground-water discharge to ground-water recharge. Note that in the hydrologic system depicted in (A) and (B), the quality of the stream water generally will have little effect on the quality of ground water. In the case of the well pumping at the higher rate in (C), however, the quality of the stream water can affect the quality of ground water between the well and the stream, as well as the quality of the water withdrawn from the well. Although a stream is used in this example, the general concepts apply to all surface-water bodies, including lakes, reservoirs, wetlands, and estuaries.

[16] Alley, W.M., T.E. Reilly, and O.L. Franke, 1999, Sustainability of Ground-Water Resources: U.S. Geological Survey Circular 1186, 79 p. Available online at http://pubs.usgs.gov/circ/circ1186/html/gw_effect.html.

A series of continuously recording stream gages on a stream can provide long-term flow data for analyses using the base-flow index (BFI) or flow duration curves. Such analyses can be used to separate out gains or losses of base flow between the gages. A pumping well can change the quantity of water naturally discharging to a stream, as well as the direction of ground water flux to a stream under different pumping rates.[17] The closer the well is to a stream, the more likely measurable affects will occur. Moreover, the greater the long-term pumping rate, the greater the likelihood that the stream will be affected. In cases where a gaged stream is influenced by the presence of a well, it may be possible to observe and directly measure streamflow losses due to pumping withdrawals. The effects of well withdrawals could be observed at one or multiple stream gages, along the stream reach adjacent to the well, depending on the distance between the well and the stream. Procedures for utilizing continuous gaging techniques have been published by the USGS and are available through the USGS website, "Techniques of Water-Resources Investigations Reports" (https://pubs.usgs.gov/twri/index090905.html). Continuous gaging is discussed in "Techniques of Water-Resources Investigations Reports" Book 3, Chapter A6, General procedure for gaging streams.[18]

A seepage run is a direct way to accurately measure gains and losses of stream discharge. The process is an intensive data collection effort where discharge measurements are made at several locations along a stream reach. The time between the first and last discharge measurement is minimized to reduce the effects of temporal variability. Ideally, a seepage run would be performed on a day where stream discharge is stable, during base-flow or low-flow conditions. A current meter is used to measure flow velocities in designated subsection areas across the stream channel. The product of the subsection areas and velocities (perpendicular to flow direction) are summed to provide the total flow for that stream section. Procedures used in measuring stream discharge across a section have been outlined, and the following formula[19] represents how stream discharge is computed at a specific section:

$$Q = \sum (a\ v)$$

Where: Q = total cross-sectional discharge
a = individual subsection area
v = mean velocity normal to the subsection

[17] Alley, W. M., Reilly, T. E., and Franke, O. L., 1999, Sustainability of ground-water resources: U. S. Geological Survey Circular 1186, 86 p.

[18] Carter, R.W. and Davidian, J., 1968, Chapter A6, General procedure for gaging streams, Book 3, Applications of Hydraulics, Techniques of Water Resources Investigations of the U.S. Geological Survey. Available online at http://pubs.usgs.gov/twri/twri3-A6/html/pdf.html.

[19] Rantz, S. E. and others, 1982, Measurement and computation of streamflow: volume 1. measurement of stage and discharge: U. S. Geological Survey Water-Supply Paper 2175, 284 p.

The accuracy of the current-meter measurements depends upon choosing good cross-sections with little or no turbulent flow. These are referred to as synoptic streamflow measurements since they were performed on the same day and under the same flow conditions.[20] In some studies, seepage runs are repeated several times over a period of time (using the same measuring sites) to provide an accurate assessment of a stream's gains and losses. Seepage run data may be supplemented by concurrent measurements of specific conductance and temperature, which can aid in the interpretation of the data.

Seepage runs have been used in various stream scenarios to study such parameters as gains to stream base-flow discharge, streamflow losses to the basal lens and coastal sediments, and the impacts of surface water diversions and ground water pumpage.[21] Ideally, prior to conducting a pump test on a well that may affect streamflow, baseline discharge data should be collected along the stream reach most likely to experience impacts. A detailed survey of the stream reach should be conducted before the pump test to determine any obvious changes in flow (gains or losses). Discharge measuring sites should then be established to monitor flow before, during, and after the test. There should be one or more upstream monitoring sites, one or more monitoring sites adjacent to the well, and one or more monitoring sites downstream of the well. Monitoring can be done by direct flow measurements using a flow meter, or by installing temporary weirs and/or partial flumes. Pressure transducers can be used to measure changes in stream stage upstream of the weir or flume before, during, and after the test. Procedures for utilizing seepage run techniques are available from the USGS "Techniques of Water-Resources Investigations Reports" website (https://pubs.usgs.gov/twri/index090905.html) and are discussed in "Techniques of Water-Resources Investigations Reports" Book 4, Chapter B1, Low-flow investigations.[22]

There are situations where direct stream monitoring will not provide definitive results as to the effects of pumping on stream discharge. Observed geohydrological conditions may result from a complex mix of geologic formations, aquifers, and streams. Also, human errors in data collection and/or recording can occur during streamflow measurements using flow meters and stream gages (assumed to be about 5 percent). Natural events, of course, can also affect data quality.

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[20] Fontaine, 1996.

[21] Takasaki, K. J., Hirashima, G. T., and Lubke, E. R., 1969, Water resources of windward Oahu, Hawaii: U. S. Geological Survey, Water-Supply Paper 1894, prepared in cooperation with Dept. of Land and Natural Resource, State of Hawaii, 119 p.; Izuka, S. K., 1992, Geology and stream infiltration of North Halawa Valley, Oahu, Hawaii: U. S. Geological Survey Water Resources Investigations Report 91-4197, prepared in cooperation with the Dept. of Transportation, State of Hawaii, 21 p.; Oki, D. S., Wolff, R. H., and Perreault, J. A., 2006, Effects of surface-diversion and ground-water withdrawal on streamflow and habitat, Punaluu Stream, Oahu, Hawaii: U. S. Geological Survey Scientific Investigations Report 2006-5153, prepared in cooperation with the Honolulu Board of Water Supply, 104 p.

[22] Riggs, H.C., 1972, Chapter B1, Low-Flow Investigations, Book 4, Hydrologic Analysis and Interpretation, Techniques of Water Resources Investigations of the U.S. Geological Survey. Available online at http://pubs.usgs.gov/twri/twri4b1/pdf/twri_4-B1_a.pdf.

Rainfall events during pump tests can skew data such that any pumping-induced losses to streamflow are masked by gains to stream discharge caused by runoff and infiltration. Also, the lag time between pumping and the observation of surface water impacts may vary. In some cases, a pump test that lasts for 120 hours (5 days) may not be long enough to show depletions in streamflow, although continued monitoring after the test may display changes in low-flow characteristics.

Indirect Methods for Assessing Ground Water/Surface Water Interaction. Although it is ideal to assess ground water/surface water interaction through the analysis of measurements taken in the field, the logistics and costs associated with direct measurement methods are often prohibitive. Thus, investigators employ various indirect methods to assess the interaction of ground and surface water resources. Indirect assessment methods include numerical ground water models and analytical methods.

Numerical models are generally considered superior to analytical models. However, numerical models require detailed data inputs for multiple variables and such data is not available for most areas of the State. In addition, to date, no numerical models designed for Hawai‘i aquifers have been designed to account for ground water/surface water interaction. Therefore, ground water/surface water interaction in Hawai‘i is primarily assessed through the use of analytical models, which are simpler, require fewer data inputs, and are more easily applied than numerical models.

CWRM is primarily concerned with ground water/surface water interaction with respect to potential well impacts on surface water resources. These issues typically arise when a well is proposed near a stream. A variety of methods may be used to estimate the degree to which a proposed well may impact stream flow. Historically, CWRM has used two methods to estimate stream flow impacts: (1) estimating ground water drawdown based on the Theis equation and (2) estimating stream loss utilizing a stream depletion equation based on work by Sophocleous and others. In the first method, the hydraulic conductivity of the aquifer is determined from pump test data. This hydraulic conductivity is then input into the Theis equation to calculate drawdown of the water table at a given distance from the pumping well (e.g. distance to the stream). Potential impacts to the stream are then assessed based on this predicted drawdown. For method two, the hydraulic conductivity of the aquifer is determined from pump test data. This hydraulic conductivity is then input into a stream depletion equation to calculate stream loss, for a given stream reach, as a percentage of the pumping rate of the well.

As a part of the well permit application process, CWRM requires a pump test to be performed for all new wells with a proposed pumping rate greater than 50 GPM. Data from these tests are used for an initial determination on the potential for the well to impact nearby streams, marshes, or other surface water bodies. If it is determined that a new well is likely to adversely impact a surface water body, CWRM may take several actions, including, but not limited to: (1) requiring additional testing and monitoring activities prior to, or as a condition of, permit application approval, (2) submission of an instream flow standard amendment application, (3) approval of the well permit at a reduced pumping rate if it is a requirement of the instream flow standard amendment or if subsequent pumping tests indicate that operation of the well at a lower pump rate will not impact any surface water bodies, or (4) denial of the permit application.

Examples of Ground Water/Surface Water Interaction

Basal Ground Water as Spring Discharge in Pearl Harbor. As mentioned above, many streams are intermittent in their middle reaches and become perennial in their lower reaches due to their intersection of a basal lens. This is particularly the case in Pearl Harbor. Waikele and Waiawa springs are located in the Pearl Harbor Aquifer Sector Area and offer the best examples of surface water where base-flow discharge is dependent upon head.[23]

Oki[24] in the CENCOR numerical model (see **Table F-10**), used the head-discharge relationship at Kalauao Springs in Pearl Harbor to analyze the effects of pumpage to discharge. The base-case was the Visher and Mink[25] condition when agricultural recharge and pumpage was at steady-state or 1950's conditions. For future pumpage scenarios, Oki used the 1967-90 measured head-discharge relationships when agricultural activities ceased as a base-case. The future pumpage scenarios provide an estimate on the loss of basal discharge at one of the Pearl Harbor springs. Future numerical model simulations can calibrate to other Pearl Harbor springs' head-discharge relationships to deduce the amount of discharge reduction throughout the Pearl Harbor area for different pumpage scenarios.

A part of the cooperative agreement between CWRM and the USGS is to directly measure flow and sample the Pearl Harbor springs on a biannual basis. These data can be directly correlated to water levels in monitor wells and correlated to actual pumpage in the region.

Basal Ground Water as Leakage into Marshes. Basal water also discharges through the caprock and from basal and/or caprock springs in low-lying areas forming marshes and anchialine ponds. Basal water leakage is predominant in the Kahuku area where Punamanō and Ki‘i marsh and pond complexes are formed from rainfall, runoff, diffuse leakage of ground water, and from two known springs.[26] In addition there are several flowing artesian wells which

[23] Visher, F. N. and Mink, J. F., 1964, Ground-water resources in Southern Oahu, Hawaii: U. S. Geological Survey Water-Supply Paper 1778, prepared in cooperation with the Division of Land and Water Development, Dept. of Land and Natural Resources, State of Hawaii, 133 p.

[24] Oki, D. S., 1998, Geohydrology of the Central Oahu, Hawaii, ground-water flow system and numerical simulation of the effects of additional pumpage: U. S. Geological Survey Water-Resources Investigations Report 97-4276, prepared in cooperation with the Honolulu Board of Water Supply, 132 p.

[25] Visher and Mink, 1964.

[26] Hunt, C. D., and DeCarlo, E. H., 2000, Hydrology and water and sediment quality at James Campbell National Wildlife Refuge near Kahuku, Island of Oahu, Hawaii: U. S. Geological Survey Water-Resources Investigations Report 99-4171, prepared in cooperation with the U. S. Fish and Wildlife Service, Dept. of Interior, 85 p.

supply water to James Campbell Wildlife Refuge at Kiʻi Marsh. The sediments forming the caprock that underlies the marshes, create a semi-confined Koʻolau basal aquifer. With the basal aquifer having a potentiometric head of about 15 feet above sea level and the elevation of the marsh is only a few feet above sea level, there is ground water leakage through the sediments. Any reduction in the potentiometric head by pumping basal ground water will reduce the amount of leakage through the caprock. The actual amount of leakage cannot be measured directly, but up-gradient increases in basal ground water pumpage will reduce the leakage into the marsh by the same amount.

Kaloko-Honokōhau National Historical Park, located on the Kona coast of the Island of Hawaiʻi, is an example of an area where anchialine ponds are present. However, anchialine ponds with greater biodiversity can be found in other areas of the state.

Development of High-Level Ground Water and Impacts to Streams. The development of ground water resources in Hawaiʻi has historically been driven by municipal and agricultural demands. Horizontal tunnels, large shafts, and traditional wells have been constructed to yield water from both basal aquifers and high-level aquifers. The development of high-level aquifers in some areas has been observed to impact stream flow where surface water discharge was dependent upon dike compartment stores.

Between 1900 and 1950, many high-level water sources were developed to supplement plantation irrigation systems. The plantations drilled horizontal tunnels to tap dike impounded water, which was then gravity-fed to irrigation ditches and distribution systems. Tunnels were developed in mountain areas where high spring and stream discharge provided good surface indicators of ground water accumulated in dike compartments. Spring discharge and streamflow, however, was observed to decrease after tunnel development, as the tunnels effectively captured ground water flows before the water could issue forth from springs and seeps.

An example of an area where tunnels impact surface water resources can be found in Windward Oʻahu, where the Waiāhole Ditch system tunnels capture water from numerous dike-impounded reservoirs. Over time, dike-impounded water was depleted as it discharged through the tunnels. Meanwhile, stream flow diminished as the dike water no longer contributed to flow.

As awareness of surface water impacts increased, water development efforts began to modify tunnel construction. Engineers introduced concrete bulkheads in tunnels to simulate dike boundaries, control water discharge, and to allow ground water to rebuild as storage. The success of bulkheading varies from site to site, and many questions remain as to the effectiveness of such installations in facilitating storage recovery.

Wells have also been used to develop high-level aquifers, and well withdrawals have been observed to impact vicinity surface water resources. In 1963, the Honolulu Board of Water Supply drilled two exploratory wells in Waiheʻe Valley, Oʻahu (T-114 and T-115 wells 2751-02, 03, respectively). A temporary weir was constructed downstream from the wells to measure changes in stream discharge during the five-day well pump testing. Measurements at the weir during testing indicated that well withdrawals resulted in loss of stream flow and that there are also some alluvial contributions to ground water. Pumping of these wells has been restricted by court order[27] such that at least 2.78 MGD of water must be allowed to flow downstream.

Examples Where Surface and Ground Water Do Not Interact. There are cases where pumping wells located near streams have been determined not to affect proximal streamflow. When the streambed is higher than the ground water table, well withdrawals typically do not impact streams. For example, wells (e.g. Mokuhau wells) in Wailuku, Maui, which pump basal ground water from 10 feet above sea level, do not impact the nearby ʻĪao Stream, which is located several hundred feet above sea level. A similar condition exists with the North Waiheʻe Wells located in the neighboring Waiheʻe Aquifer System Area. Water levels are approximately eight feet above sea level and the Waiheʻe River streambed invert elevation is much higher.

Well pumping tends not to impact streams where the streambed is separated from the ground water table by perching members. In the Honolulu area, the Board of Water Supply has drilled wells into the basal aquifer (e.g., Nuʻuanu, Mānoa, and Pālolo) that do not affect vicinity streams. In these instances, streams are not affected by wells because streamflow is dependent upon shallow alluvial aquifers that are not connected to basal ground water aquifers.

Recommendations for Assessing Ground and Surface Water Interaction

The following recommendations are intended to guide future CWRM efforts to improve the assessment of ground and surface water interaction:

- Identify sites statewide where it would be appropriate to conduct seepage runs and incorporate seepage run data collection into the monitoring program.
- Ensure adequate coverage of long-term stream gage sites and identify appropriate low-flow partial record sites.
- Ensure adequate baseline data collection prior to new source development. Coordinate data collection based upon long-range county plans for water development.
- Establish a statewide hydrologic monitoring network which will provide a basis for calibrating and validating numerical models of ground water/surface water interaction.
- Promote and encourage the use of calibrated local-scale numerical model of ground water flow in basal aquifers to assess ground water/surface water interaction as part of the well permitting process. In the modeling area, the ground water head and stream base flow are influenced by the proposed pumping.

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[27] Reppun v. Board of Water Supply, 1982, 65 Haw. 531, 656 P.d 57, cert. denied, 471 U.S. 014, 105 S. Ct 2016, 85 L Ed 2d 298 (1985).

F.4.3.3 Assessing Aquifer Sustainable Yield

Natural resources are commonly classified as either renewable: capable of being replenished as rapidly as they are used; or non-renewable: a result of accumulation over a long period of geologic time. Ground water, replenished by rainfall recharge, is universally classified as a renewable resource. However, the amount of ground water that can be developed in any Hawai‘i aquifer is limited by the amount of natural recharge. Additionally, not all natural recharge an aquifer receives can be developed. Some aquifer outflow or leakage must be maintained to prevent seawater intrusion or to maintain some perennial streamflow. Therefore, the sustainable yield of an aquifer normally represents a percentage of the natural recharge. Ideally, this percentage is determined by considering all relevant aquifer hydrogeologic properties and their effects on temporal and spatial variation in flow, hydraulic head, and storage. However, the State Water Code provides CWRM some flexibility in using other methods to define sustainable yield as provided by HRS §174C-3:

> *"'Sustainable yield' means the maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission."*

The discretionary and flexible nature of the sustainable yield term allowed CWRM to set chloride limits rather than pumpage limits in the ‘Ewa Caprock.

Ground water models are used as tools in ground water management. This section provides a general summary of ground water modeling efforts as they have been applied in Hawai‘i to evaluate aquifer sustainable yield. As background to support the modeling discussion, a brief explanation of ground water storage and movement parameters is provided.

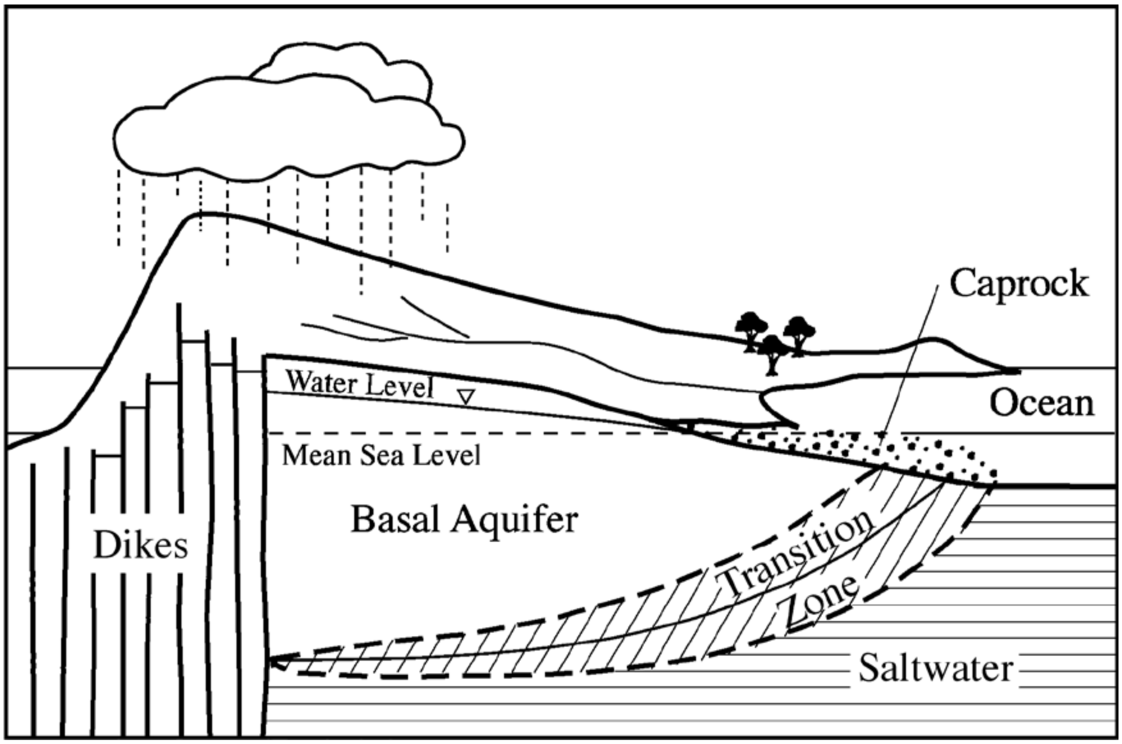
Ground Water Storage and Movement

According to the mass conservation principle, the total storage in an aquifer changes when its inflow is not balanced by its outflow. Under natural conditions, the aquifer is in a hydrologic balance such that the inflow, or the rate of natural rainfall recharge, equals the outflow or the coastal leakage. Thus, the volume of aquifer storage remains constant.

Hydraulic head, or the water level as it relates to water pressure, is an important variable. The spatial distribution of the hydraulic head or gradient determines the speed of water movement. The hydraulic head also determines the storage of an aquifer. The hydraulic head of a basal aquifer is the highest at the inland boundary and gradually reduces toward the coastline. This spatial variation of the hydraulic head induces ground water flow from mountain areas toward the ocean (see **Figure F-12**).

Forced draft or pumping has disrupted the natural balance of Hawai‘i aquifers. This is evident in the decline of hydraulic head and the reduction of storage. If the rate of forced draft from an aquifer remains constant, the aquifer would eventually reach a new hydrologic balance with a smaller storage. In principle, if the rate of forced draft equals the rate of natural recharge, there will be no leakage outflow and no storage. The hydraulic head or aquifer storage would be reduced to zero. This is not an acceptable scenario. As aquifer storage is reduced, the transition zone would grow to occupy the entire aquifer, gradually replacing all freshwater with brackish or saltwater. Therefore, as a practical matter, it is not possible to create a well network that will capture all recharge.

Figure F-12 Hydrogeologic features of a typical Hawaiian basal aquifer



An aquifer's value as a source of fresh water can be evaluated in terms of hydrogeologic properties that dictate ground water storage and ground water movement. These properties are measured in terms of porosity, storage coefficient, hydraulic conductivity, and transmissivity.

An aquifer's ability to store ground water is determined by porosity and the storage coefficient. Porosity is the ratio of the aquifer's void volume to the total volume of rock material. The void volume of an aquifer is the volume occupied entirely by water. Thus, porosity indicates the maximum amount of water that an aquifer can contain. Generally, only a portion of this water can be developed and extracted for water supply; this is referred to as specific yield. The remaining volume of water is retained as a film on rock surfaces.

The volume of water stored in an aquifer changes in response to hydraulic pressure. The storage coefficient is defined as the volume released from or taken into storage per unit area of the aquifer per unit change in hydraulic head. The typical Hawaiian basal aquifer is unconfined, where the water table comprises the upper boundary (see **Figure F-12**). In an unconfined aquifer, the effective porosity or specific yield is equal to the storage coefficient.

Ground water movement through an aquifer can be measured in terms of hydraulic conductivity or transmissivity. Hydraulic conductivity can be described as the ease with which water moves through the aquifer. Transmissivity is the product of hydraulic conductivity and the depth of flow.

Ground water supplies may be vulnerable to contamination due to human-induced and natural conditions. The impacts of contamination can be amplified and facilitated by ground water movement. Chemical leaching and seawater intrusion are two common sources of contamination. Chemical leaching occurs when residual pesticides, petrochemicals, or other contaminants percolate down from upper soil layers into the freshwater lens. Saltwater intrusion occurs when increasingly brackish water infiltrates into the freshwater lens. This can occur due to (1) improper pumping of a production well, or (2) over pumping of the aquifer, or (3) migration of the transition zone inland and/or vertically upward.

The susceptibility of an aquifer to contamination can be measured by evaluating advection and dispersion. Advection is the transport of contaminants, as water carries impurities in the direction of flow. Dispersion includes: 1) microscopic mechanical mixing due to varying pore spaces through which water flows, and 2) molecular diffusion. Diffusion is defined by Fick's law as the movement of a fluid from an area of higher concentration to an area of lower concentration. Advection and the mechanical mixing portion of dispersion constitutes the majority of contaminant movement within an aquifer while the diffusion component of dispersion usually has much less effect in the spreading of contaminants.

As described earlier, storage and movement of ground water in basal aquifers is also influenced by the Ghyben-Herzberg equilibrium formula. However, though this formula gives satisfactory results where ground water flow is horizontal, in cases where vertical flow is encountered, there may be significant deviation from the 1 to 40 relationship. Vertical flow can be encountered near the coastline and in instances where there is vertical flow in monitoring wells that penetrate differing layers of geologic and aquifer formations.

Laboratory or field tests can be used to assess the parameters described above. Laboratory tests are less reliable, as only a limited portion of the rock matrix can be evaluated. Hawai‘i aquifers are highly heterogeneous and, at this time, only statistically describable aquifer parameters can be assigned to Hawai‘i aquifers on a large scale.[28] Field tests can provide

[28] Lau, L. Stephen and Mink, J.F., *Hydrology of the Hawaiian Islands*, University of Hawaii Press: Honolulu, 2006.

effective values appropriate for regional studies, however, site-specific pumping tests should be conducted to evaluate local conditions.

Ground Water Management Model Development and Application

Many types of models have been developed and applied in the U.S. and elsewhere for simulating ground water flow and solute transport. These models help to address sustainability issues. The early simulation attempts used analog models such as sand boxes, electrical conductivity sheets, and resistance-capacitance networks. Analytical models such as the Robust Analytical Model (RAM) have been, and continue to be, used in Hawaiʻi with limited ground water data to estimate sustainable yields. More recently, mathematical models have been developed that take full advantage of the rapid advancement of numerical methods and computer technology through what is commonly referred to as numerical models. Finite-difference, finite-element, and other boundary-integral numerical modeling techniques are important tools that should be used to aid in the management of well infrastructure and other ground water management problems where sufficient data and monitoring exist.

Mathematical models of ground water flow are formulated by combining the mass conservation principle and Darcy's law of ground water movement. Darcy's law states that the ground water flow rate can be calculated if the hydraulic head gradient and hydraulic conductivity is known. A conceptual ground water flow model can simulate a basal aquifer when the width of the transition zone is small relative to the thickness of the aquifer. In this case, the freshwater and saltwater are considered to be immiscible fluids separated by a sharp interface. This type of sharp interface model is adequate if the purpose of modeling analysis is to determine the general position, shape, and behavior of the interface; water levels; and flow directions in response to climatic and pumping stresses.

The conceptual sharp interface model may be further divided into two categories: freshwater flow models and coupled freshwater-saltwater flow models. The freshwater flow models are formulated by assuming the saltwater is stationary. The lower boundary of the freshwater model or the sharp interface can then be located by the Ghyben-Herzberg formula.[29] Coupled freshwater-saltwater models are formulated by assuming both freshwater and underlying saltwater are moving. The sharp interface of a coupled freshwater-saltwater flow model can be located based on Hubbert formula.[30]

Mathematical models of ground water solute transport, the movement of solutes in ground water systems, are formulated by combining the mass conservation principle and Fick's law of dispersion. Fick's law states that the mixing of a solute in an aquifer can be calculated if the

[29] Liu, C.C.K., Lau, L.S. and Mink, J.F., 1983, Groundwater Model for a Thick Freshwater Lens, *Ground Water*, 21(3):293-300.

[30] Liu, et al.1983; Essaid, H. I., 1986, A comparison of the coupled fresh water-salt water flow and the Ghyben-Herzberg sharp interface approaches to modeling of transient behavior in coastal aquifer systems, *Journal of Hydrology,* 86:169–193.

solute concentration gradient and dispersion coefficient are known. For modeling reactive chemicals, additional mathematical terms representing relevant reaction kinetics must also be included in the transport model formulation.

Because the solution of a transport model requires prior knowledge of flow velocity, solute transport modeling must be conducted following a flow simulation. The flow simulation calculates the flow velocity distribution in the aquifer, which is subsequently applied in transport simulation to calculate the salinity distribution. In modeling seawater intrusion, salinity re-distribution may cause appreciable change in water density, which is a flow model variable. Therefore, a comprehensive ground water model must combine both flow and transport simulation. The flow simulation is first conducted to calculate velocity distribution. The velocity distribution is then used by the transport model to calculate salinity distribution. The density change caused by the new salinity distribution is then determined and used to re-calculate the velocity distribution. The process must continue until stable velocity and salinity distributions are established. SUTRA, a numerical ground water model developed by the US Geological Survey, solved coupled flow and solute transport equations.[31]

Formerly, simple analytical ground water models were developed and tested in aquifers with reasonably defined geological structures and hydrology. Mathematical modeling using simple analytical models highlights the relative importance of aquifer hydrogeologic properties. With the increasing power of computers, the accessibility to and use of more complex numerical ground water models and computer codes has become more important. However, before a numerical ground water model can be solely relied upon for prediction and management decisions, a rigorous process of model calibration and verification must be completed. The general procedure in model calibration and verification is to estimate a range of values for the ground water flow and the solute transport parameters, then test the model by comparing the calculated hydraulic head and salinity distribution to the observed values. The results of an adequately-calibrated model will reasonably emulate the observed results of historical events that provide the basis for estimated parameters. Anderson provides a very good detailed explanation of numerical model development.[32] Additionally, CWRM has provided a *Guide for Documentation for Ground Water Modelling Reports* since 1994.

A comprehensive numerical ground water model contains many model parameters. It may also consist of a huge numerical network with up to one million nodes or computational units. In principle, each node may have different model parameters to address the real-world heterogeneity of an aquifer. Therefore, a very close match of calculated and observed head and

[31] Voss, C.J., 1984, A finite-element Simulation Model for Saturated-unsaturated, Fluid-density-dependent Groundwater Flow and Transport Flow with Energy Transport or Chemically Reactive Single-species Solute Transport, *U.S. Geological Survey Water Resources Investigation Report* 84-4369.

[32] Anderson, M.P., Woessner, W.W., 1992, Applied Groundwater Modeling – Simulation of Flow and Advective Transport, 381 p.

salinity distribution data is difficult but may be achieved by the simultaneous manipulation of several model parameters.

Inaccurate model calibrations can be corrected by model verification. A model is considered verified if calculated results can reasonably emulate a historical event, or reasonably predict the behavior of water levels under changing circumstances based on an actual data set. New pumpage distribution patterns or changes in recharge due to reduced irrigation are typical examples of changing circumstances. Ideally, some judgment of the values of model parameters should be practiced. In model calibration and verification, it is advantageous for the investigators who developed the model and those who have gathered field data to participate in the calibration and verification process.

Numerical Ground Water Modeling Efforts in Hawai‘i

Table F-7 is a listing of numerical modeling efforts in Hawai‘i that have been reviewed by CWRM. This is not an exhaustive listing, as there are other private and public reports available that have not been reviewed in depth by CWRM. As reports come to the attention and are reviewed by CWRM these documents are compiled in CWRM's digital library for public information. In addition, public and private reports exist which have valuable hydrologic information but are not ground water flow models (e.g., recharge studies).

Analytical Ground Water Modeling Efforts in Hawai‘i

Table F-7 also lists analytical modeling efforts that have been reviewed by CWRM. This is not an exhaustive listing as there are other private and public reports available. In addition, public and private reports exist which have valuable hydrologic information but are not ground water flow models (e.g., recharge studies).

An analytical model for a particular ground water system can be formulated using simplifying assumptions for system boundaries, flow, and transport processes. With these simplifying assumptions, theoretical or mathematically derived solutions of the model governing equations can be obtained.

Analytical ground water models are used extensively in ground water management for the following reasons:

- Analytical models are essential for the design of field experiments and subsequent data interpretation to estimate aquifer flow and transport parameters;

- Analytical models are useful modeling tools for preliminary ground water investigations; and

- Analytical models can be used to test comprehensive numerical models through comparison of modeling results for simplified conditions and scenarios.

Table F-7 Summary of Mathematical Ground Water Flow Models Reports in Hawai‘i

YEAR	MODEL	APPLICATION	REFERENCES
1974	GE-TEMPO	Long-term head variability in Palolo aquifer, O‘ahu	Meyers, C.K., Kleinecke, D.C., Todd, D.K., and Ewing, L.E., 1974
1980	Robust Analytical Model (RAM)	Analytical model to assess sustainable yields of Southern O‘ahu	Mink, J.F., WRRC prepared for Honolulu BWS
1981	2-D Flow Model	Ground water head variability in Pearl Harbor aquifer, O‘ahu	Liu, C.C.K., Lau, L.S. and Mink, J.F., WRRC TR 139
Early to Mid-80s	Methods of Characteristics (MOC)	2-D/3-D finite difference model of ground water and chemical transport of pesticide residuals in Pearl Harbor aquifer	Konikow, L.F., and Bredehoeft, J.D., 1978 Orr, Shlomo, and Lau, L.S., 1987
1985	AQUIFEM-Salt	2-D finite element to water systems in Southeast O‘ahu	Eyre, P., Ewart, C., Shade, P. USGS WRIR 85-4270
1990	RAM	Analytical ground water model for estimating sustainable yield values in 1990 WRPP	Mink, J.F. Mink & Yuen, prepared for the Water Commission
1993 to 1994	DYNSYSTEM	3-D finite element to study ‘Ewa marina construction effects on ‘Ewa caprock	Camp Dresser & McKee, 4 Volumes, prepared for HASEKO (‘Ewa) Inc., CCH-OA96-1
1995	AQUIFEM-Salt	2-D finite element to study water level changes due to increased pumping in Hawi, Big Island.	Underwood, M., Meyer, W. Souza, W. USGS WRIR 95-4113
1995	AQUIFEM-Salt	2-D finite element to study water level changes due to increased pumping from Barbers Point Shaft on Waianae Aquifer.	Souza, W., Meyer, W. USGS WRIR 95-4206
1996	Modular Finite Difference Flow (MODFLOW)	2-D finite difference to study the effects of pumpage on water levels for the entire island of Lanai	Hardy, R. CWRM R-1
1996	MODFLOW	2-D finite difference to study connection between caprock and basal aquifers	Willis, R., prepared for The Hawai’i-La’ieikawai Assoc. Inc., CCH-OA96-02
1996	Saturated-Unsaturated Transport (SUTRA)	2-D finite element to study pumpage impacts to water levels on cross-section of ‘Ewa Caprock	Oki, D., Souza, W., Bolke, E. Bauer. G USGS OFR 96-442

Table F-7 (continued)
Summary of Mathematical Ground Water Flow Models Reports in Hawai‘i

YEAR	MODEL	APPLICATION	REFERENCES
1997	AQUIFEM-Salt	2-D finite element to study pumpage impacts to water levels and coastal leakage for entire island of Molokai	Oki, D. USGS WRIR 97-4176
1998	SHARP	Quasi 3-D finite difference to study pumpage impacts to water levels in Central O‘ahu	Oki, D. USGS WRIR 97-4276
1998	SHARP	Quasi 3-D finite difference to study pumpage impacts to water levels in Līhu‘e Kauai	Izuka, S. Gingerich, S. WRIR 98-4031
1998	RAM	Study on sustainable yield for Waipahu, Waiawa and Waimalu Aquifer Systems	Mink, J.F. Mink & Yuen prepared for LURF
1998	RAM	Study on sustainable yield of ‘Ewa-Kunia Aquifer System	Mink, J.F. Mink & Yuen prepared for Estate of James Campbell
1998	FEMWATER	3-D finite element coupled flow and transport to model the ‘Ewa Plain	Woodward Clyde, prepared for C&C of Honolulu
1999	SHARP	Quasi 3-D finite difference to study water levels and coastal leakage at Kaloko-Honokōhau National Park	Oki, D., Tribble, G., Souza, W., Bolke, E. USGS WRIR 99-4073
2001	RAM/SHARP	Comparison between RAM and numerical model results	Oki, D., Meyer. W. USGS WRIR 00-4244
2001	SHARP	Quasi 3-D finite difference to study water levels, transition zone, and surface water impacts in Līhu‘e Basin Kauai	Izuka, S., Oki, D. USGS WRIR 01-4200
2002	AQUIFEM-Salt	2-D finite element ground water flow model to study Hawi area on Big Island	Oki, D. 2002, USGS WRIR 02-4006
2005	3D SUTRA	Simulation of Pearl Harbor variable density flow	Gingerich, S.B, Voss, C.I., Hydrogeol J (2005) 13:436-450
2005	FEFLOW	3-D finite element simulation to study transition zone movement due to pumping on the Honolulu aquifer.	Todd Engineers, prepared for BWS 2005
2005	SUTRA	2-D finite element to simulate effects of Honolulu Valley fills on pumping distribution	Oki D. USGS SIR 2005-5253

Table F-7 (continued)
Summary of Mathematical Ground Water Flow Models Reports in Hawaiʻi

YEAR	MODEL	APPLICATION	REFERENCES
2006	MODFLOW	3-D finite difference study of the Māhukona Aquifer System	Spengler, S., Pacific Hydrogeologic, LLC
2006	AQUIFEM-Salt	2-D finite element simulation to study impacts of future pumpage on water levels and coastal leakage on Molokai	Oki, D. USGS SIR 2006-5177
2006	RAM2	Analytical flow & transport model to estimate sustainable yield of Pearl Harbor	Liu, C.C.K., 2006.WRRC PR-2006-06
2006	MODFLOW	3-D finite difference study for DOH SWAP program to identify well capture zones	Whitttier, R, El-Kadi, A., et. al. WRRC prepared for State of Hawaiʻi DOH
2007	AQUIFEM-Salt	2-D finite element simulation to study impacts of pumpage on water levels and coastal leakage on Kaunakakai Stream Molokai	Oki, D. USGS SIR 2007-5128
2007	RAM2	Modified RAM that includes deep monitor well salinity profile data for estimating sustainable yield values in 2008 WRPP	Liu, C.C.K., 2007.WRRC PR-2008-06
2008	SUTRA	Ground water availability in Wailuku Maui	Gingerich, S.B, USGS SIR 2008-5236
2011	MODFLOW/ SEAWAT	Accessing potential effects of dry wells on Island of Hawaiʻi	Izuka, S.,USGS SIR 2011-5072
2012	SUTRA	Ground water availability in Lahaina Maui	Gingerich, S.B, Engott, J.A., USGS SIR 2012-5010

Analytical Ground Water Flow Model RAM

In Hawaiʻi, the most commonly used analytical ground water model is the robust analytical model (RAM) [33] derived by Mink. Sustainable yield values of Hawaiʻi basal aquifers were estimated by RAM and included in the 1990 WRPP.

[33] Mink, 1980; Mink, J.F., 1981, Determination of Sustainable Yields in Basal Aquifer, in: *Groundwater in Hawaii-A Century of Progress,* Book published by the Water Resources Research Center, University of Hawaii at Mānoa, pp.101-116.

In RAM, a basal aquifer is represented conceptually by two completely stirred tank reactors (CSTRs) separated by a sharp interface (see **Figure F-12**). The fresh water in the upper CSTR flows at a constant rate of $L = I - D$, where L is the coastal leakage; I is the natural rainfall recharge, a constant; and D is the pumping rate, or pumping minus irrigation return flow. The saltwater in the lower CSTR is stationary. RAM calculates the variations over time of the hydraulic head (h) in a basal aquifer in response to pumping stress. The steady-state solution of RAM indicates a simple relationship between the hydraulic head and the pumping rate. This relationship is presented graphically in **Figure F-13**.

Figure F-13 Conceptual formulation of the basal aquifer in the robust analytical model (RAM)

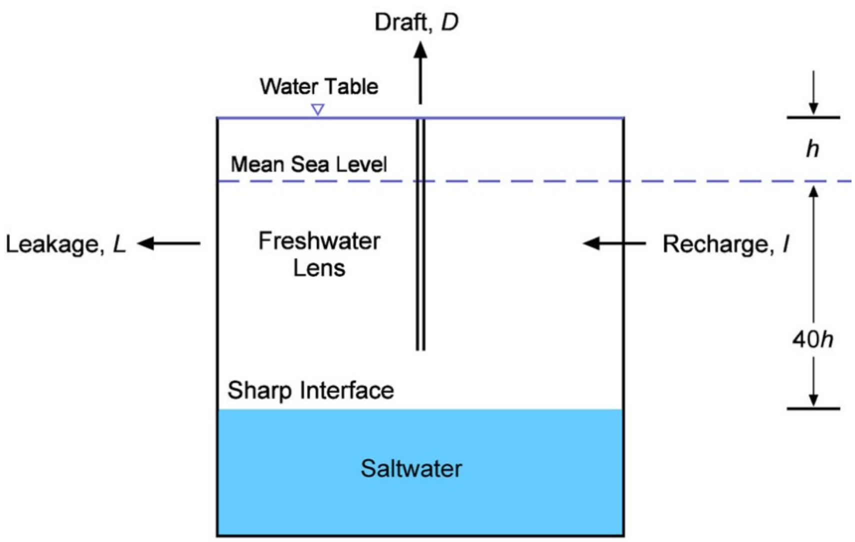
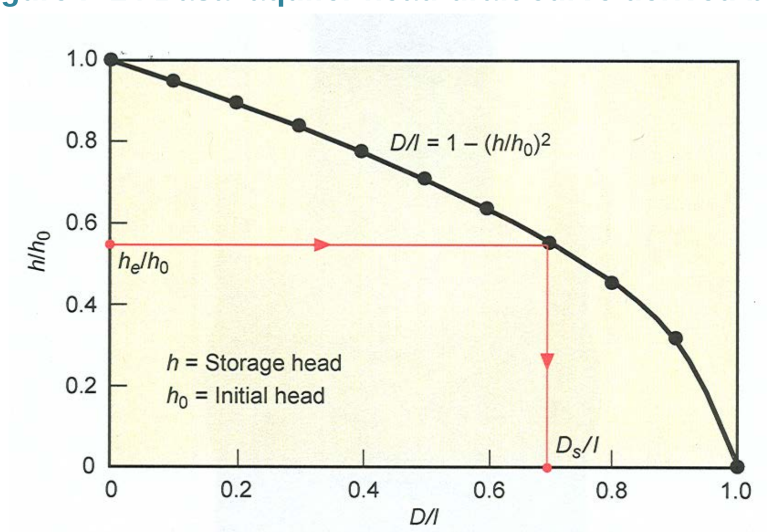


Figure F-14 Basal aquifer head-draft curve derived by RAM.



Based on Mink's $D_s/I = 1-(h_e/h_o)^2$ or $D_s = 1-(h_e/h_o)^2$ or

$$\text{Sustainable Yield} = \text{Recharge} \times \left\{1 - \left(\frac{\text{Equilibrium head}}{\text{Initial head}}\right)^2\right\}$$

According to RAM, a parabolic relationship of hydraulic head and draft rate exists when a basal aquifer is at a steady state, or when recharge to the aquifer equals leakage plus pumping or forced draft. **Figure** F-14 shows a plot of head vs. draft in terms of dimensionless variables. The ordinate is a dimensionless variable of head, or h/h_0, where h_0 is constant initial head. The abscissa is a dimensionless variable of draft rate, or *D/I*.

According to RAM, the sustainable yield of a basal aquifer relates directly to its minimum equilibrium head. Mink stated that "the clearest expression of sustainable yield is that of allowable net draft for a selected (minimum) equilibrium head."[34] Sustainable yield, D_s, represents the maximum amount of water that can be withdrawn before a given equilibrium head, h_e, is compromised.

The response of a basal aquifer to pumping stress can be measured in terms of hydraulic head decline and the expansion and upward movement of the transition zone. This expansion and upward movement is a prelude to seawater intrusion. Acceptable source-water salinity in Hawaiʻi is 250 mg/L chlorides or less. Seawater intrusion occurs when water with salinity higher than 250 mg/L chlorides reaches the bottom of a pumping well. Therefore, the minimum equilibrium hydraulic head can generally be defined as the hydraulic head that must be maintained to prevent seawater intrusion into a particular well.

The minimum equilibrium head of a well cannot be determined analytically by solving the governing flow equation of RAM as it does not consider saltwater movement or well upconing issues for the spatial distribution of actual wells. Therefore, RAM estimates sustainable yield by establishing a minimum equilibrium head based on selected important well depth within an aquifer or, in the absence of a selected well site, it relies on a relationship for selecting minimum equilibrium head, as suggested by CWRM in the 1990 WRPP (see **Table** F-8**)**. In this WRPP update, CWRM generally used the table to reassess sustainable yields rather than rely on a single important well site.

In short, the ratios of equilibrium heads and percentages of recharge show a precautionary approach to setting sustainable yields for basal aquifers. Basal aquifers where heads show a thin lens are allowed a smaller portion of recharge than thick basal lens. Originally, this was intended to protect well infrastructure from saltwater intrusion due to upconing effects, but an added benefit is that coastal leakage is allowed to continue in significant amounts to the ocean even at sustainable yield estimations. These ratios were not intended for other aquifer types such as perched or high-level dike confined aquifer systems that may predominate an area.

After an equilibrium head (h_e) and thus (h_e/ h_0) is selected, this value is inserted into **Figure** F-13 to obtain the dimensionless variable of draft or D_s/I. Multiplying this value by the known recharge rate gives the sustainable yield.

[34] Mink, 1980.

Table F-8 Relationships between initial head and minimum equilibrium head of Hawai‘i basal aquifers.[35]

The range of initial head, h_0 (ft)	Ratio of minimum equilibrium head and initial head (h_e/h_0)	D_s/I or SY = %of Recharge
4 – 10	0.75	0.44
11 – 15	0.70	0.51
16 – 20	0.65	0.58
21 – 25	0.60	0.64
> 26 and High-Level	0.50	0.75

Key assumptions of RAM include the following:

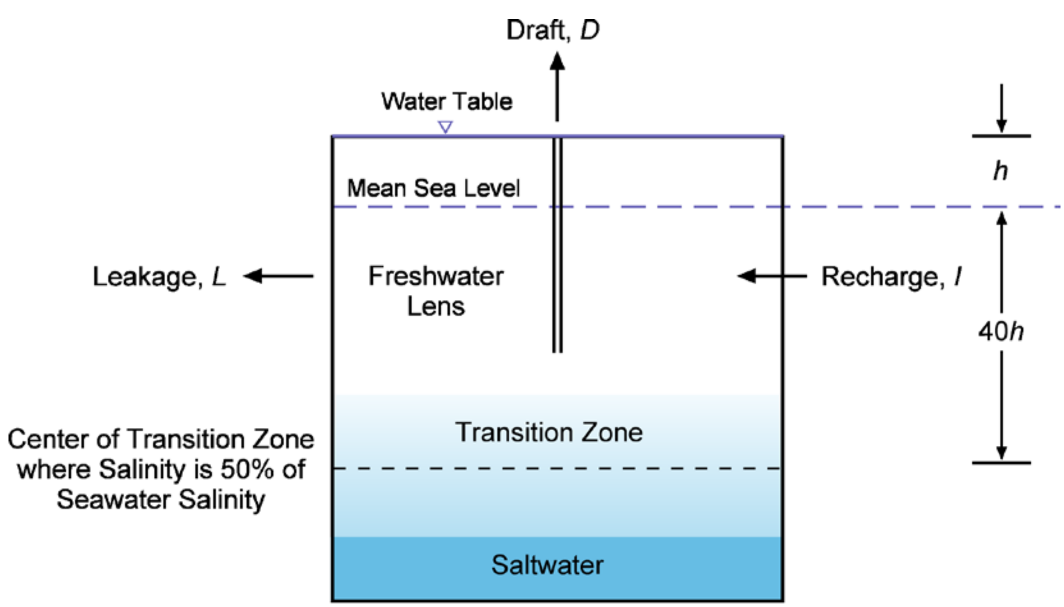
- Freshwater occurs as a basal lens floating on top of sea water;
- A sharp interface exists between the fresh and sea water;
- The aquifer is unconfined, its properties are homogeneous and isotropic, and its thickness is constant;
- Ground water flow is uniform and laminar;
- Head is equivalent to Storage Head; and
- Wells are optimally placed throughout the aquifer system area.
- Important limitations of RAM include the following:
- RAM ignores the spatial distribution of (1) recharge, (2) actual well placement, and (3) actual well pumpage;
- Many of the “initial heads” used in the RAM calculation were estimated due to the absence of pre-development ground water data;
- The “minimum equilibrium head” used in the RAM equation is an estimate based on empirical relationships. It cannot be determined analytically;

[35] State of Hawaii Department of Land and Natural Resources, Commission on Water Resource Management, 1990, *Hawaii Water Plan, Water Resources Protection Plan:* Honolulu, Hawaii.

- RAM does not account for (1) convection and dispersion, (2) variability in the transition zone, (3) flow between aquifer system areas, (4) aquifer system area boundary conditions (such as caprock), and (5) the needs of ground water dependent ecosystems; and
- RAM does not model ground water flow in three-dimensions.

Analytical Ground Water Flow and Transport Model RAM2
The modified RAM (or RAM2,) consists of two submodels. The flow submodel takes the form of RAM. The transport submodel simulates the variation of salinity over time in the transition zone of a basal aquifer in response to pumping stress. In RAM2, a basal aquifer is represented conceptually as two completely stirred tank reactors separated by a transition zone of varying salinity (see **Figure F-15**).

Figure F-15 Conceptual formulation of the basal aquifer model RAM2



Assessing Sustainable Yield of the Hawaiian Basal Aquifers by RAM and RAM2
Ideally, the sustainable yield of a basal aquifer would be determined through a numerical simulation using a comprehensive three-dimensional flow and transport model. However, the application of a comprehensive model for this purpose requires significant time and money to produce and is difficult to use. Comprehensive numerical model parameters are very complex and are difficult to quantify. Simple analytical models such as RAM and RAM2 are currently more readily applied to estimate sustainable yields for water planning purposes, especially given the complexities of estimating recharge alone.

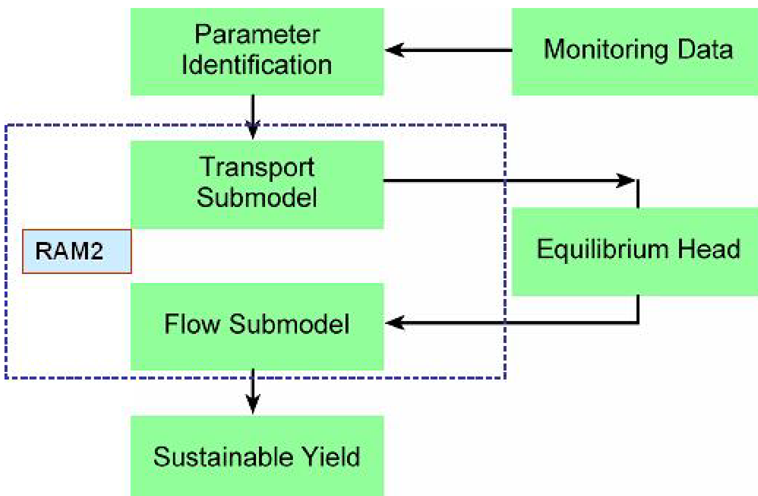
The sustainable yield of Hawai‘i basal aquifers can be determined by the integrated application of both the flow and transport submodels of RAM2. The modeling procedure, as shown in **Figure F-16**, consists of the following steps:

1) Use hydraulic heads and salinity profiles from deep monitoring wells and previous studies to estimate the transport parameter values (i.e., dispersion coefficient and mean hydraulic resident time);

2) Use the transport submodel to calculate the minimum equilibrium hydraulic head; and

3) Use the flow submodel to determine the sustainable yield.

Figure F-16 RAM2 modeling procedure



RAM2 was used by two recent studies[36] to re-evaluate the sustainable yield of a few selected Hawai‘i basal aquifers. **Table F-9** summarizes the results of sustainable yield estimation by both RAM and RAM2.

[36] Liu, 2006; Liu, 2007.

Table F-9 Sustainable yield estimation of selected Hawai‘i basal aquifers

Aquifer	Areas (mi^2)	Natural Recharge (in.)	Estimated Sustainable Yield (MGD) RAM	RAM2
O‘ahu				
‘Ewa-Kunia	28.1	24.0	11.0	19.4
Waipahu-Waiawa	60.7	136.3	102.0	110.3
Waimalu	32.1	59.7	45.0	48.3
Moanalua	10.9	24.0	18.0	15.8
Kalihi	6.3	12.0	9.0	8.7
Beretania	8.6	20.0	15.0	13.9
Kaimukī	14.4	8.7	--	6.5
Maui				
‘Īao	24.7	28.0	20.0	18.5
Moloka‘i				
Kualapu‘u	13.0	9.0	7.0	5.0

Note: According to CWRM, area of Iao is 17.81 mi^2 and area of Kualapuu is 18.2 mi^2

Production Wells in Hawai‘i Basal Aquifers: Operation and Safe Yield

The sustainable yield of Hawai‘i basal aquifers represents the maximum aquifer pumping rate (i.e. allowable draft) assuming optimal placement of wells. In principle, if optimally distributed, each of production well in a basal aquifer can be assigned an allowable draft such that the total draft from the aquifer is equal to or less than the sustainable yield. However, the safe yield of an individual production well is also limited by the localized ground water behavior near the well in response to its pumpage. Specific yields, upconing, and pump intake altitudes can severely limit the safe yield of an individual well while the aquifer as a whole is not threatened. Examples of this are wells drilled too deep, too shallow, or are located in very tight (low permeability) formations. The safe yield of an individual production well may be less than the allowable draft based on any model prediction because of localized operational limitations. Safe yield can be optimized in a production well with proper well design, location, and operation. Further, safe yield of an aquifer based on well infrastructure is best estimated utilizing a calibrated and validated numerical model based on sufficient hydrologic data.

Decline in Specific Capacity

Sustainable yield is evaluated assuming an aquifer is experiencing steady state conditions. It should be noted that this assumption does not account for operational conditions at a given production well. A basal aquifer’s transient response to pumping stress, in the vicinity of a well, may include a decline in specific capacity and/or upconing.

The safe yield of an individual production well is partly controlled by the specific capacity and the available drawdown of that well. When a well is pumped, water is removed from the aquifer surrounding the well, and the water level or hydraulic head is lowered. The drawdown is defined as the vertical distance the water level within the well bore is lowered from the original static (non-pumping) water level. The specific capacity of a production well is its yield per unit drawdown. Available drawdown is the difference between the static head and the lowest practical head, which is normally determined at the time of well construction.

Decline in the specific capacity of a well is measured in terms of operating head. The operating head indicates the transient response of an aquifer to pumping stress. This is usually measured in the field while the aquifer is being pumped. The hydraulic head of a basal aquifer is governed by the Ghyben–Herzberg formula and is called the storage head. The storage head of a large aquifer declines slowly in response to pumping stress. For example, the average decline of the storage head of the Pearl Harbor aquifer was less than 0.25 feet per year during the last 100 years;[37] during the same period, the measured seasonal changes of the operating head near a pumping well in the Pearl Harbor aquifer fluctuated as much as 10 feet. At pumping wells, operating heads are less than storage heads due to turbulent flow into the well. Therefore, operating heads reflect both well inefficiancies and aquifer storage heads.

In Hawai‘i, the ground water is often pumped from several production wells in a well field. The drawdown at a given well field is equal to the superposition sum of the individual well drawdowns. In general, wells in a well field should be spaced as far apart as possible to minimize well interference. However, economic factors including the cost and availability of land may dictate the implementation of a least-cost well layout, which results in some interference. Both the specific capacity and the available drawdown for each well in a well field must be closely monitored to achieve for satisfactory well operation.

Deterioration in Water Quality (Saltwater intrusion)

When water from a basal aquifer is pumped through a well, pumping stress causes a localized rising of the underlying saltwater. This phenomenon is called upconing.[38] Most past upconing studies and ground water flow models assumed the existence of a sharp interface between freshwater and the underlying saltwater. However, in real-world basal aquifers a gradual transition zone exists between the freshwater and the underlying saltwater (see **Figure F-11**), which appear to differ between aquifer system areas based on deep monitor well data. Also, the nearshore toe of the basal aquifer will shift inland as cumulative pumpage is increased and captures leakage to the ocean. These are significant issues regarding well susceptibility to saltwater intrusion. Mathematical models can and have been used by CWRM to estimate upconing and saltwater intrusion, but the dynamics of the transition zone are not well understood.

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[37] Mink, 1980.

[38] Todd, D.K., 1980. Groundwater Hydrology, John Wiley & Sons: New York.

Upconing can be minimized through the proper design and operation of production wells. Generally, wells should have the maximum possible vertical separation from the saltwater zone. This is why in the *Hawaii Well Construction Standards,* all new basal well depths are limited the top ¼ of the thickness of the basal lens encountered during construction. This will reduce the capacity of an individual well but provides a method to optimize the resource and protect future constructed well infrastructure. Wells should also be pumped at a low, uniform rate. The total number of production wells in a well field, well spacing, and pumping rates can be optimized using numerical modeling analyses.

Recommendations for Assessing Sustainable Yield

Ground water can be managed through an understanding of sustainable yield, which is defined as the maximum amount of water that may normally be withdrawn from a source without significantly impairing the source. This definition gives CWRM flexibility to consider and redefine sustainable yields with time and based on case-by-case circumstances. At this time, the sustainable yield of the Hawaiʻi basal aquifers is being evaluated by using analytical ground water models such as the robust analytical model (RAM) and the modified RAM, or RAM2. However, in some areas, including Honolulu, Pearl Harbor, Lanai, Molokaʻi, and (soon) West Maui numerical ground water models have been used to help assess the sustainability of the ground water and refine the uncertainty of analytical ground water models. Additionally, the ʻEwa Caprock area has used a general chloride limit for irrigation wells to establish overall aquifer area sustainable yield.

The most immediate area that requires further investigation is the rate of natural recharge. Reported values of natural recharge vary significantly. These values have been derived from various past studies using differing hydrologic balance analyses. Climate change and data from the last 25 years should also be included into recharge analysis. Recharge should also be standardized such that model studies are comparable. Critical issues for recharge include:

- Estimation of runoff;
- Soil-moisture storage and its relationship to evapotranspiration;
- Assessment of fog drip on precipitation;
- Time steps (daily vs. monthly vs. annual);
- Land use (urban vs. rural vs. agriculture); and
- Results based on CWRM formal aquifer system areas.

A second area that requires further investigation is the interaction between ground water and streamflow. In cases where a stream is hydraulically connected to an aquifer, well withdrawals from the aquifer may cause depletion in the base flow of the stream. This is a concern, as adequate stream flow must be maintained to support instream uses. CWRM must consider ground water/streamflow interactions in its evaluation of sustainable yield and in its review of well-permit applications. Also, numerical models must include the baseflow of streams as part of their calibration analysis.

A third area that requires further study is the salinity transport in the transition zone of basal aquifers. This transport is driven by ground water flow and solute dispersion. Additionally, the effects of bore hole flow in deep monitor wells can introduce complexity in salinity profiles. A recently developed field tracer method by a research team at the University of Hawaiʻi estimates the value of the dispersion coefficient of a basal aquifer by using the salinity profiles observed at deep monitoring wells. The success of this method depends on: how accurately the salinity profile is measured at a deep monitoring well; and how accurately the travel time to the monitoring well is determined. More accurate estimates of the dispersion coefficient can be achieved by establishing ground water monitoring well networks, and by mathematical simulations of the head and velocity distributions.

A fourth area that requires further study is impacts of reducing coastal leakage through pumping and how this might be factored in to sustainable yield estimates. Though §174C-4, HRS of the Water Code states nothing under the chapter of the Code shall apply to coastal waters, this is becoming an increasingly important issue raised through public comments received by CWRM through its processing of other Code responsibilities.

Fifth, more study on spatially detailed analysis of safe yield or well infrastructure along with water use and development plan scenarios is required. Though RAM has its idealized optimization assumptions and RAM2 is formulated by including salinity transport considerations, these models do not simulate the spatial variations of ground water flow and solute transport. Though more spatially detailed analysis can be achieved through monitoring of field data and, if sufficient data exists, numerical ground water models, these approaches must consider clearly defined future land development and pumpage scenarios. Before these comprehensive models can be applied, careful model calibration and verification must be conducted based on adequate field data to ensure that the comprehensive model is a viable management tool. Comprehensive local-scale models may be used for the design and operation of well fields where model parameters can be readily estimated based on sufficient hydrologic data and site-specific field aquifer tests.

Sixth, in the interest of responsible management and protection of water resources and environmental quality, CWRM should expand and improve its hydrologic monitoring network and water use reporting to achieve statewide coverage and to better assess sustainable yields based on actual data.

Lastly, CWRM should consider adaptive management concepts to link the preceding recommendations, which span both science and societal values. CWRM should explore how adaptive management concepts can be applied to the estimation of sustainable yields. CWRM's permit process applies adaptive management concepts and considers other factors, such as rights that affect individual well owners. However, the potential application and incorporation of adaptive management concepts in the estimation of aquifer sustainable yield has yet to be evaluated.

F.4.4 Establishment of the 1990 Sustainable Yield Estimates and Subsequent Updates

In 1980, the Honolulu BWS commissioned hydrologists at the University of Hawai‘i to develop a model to determine sustainable yields for ground water aquifers in Hawai‘i. The result was the analytical model known as RAM. Sustainable yield estimates derived via RAM reflect the maximum sustainable average-daily-pumpage rates over an entire aquifer system area, assuming wells are spaced optimally throughout the system. These RAM-derived sustainable yield estimates were incorporated into the 1990 WRPP. In cases where RAM-predicted sustainable yield did not correlate with actual observed conditions in an aquifer system area, CWRM evaluated irrigation practices, historical aquifer pumpage, and other data to refine the RAM estimate. This refined estimate was adopted by CWRM, rather than the strict RAM derived valued. A complete list of the 1990 sustainable yield estimates are presented in **Table F-10**.

In 1993, CWRM adopted an Aquifer System Area approach to organize and manage ground water resources. This superseded the previous method of managing aquifers by larger Sector area boundaries. The Aquifer System Area approach allows for better optimization of well placement and is a better indicator of where water is located within a Sector area. It is the simplest method for optimizing development of the island's ground water resources while ensuring long-term sustainability from the planning and regulatory perspective. As a result of the new management approach, some aquifer system areas were subdivided into multiple systems and others were consolidated into single systems. This resulted in significant changes in the distribution of sustainable yields amongst affected aquifer system areas. Identification of the aquifers systems that were affected and descriptions of the changes that took place are provided in Comment 6 of **Table F-10**.

In 1997, CWRM recognized and adopted the first caprock aquifer sector. The ‘Ewa Caprock Aquifer Sector includes three aquifer system areas. Because the ‘Ewa Caprock Aquifer System Areas overlie basal ground water bodies of other aquifer sectors and systems, and because the dynamics of ground water communication between the caprock and basal aquifers is unclear, CWRM established sustainable yields for the ‘Ewa Caprock Aquifer System Areas based on the chloride content of ground water in individual irrigation wells rather than on average-daily-pumping rates across the aquifer system area, as was done for the basal aquifers. A sustainable yield of 1,000mg/L chloride was adopted for all three ‘Ewa Caprock Aquifer System Areas (see **Table F-12**).

Revisions of individual aquifer system area sustainable yields have also occurred on a case-by-case basis in response to the availability of new data. Sustainable yield estimates have been revised based on recharge studies, ground water models, other hydrogeologic studies, pumpage and deep monitor well data, and the identification of errors in previous models or studies. All revisions to the sustainable yields have taken place in accordance with statutory requirements, and revised sustainable yield estimates adopted by CWRM are official and are used for regulatory and planning purposes.

F.4.4.1 Selection of the 2019 Sustainable Yields

CWRM re-evaluated all sustainable yields for ground water hydrologic units (aka aquifer system areas). The re-evaluation entailed the following steps:

1. Review of sustainable yield calculation models, recharge calculations, deep monitoring well data, historical pumping data, numerical models for predicting infrastructure safe yields, and other hydrogeologic data and studies;

2. Comparison of the previously adopted sustainable yields (those in effect as of August 28, 2008) against those predicted by other models; and

3. Identification of the most appropriate sustainable yield for each aquifer based on conclusions drawn from steps 1 and 2.

CWRM considered four sustainable yield data sets in its evaluation: RAM (1990), RAM (2008), RAM + Updated Recharge, and RAM2 + Updated Recharge. RAM 1990 is the original WRPP 1990 sustainable yield calculations. RAM (2008) is the recalculation of the corrected minimum RAM (2008) values from this 2019 review. The recalculation was conducted when errors were found in the original 1990 calculations. RAM + Updated Recharge consists of sustainable yield estimates resulting from the input of the latest updated recharge estimates into RAM since the 2008 revision and some D/I updates. RAM2 + Updated Recharge consists of sustainable yield estimates predicted by the RAM2 using the original and latest recharge estimates for those few areas with deep monitor well data.

Sustainable yield estimates by models other than RAM or RAM2 were available for some areas; however, because the areas modeled did not match the aquifer system area boundaries, the values could not practically be compared to existing sustainable yield values. Similar issues were encountered with some recharge studies. Therefore, these models and studies were eliminated from consideration. However, some recent recharge studies have been analyzed within CWRM's aquifer hydrologic unit (aquifer system area) approach. Those recharge studies that provided results within this approach are considered in this update.

The sustainable yields for the four data sets considered are listed in **Table F-10**. In addition to these four data sets, CWRM considered the Previously Adopted SY (2007) when the value originated from a CWRM action or a numerical ground water model study. The original uncorrected 1990 RAM sustainable yield numbers are no longer shown in the table for reference since they were not considered in the selection process and are now superseded by the RAM (2008) numbers, which correct known math errors in the original 1990 estimates. The comments in **Table F-10** also provide historical background on changes to aquifer system area boundaries and changes to sustainable yield values.

For a given aquifer system area, the range of sustainable yield estimates shown in **Table F-10** demonstrates that the estimation of aquifer sustainable yields is not an exact science. Insufficient hydrologic, geologic, and meteorological data require the estimation of critical input parameters in any sustainable yield model. Differences in estimates of these input parameters, and in how they are incorporated in a model, can produce a wide range in predicted sustainable yield values for a given aquifer.

Given the range of predicted sustainable yields for each aquifer, and the inherent uncertainty in each prediction, CWRM has applied the *precautionary principle* in selecting sustainable yields for adoption in this update to the WRPP. Application of the precautionary principle is appropriate in light of CWRM's role as a trustee of Hawai'i's water resources.

In general, the lowest predicted sustainable yield for an aquifer system area, as shown in **Table F-10**, was selected as the 2019 Sustainable Yield. Exceptions to this rule were recognized on a case-by-case basis and alternative sustainable yields were selected depending on the following:

For Aquifer Systems with predominantly basal resources:

- Presence of an operational deep monitor well and other publicly available hydrogeologic data, such as:
    - Recharge studies that follow the convention of **Section F.4.3.1**;
    - Complete and significant record of historical pumpage, chloride, and water-level data;
    - Numerical model studies for establishing infrastructure safe yields; or
    - Other hydrologic and geologic studies reviewed and accepted by CWRM staff.

- Ground water inputs from adjacent aquifers
- Post-1990 WRPP CWRM actions
- Errors in mathematical calculations
- Clerical errors.

For Aquifer Systems with predominantly high-level resources:

- Presence of an operational ground water-level monitoring network and a stream monitoring network, where applicable, to ensure compliance with instream flow standards, and other publicly available hydrogeologic data, such as:
    - Recharge studies that follow the convention of **Section F.4.3.1**;
    - Complete and significant record of historical pumpage, chloride, and water-level data;
    - Numerical model studies for establishing infrastructure safe yields; or
    - Other hydrologic and geologic studies reviewed and accepted by CWRM staff.
- Errors in mathematical calculations

For basal aquifer-dominated aquifer system areas, the existence of an operational deep monitor well is critical in determining the location and characteristics of the transition zone and provides an early warning system on the sustainability of the resource. In high-level aquifer dominated aquifer system areas, a robust operational ground water-level monitoring network provides more valuable information than deep monitor wells to assess the sustainability of the resource. In addition, in high-level aquifer systems where existing pumping wells have the potential to impact perennial stream flows, a stream monitoring network provides essential sustainability data.

When monitoring data (well and/or stream), coupled with other scientifically sound, public, and CWRM-vetted aquifer-specific hydrologic, geologic, or other studies strongly suggested that the lowest predicted sustainable yield in **Table F-10** underestimated the sustainable yield, then selection of an alternatively higher sustainable yield was justified. In cases where an alternate sustainable yield was selected, the basis for the selection is called out in **Table F-10** in the Alternate 2019 SY Selection Criteria column and additional information is provided in the table comments.

Table F-11 lists the 2019 sustainable yields for basal and high-level aquifers along with planning comments and aquifer notes. **Table F-12** lists the 2019 sustainable yields for caprock aquifers. Maps illustrating the ground water hydrologic unit boundaries and the 2019 sustainable yield for each aquifer system area are included as **Figure F-17** through **Figure F-22**.

Table F-10 Comparison of Predicted Sustainable Yields Considered by CWRM Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected [(1)]	RAM + Updated Information [(2)]	RAM 2 + Updated Information [(2)]	*SY Range (2019)* [(3)]	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
Hawaiʻi									
Kohala	Hāwī	27	13	11-29	~	*11-29*	13	**11**	~
Kohala	Waimanu	109	110	122-128	~	*110-128*	110	**110**	~
Kohala	Māhukona	16	17	10-11	~	*10-17*	17	**10**	*(29)*
E. Mauna Kea	Honokaʻa	31	31	29	~	*29-31*	31	**29**	~
E. Mauna Kea	Paʻauilo	59	60	56	~	*56-60*	60	**56**	~
E. Mauna Kea	Hakalau	150	150	166	~	*150-166*	150	**150**	~
E. Mauna Kea	Onomea	143	147	189	~	*147-189*	147	**147**	~
W. Mauna Kea	Waimea	23	24	16	~	*16-24*	24	**16**	*(29)*
NE. Mauna Loa	Hilo	349	349	379	~	*349-379*	349	**349**	~
NE. Mauna Loa	Keaʻau	395	395	429	~	*395-429*	395	**395**	~
SE. Mauna Loa	ʻŌlaʻa	124	125	211	~	*125-211*	125	**125**	~
SE. Mauna Loa	Kapāpala	19	19	53	~	*19-53*	19	**19**	~
SE. Mauna Loa	Nāʻālehu	117	118	213	~	*118-213*	118	**118**	~
SE. Mauna Loa	Ka Lae	31	31	48	~	*31-48*	31	**31**	~
SW. Mauna Loa	Manukā	42	25	83	~	*25-83*	25	**25**	~
SW. Mauna Loa	Kaʻapuna	50	51	54-97	~	*51-97*	51	**51**	~
SW. Mauna Loa	Kealakekua	38	38	54-88	~	*38-88*	38	**38**	~
NW. Mauna Loa	ʻAnaehoʻomalu	30	30	77	~	*30-77*	30	**30**	*(29)*
Kīlauea	Pāhoa	435	437	432	~	*432-437*	437	**432**	~
Kīlauea	Kalapana	157	158	234	~	*158-234*	158	**158**	~
Kīlauea	Hilina	9	9	35	~	*9-35*	9	**20**	*(27)*
Kīlauea	Keaīwa	17	17	45	~	*17-45*	17	**17**	~
Hualālai	Keauhou	38	38	80	~	38-80	38	**38**	~
Hualālai	Kīholo	18	18	40	~	18-40	18	**18**	~

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected (1)	RAM + Updated Information (2)	RAM 2 + Updated Information (2)	*SY Range (2019)* (3)	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
Kauaʻi									
Līhuʻe	Koloa	30	29	33	~	*29-33*	30	**29**	~
Līhuʻe	Hanamāʻulu	40	36	27	~	*27-40*	36	**27**	~
Līhuʻe	Wailua	60	43	51	~	*51-60*	43	**51**	*(28)*
Līhuʻe	Anahola	36	17	21	~	*21-36*	17	**21**	*(28)*
Līhuʻe	Kīlauea	17	5	10	~	*10-17*	5	**10**	*(28)*
Hanalei	Kalihiwai	16	22	16-22	~	*16-22*	11	**16**	*(28)*
Hanalei	Hanalei	35	34	35-47	~	*35-47*	34	**35**	*(28)*
Hanalei	Wainiha	24	24	82	~	*24-82*	24	**24**	~
Hanalei	Nāpali	20	17	28	~	*20-28*	17	**20**	*(28)*
Waimea	Kekaha	12	10	15	~	*10-15*	10	**10**	~
Waimea	Waimea	42	37	48	~	*37-48*	37	**37**	~
Waimea	Makaweli	30	26	43	~	*26-43*	26	**26**	~
Waimea	Hanapēpē	26	22	226	~	*22-26*	22	**22**	~
Lānaʻi									
Central	Windward	3(4)	3	5	~	*3-12*	3	**3**	~
Central	Leeward	3(4)	3	5	~	*3-6*	3	**3**	~
Mahana Sector	Hauola	~	~	3	~	~-3	0	~0	~
Mahana Sector	Maunalei	~	~	2	~	~-2	0	~0	~
Mahana Sector	Paoma	~	~	4	~	~-4	0	~0	~
Kaʻa	Honopū	~	~	4	~	~-4	0	~0	~
Kaʻa	Kaumalapau	~	~	2	~	~-2	0	~0	~
Kanao	Lealia	~	~	1	~	~-1	0	~0	~
Kanao	Manele	~	~	1	~	~-1	0	~0	~

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected *(1)*	RAM + Updated Information *(2)*	RAM 2 + Updated Information *(2)*	*SY Range (2019)* *(3)*	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
Maui									
Wailuku	Waikapu	2	3	6-8	~	*3-8*	3	**3**	~
Wailuku	Iao	20[5]	10	23-28	19-24	*10-28*	20	**20**[15]	*(9a-c, 11)*
Wailuku	Waihee	8	6	15-23	~	*6-23*	8	**8**[16]	*(9a, 9c)*
Wailuku	Kahakuloa	8	5	7-8	~	*5-8*	5	**5**	~
Lahaina	Honokōhau	10	9	14-17	~	*9-17*	9	**9**	~
Lahaina	Honolua	8	8	8-11	~	*8-11*	8	**8**	~
Lahaina	Honokowai	8	6	12-16	~	*6-16*	6	**6**	~
Lahaina	Launiupoko	8	7	13-18	~	*7-18*	7	**7**	~
Lahaina	Olowalu	3	2	6-7	~	*2-7*	2	**2**	~
Lahaina	Ukumehame	3	2	5-6	~	*2-6*	2	**2**	~
Central	Kahului	1	1	1-10	~	*1-10*	1	**1**[32]	~
Central	Paia	8	7	8-33	~	*7-33*	7	**7**[32]	~
Central	Makawao	7	7	20-25	~	*7-25*	7	**7**	~
Central	Kamaole	11	11	11-16	~	*11-16*	11	**11**	~
Koolau	Haiku	31	24	24-27	~	*24-31*	27	**24**	~
Koolau	Honopou	29	16	16-25	~	*16-29*	25	**16**	~
Koolau	Waikamoi	46	37	37-40	~	*37-46*	40	**37**	~
Koolau	Keanae	96	75	75-83	~	*75-96*	83	**75**	~
Hana	Kuhiwa	16	14	14-38	~	*14-38*	16	**14**	~
Hana	Kawaipapa	48	31	31-48	~	*31-48*	48	**31**	~

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected *(1)*	RAM + Updated Information *(2)*	RAM 2 + Updated Information *(2)*	*SY Range (2019)* *(3)*	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
Maui (continued)									
Hana	Waihoi	20	18	18-24	~	*18-24*	18	**18**	~
Hana	Kipahulu	49	15	15-57	~	*15-57*	42	**15**	~
Kahikinui	Kaupo	18	16	13-17	~	*13-17*	16	**13**	~
Kahikinui	Nakula	7	7	7-15	~	*7-15*	7	**7**	~
Kahikinui	Lualailua	11	11	11	~	*11-15*	11	**11**	~
Molokai									
West	Kaluakoi	2	2	2-4	~	*2-4*	2	**2**	~
West	Punakou	2	2	3	~	*2-3*	2	**2**	~
Central	Hoolehua	2	2	2	~	*2*	2	**2**	~
Central	Pala'au	2	2	3	~	*2-3*	2	**2**	~
Central	Kualapuu	7	4	5-8	5-6	*5-8*	5 [(6)]	**5** [(17)]	*(9a, 9c-d, 10)*
Southeast	Kamiloloa	3	3	5	~	*3-5*	3	**3**	~
Southeast	Kawela	5	5	10	~	*5-10*	5	**5**	~
Southeast	Ualapue	8	8	8-11	~	*8-11*	8	**8**	~
Southeast	Waialua	8	6	6-8	~	*6-8*	6	**6**	~
Northeast	Kalaupapa	2	2	4	~	*2-4*	2	**2**	~
Northeast	Kahanui	3	3	9	~	*3-9*	3	**3**	~
Northeast	Waikolu	5	5	8	~	*5-8*	5	**5**	~
Northeast	Haupu	2	2	5-6	~	*2-6*	2	**2**	~
Northeast	Pelekunu	9	9	12-14	~	*9-14*	9	**9**	~
Northeast	Wailau	15	15	29	~	*15-29*	15	**15**	~
Northeast	Halawa	8	8	11	~	*8-11*	8	**8**	~

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected (1)	RAM + Updated Information (2)	RAM 2 + Updated Information (2)	*SY Range (2019)* (3)	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
O‘ahu									
Honolulu	Pālolo	5	4	4-8	5-6	4-8	5	**5**	(33)
Honolulu	Nu‘uanu	15	14	12-19	12-14	12-19	14	**14**	(31)
Honolulu	Kalihi	9	9	7-13	7-9	7-13	9	**9**	(31)
Honolulu	Moanalua	18	17	13-25	13-17	13-25	16	**16**	(31)
Honolulu	Waialae(7a)	3	3	~	~	~	~	~	~
Honolulu	Waialae-West(7a)	~	4	2-3	~	2-3	4(7a)	**2.5**(19)	~
Honolulu	Waialae-East(7a)	~	2	4-10	~	2-10	2(7a)	**2**(18)	~
Pearl Harbor	Waimalu	45	47(20)	42-84	48-50	42-84	45	**45**(20)	*(9a-c)*
Pearl Harbor	Waiawa(7c)	52	See Waipahu-Waiawa	~	~	~	~	~	~
Pearl Harbor	Waipahu(7c)	50	See Waipahu-Waiawa	~	~	~	~	~	~
Pearl Harbor	Waipahu-Waiawa(7c)	~	107	105-180	105-110	105-180	104(8)	**105**(21)	
Pearl Harbor	‘Ewa(7d)	3	See ‘Ewa-Kunia	~	~	~	~	~	~
Pearl Harbor	Kunia(7d)	8	See ‘Ewa-Kunia	~	~	~	~	~	~
Pearl Harbor	‘Ewa-Kunia(7d)	~	10	15-20	15-19	*15-20*	16(8)	**16**(22)	*(9a-d, 10, 11)*
Pearl Harbor	Makaīwa(7e)	~	0	<1	~	*<1*	0	**~**	~
Central	Wahiawā (7b)	104	23	141	~	*23-141*	23(7b)	**23**(23)	*(11)*

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Aquifer Sector	Aquifer System	RAM (1990)	RAM (2008) corrected *(1)*	RAM + Updated Information *(2)*	RAM 2 + Updated Information *(2)*	*SY Range (2019)* *(3)*	Previously Adopted SY (2008)	Sustainable Yield (2019)	Alternate 2019 SY Selection Criteria
Oʻahu (continued)									
Waiʻanae	Nānākuli	1	1	1	~	*1-2*	2	1	~
Waiʻanae	Lualualei	4	3	4-9	~	*3-9*	4	3	~
Waiʻanae	Waiʻanae	2	2	3-4	~	*2-4*	3	**3**(24)	*(14a-b,d)*
Waiʻanae	Mākaha	3	3	4-6	~	*3-6*	3	**3**	~
Waiʻanae	Keaʻau	4	4	3-7	~	*3-7*	4	**3**	~
North	Mokulēʻia	9	8	17-29	~	*8-29*	8	**17***(30)*	*(10)*
North	Waialua	5	4	17-30	~	*4-30*	25(7b)	**17(25)**	(10)
North	Kawailoa	32	29	22-40	~	*22-40*	29	**22**	~
Windward	Koʻolauloa	42	36	35-41	~	*35-41*	36	**35**	~
Windward	Kahana	15	15	21-23	~	*15-23*	15	**15**	~
Windward	Koʻolaupoko	30	30	28-46	~	*28-46*	30	**28**	~
Windward	Waimānalo	13	10	9-25	~	*9-25*	10	**9**	~
Waiāhole(26)	Waiāhole(26)	~	15	15	~	*15*	~	**15(26)**	~

Notes:

~	Not Calculated
CWRM	Commission on Water Resource Management
RAM	Robust Analytical Model
SY	Sustainable Yield
WRPP	Water Resources Protection Plan

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

General Comments & Historical Background on Changes to Aquifer System Boundaries and Sustainable Yield Values
(1) Corrected minimum for 2008 WRPP SY based on 2017 review of RAM D/I, recharge that should have been used in 2008, or mathematical errors)
(2) RAM or RAM 2 methodology using updated best information available for recharge estimates. In cases where multiple valid studies were published ranges of SY are shown.
(3) 2019 SY Range - The bounds of the sustainable yield range were set based on the minimum and maximum estimates resulting from the comparison between the green columns: corrected RAM 2008, RAM + Updated best available Information, and RAM 2 + Updated best available Information.
(4) The Sustainable Yield values for the Windward and Leeward Aquifer System Areas were calculated in 1990 but were accidentally omitted from the Water Resources Protection Plan.
(5) The 20 MGD sustainable yield number is based on a higher recharge value than that reported in the 1990 WRPP. This higher recharge value, along with a slightly modified version of the RAM equation into which it was input, were believed by John F. Mink (developer of the RAM) to more accurately reflect conditions in the Iao Aquifer System Area based on historical behavior. *Reference: Mink, John.F, 1995, Sustainable Yields Maui and Molokai, Letter to the CWRM from Mink & Yuen Inc., dated September 9, 1995.*
(6) In 1993, a mathematical error was discovered in the calculation of the 1990 sustainable yield for the Kualapuu Aquifer System Area. A recalculation of the sutainable yield by John F. Mink in 1995 resulted in a revised recommendation of 5 MGD for the sustainable yield. This number was based on (1) revised estiamtes for direct runoff and evapotranspiration, (2) a modified RAM calculation for sustainable yield, and (3) the presumption of additional recharge to the system from Waikolu Valley. *Reference: Mink, John.F, 1995, Sustainable Yields Maui and Molokai, Letter to the CWRM from Mink & Yuen Inc., dated September 9, 1995.*
(7) In 1993, CWRM adopted an aquifer system areas approach to managing ground water resources in Hawai‘i. This approach is considered the best method for optimizing development of an aquifer while ensuring long-term stability of the water resource. As a result, some aquifer system areas were divided into multiple systems, some aquifer system areas were consolidated into a single system, and new aquifer system areas were created. In addition, revised sustainable yields were proposed for several systems. Specific changes in aquifer system area management and sustainable yields are discussed below: (a) The Waialae Aquifer System Area was subdivided into two separate aquifer system areas due to the presence of a hydrologic boundary at Waialae Iki Ridge. This boundary results in a siginificant hydrologic head difference between the Waialae East and Waialae West Aquifer System Areas. In 2008 the 6 MGD sustainable yield for the original combined aquifer system was redistributed, based on the best available hydrogeologic information, with two-thirds (4MGD) going to Waialae West and one-third (2MGD) going to Waialae East. Subsequent recharge by Engott 2015 updated recharge with lower estimates.

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

General Comments & Historical Background on Changes to Aquifer System Boundaries and Sustainable Yield Values (cont.)
(7) (b)The Central Aquifer Sector (Wahiawa Aquifer System Area) was separated out from the Pearl Harbor and North Aquifer Sector Areas because the water is high-level rather than basal. The 1993 exisiting pumpage from the system, which totalled 23 MGD, was set as the sustainable yield to maintain spillover of ground water into the Pearl Harbor and North Sectors, thus ensuring sufficient ground water availability in these Sectors to meet demand. The spillover was calculated differently in the 2008 WRPP but has been updated in the 2019 WRPP the following way: • Reviewed all latest recharge updates and used the lowest Waihiawa ASA recharge (Engott 2015 (corrected) - 129.07 MGD). • Subtract the Adjusted Recharge related to the 23 MGD SY (30.67 MGD) from the 129.07 MGD to determine Total Spillover Amount (98.4 MGD) available. • Then split the Total Spillover Amount in half (49.2 MGD), assigning one-half to Pearl Harbor (Waipahu-Waiawa and Ewa-Kunia Aquifer Systems) and one-half to the North (Mokuleia, Waialua, and Kawailoa Aquifer Systems). • For the Pearl Harbor Aquifer Sector Area half of the Total Spillover Amount, assign 85% to the Waipahu-Waiawa Aquifer System Area and 15% to the Ewa-Kunia Aquifer System Area based on the length of their borders with the Wahiawa Aquifer System Area. • For the North Aquifer SectorArea half of the Total Spillover Amount assigns 33% to the Mokuleia Aquifer System Area, 45% to the Waialua Aquifer System Area and 22% to the Kawailoa Aquifer System Area based on the length of their borders with the Wahiawa Aquifer System Area. • Then for all the affected Aquifer System Areas, add the Spillover Amount assigned to each Aquifer System Area Recharge provided in each respective study Using the Revised Recharge multiplied by the D/I for each Aquifer System Area provides the Revised Sustainable Yields. (c) The Waipahu and Waiawa Aquifer System Areas were combined to allow for more flexibility in pumping. The original subdivision of the aquifer system area was not based on hydrogeologic properties. The combined Waipahu-Waiawa Aquifer System Area was assigned the aquifer code (30203). In addition, the sustainable yield for the combined aquifer system area was raised for two reasons. (1) To account for 62 MGD of additional recharge via ground water spillover from the Wahiawa Aquifer System Area (see comment 6b above) and (2) because historic pumping above the 1990 sustainable yields did not adversely affect properly installed wells, indicating that the true sustainable yield of the aquifer system area was greater than that predicted by the RAM. (d) The ‘Ewa & Kunia Aquifer System Areas were combined to manage the aquifer as a whole. The original division of the aquifer was based on the irrigation source (well water versus ditch water) and not hydrologeologic properties. The combined ‘Ewa-Kunia Aquifer System Area was assigned the aquifer code (30204). In addition, the sustainable yield for the combined aquifer system area was raised to account for 14 MGD of additional recharge via ground water spillover from the Wahiawa Aquifer System Area (see comment 6b above).

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

General Comments & Historical Background on Changes to Aquifer System Boundaries and Sustainable Yield Values (cont.)
(e) The Makaiwa Aquifer System Area was separated out from the Waianae Aquifer System Area due to a difference in ground water behavior in the two aquifer systems. No sustainable yield was established for this system. The Makaiwa Aquifer System Area was assigned the aquifer code (30205), which was previously assigned to the Kunia Aquifer System Area
(8) Sustainable Yield adopted by CWRM in 2000 was based on a review of three ground water models: RAM (analytical), RASA (numerical), CENCOR (numerical). The impetus for the reassessment of the sustainable yields was the demise of large-scale agriculture in the area and the resultant loss of significant volumes of return irrigation recharge to the aquifer systems. The three models assumed significant ground water spillover was occuring from the Central Sector into the Pearl Harbor Sector and reflected various pumping scenarios designed to protect existing infrastructure. The sustainable yield values calculated by the models provided a range of sustainable yield estimates for the ‘Ewa-Kunia and Waipahu-Waiawa Aquifer System Areas *Reference: Hawai‘i Department of Land and Natural Resources - Commission on Water Resource Management, 2000, Commission Meeting Submittal - Request for Approval to Adopt New Sustainable Yields for ‘Ewa-Kunia and Waipahu-Waiawa Aquifer Systems, Pearl Harbor Aquifer Sector, O‘ahu, dated March 15, 2000*.

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Alternate Sustainable Yield Selection Criteria
In general, the lowest predicted sustainable yield for an aquifer system area was selected as the 2008 Sustainable Yield. Exceptions to this rule were recognized on a case-by-case basis and alternative sustainable yields were selected based on the following: Basal Ground Water Source (9) - Presence of an operational deep monitor well AND other publicly available hydrogeologic data, such as: 9a - Recharge studies that follow the convention of **Section F.4.3.1** of the WRPP; 9b - Complete and significant record of historical pumpage, chloride, and water-level data; 9c - Numerical model studies for establishing infrastructure safe yields; 9d - Other hydrologic and geologic studies reviewed and accepted by CWRM Staff; or (10) - Ground water inputs from adjacent aquifers; (11) - Post 1990 WRPP CWRM actions; (12) - Errors in mathematical calculations; or (13) – Clerical errors. **High-Level Ground Water Source** (14) - Presence of an operational ground water-level monitoring network and a stream monitoring network, where applicable, to ensure compliance with instream flow standards, AND other publicly available hydrogeologic data, such as: 14a - Recharge studies that follow the convention of **Section F.4.3.1** of the WRPP; 14b - Complete and significant record of historical pumpage, chloride, and water-level data; 14c - Numerical model studies for establishing infrastructure safe yields; 14d - Other hydrologic and geologic studies reviewed and accepted by CWRM Staff

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Sustainable Yield (2019) Comments
(15) The sustainable yield for the Iao Aquifer System Area was maintained at 20 MGD as this is believed to be the best estimate to date. This 1995 estimate (see comment 5 above) falls within the range of updated predicted sustainable yields for the system. In addition, numerical models, deep monitor well data, and historical pumpage records all suggest a sustainable yield within the middle of the predicted range. *Reference: Hawai'i Department of Land and Natural Resources - Commission on Water Resource Management, 2002, Waihee Aquifer Systems State Aquifer Codes 60102 and 60103 Ground-Water Management Area Designation Findings of Fact, dated November 11, 2002.*
(16) RAM (2008) revealed an error in the calculation of the original RAM (1990) sustainable yield for the Waihee Aquifer System Area. The 1990 value is 8 MGD. The correct value is 6 MGD. However, based on (1) current ground water demands within the system, (2) the fact that the 8 MGD falls within the predicted range of sustainable yields for the aquifer system, and (3) the presence of a deep monitor well within the system that will allow for long-term monitoring of the transition zone, CWRM elected to maintain the sustainable yield at 8 MGD. Reference: Hawai'i Department of Land and Natural Resources - Commission on Water Resource Management, 2002, Waihee Aquifer Systems State Aquifer Codes 60102 and 60103 Ground-Water Management Area Designation Findings of Fact, dated November 11, 2002. Also, the Maui Department of Water Supply use of their numerical ground water model for the Iao area continues to provide a management tool where CWRM can continue to maintain the sustainable yield at 8 MGD.
(17) The Previously Adopted SY (2007) for the Kualapuu Aquifer System Area dates to a 1996 recalculation of sustainable yield based on a revised recharge number and modified RAM calculation (see comment 5 above). Based on (1) current ground water demands within the system, (2) the fact that the 5 MGD falls within the predicted range of sustainable yields for the aquifer system, (3) the presence of a deep monitor well within the system that will allow for long-term monitoring of the transition zone, and (4) the existence of ground water models for the system, CWRM elected to maintain the sustainable yield at 5 MGD.
(18) Updated recharge data and 2017 review of D/I ratio estimated the ratio as too high suggest a sustainable yield of the Waialae East Aquifer System Area is lower than the Previously Adopted SY (2008).
(19) Updated recharge data suggest that the sustainable yield of the Waialae West Aquifer System Area may be higher than the Previously Adopted SY (2008). However, 2017 review of D/I ratio estimated the ratio as too high and in the absence of a deep monitor well or ground water model, CWRM elected to maintain the sustainable yield at the more conservative number. See comment 7a above. Upon its July 16, 2019 adoption of the updated WRPP, the Commission amended the sustainable yield for Wai'alae-West from 3 to 2.5 mgd, conditioned on the Honolulu Board of Water Supply providing: 1) 100% compliance with their water use reporting requirement (i.e., monthly reporting of water levels, chlorides, and pumpages); and 2) Installation of a new deep monitor well in the Wai'alae-West Aquifer System Area.
(20) RAM (2008) revealed an error in the calculation of the original RAM (1990) sustainable yield for the Waimalu Aquifer System Area. The 1990 value is 45. The correct value is 47 MGD. However, due to exisiting salinity issues in wells in this aquifer system, CWRM elected to maintain the sustainable yield at 45 MGD. A higher sustainable yield may be possible if well placement and pumping are optimized. Waimalu Deep monitor well indicates aquifer is at equilibrium. Red Hill issue suggests keeping status quo for now while at the conclusion of Red Hill review CWRM staff considering moving boundary with Moanalua Aquifer System Area.
(21) The 2019 sustainable yield for the Waipahu-Waiawa Aquifer System Area was calculated using RAM and updated recharges and RAM2 D/I ratio rather than recalibrating the outdated numerical models. Also, see comment 7b above.

(22) The 2019 sustainable yield for the ‘Ewa-Kunia Aquifer System Area was maintained at 16 MGD as this is believed to be the best estimate to date based on historical behavior (See comments 9,10, & 11 above). Also, see comment 7b above.
(23) The sustainable yield for the Wahaiwa Aquifer System Area was held at 23 MGD to ensure sufficient ground water spillover into the Pearl Harbor and North Sectors to meet demands. Also, see Comment 7b above.

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

Sustainable Yield (2019) Comments (continued)
(24) RAM (2008) revealed an error in the calculation of the original RAM (1990) sustainable yield for the Waianae Aquifer System Area. The 1990 value originally was 3 MGD. The 2008 WRPP corrected the original value to 2 MGD. However, based on (1) current ground water demands within the system, (2) the fact that the 3 MGD falls within the predicted range of sustainable yields for the aquifer system area, (3) the presence of a ground water monitoring network, and (4) a complete and significant record of historical pumpage, chloride, and water-level data, CWRM elected to maintain the sustainable yield at 3 MGD. The importation of water into the area from the Pearl Harbor Aquifer Sector Area provides additional input into the area.
(25) The 2019 sustainable yield for Wailua Aquifer System Area was derived by assuming that 45% of the reserved recharge from the Central Sector Area spills over into the Waialua Aquifer System Area (see comment 7b above). Forty-five percent (45%) of the Pearl Harbor half of Wahiawa ASA spillover recharge was added to the recharge for the Wailua Aquifer System Area and the resulting total recharge value was used for RAM, resulting in the lowerst predicted sustainable yield of 17 MGD.
(26) From Waiahole contested case hearing CCH-OA95-1. Water available for leeward distribution from Waiahole Ditch System (not a true aquifer system area); otherwise, unused portions remain in windward streams.
(27) Based on Mink's qualification of "unreliable" and over 100% change in precipation from 2011 Giambelucca compared to 1990 Mink, the 2008 sustainable yield of 9 was multiplied by 2.25, which is the ratio between the 1990 Mink and the 2011 Giambelluca rainfall data to update the sustainable yield to 20, D/I = 0.44. SY Range 9 (1990 WRPP) - 35 (Engott, 2011) MGD.
(28) SWAP (2008) previously defined minimum of 43 MGD but used the recharge numbers from Shade, 1995 which has been superseded by Izuka & Others, 2015 and is no longer a valid minimum for two main reasons: 1. There was a large overestimation of baseflow that overestimated runoff and underestimated recharge in Shade '95. 2. Recharge in the Shade's old report was based on 1981 and 1998 land-use conditions (Līhu'e Plantation was still open). The estimates in the new report (in the "recent" data set) are for 2010 land use conditions, after the sugar plantations closed and there was a large overestimation of baseflow.
(29) Staff is considering amending the boundaries of the Māhukona, Waimea, and Anaehoomalu Aquifer System Areas based on observed behavior of existing wells within those areas. Changes in boundary conditions amongst these areas will affect and change recharge analysis and quantities; therefore, the SY estimates in this version of the plan are preliminary until further confirmation.
(30) The 2019 sustainable yield for the Mokuleia Aquifer System Area was derived by assuming that 33% of the reserved recharge from the Central Sector Area spills over into the Waialua Aquifer System Area (see comment 7b above). Thirty-three percent (33%) of the North half the Waihiawa ASA recharge spill over was added to the recharge for the Mokuleia Aquifer System Area and the resulting total recharge value was used for RAM, resulting in the lowerst predicted sustainable yield of 17 MGD.
(31) Though the latest recharge estimates from Engott 2015 and changes in D/I ratios from RAM2 created new minimums in the Nuuanu, Kalihi, and Moanalua Aquifer System Areas, and an increase in the Waimalu Aquifer System Area, the sustainable yields will remain the unchanged based on historical pumpage, observation wells & data, and numerical model(s) availability for more analysis. CWRM staff is reviewing BWS monitoring well data and attempting to gather new observation well data away from pumpage sites to further assess the sustainable yields. Also, the shared boundary between the Moanalua & Waimalu Aquifer System Areas may be adjusted as more is learned from the Red Hill Tank investigations, which will affect their areas and, in turn, sustainable yield calculations.

(32) Represents sustainable yield under natural conditions, which ignores significant return irrigation recharge from East Maui. Kahului receives additional return irrigation recharge from Na Wai Eha diversions that is ignored. Upper range of sustainable yields are more likely for current situation.
(33) Lowest minimum of 4 is due to D/I adjustments from RAM2 and resulting rounding to 4 mgd. However, CWRM staff elected to keep the current minimum at 5 mgd while it reviews BWS monitoring well data and attempting to gather new observation well data away from pumpage sites to further assess the sustainable yields.

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

References	
RAM (1990)	Sustainable Yield Values calculated using the 1990 Robust Analytical Model (RAM). *Source: Hawai'i Department of Land and Natural Resources - Commission on Water Resource Management, 1990, Water Resources Protection Plan, 127pp.*
RAM (2008)	Sustainable Yield Values recalculated by CWRM in 2008 using the 1990 Robust Analytical Model (RAM) and reported original input values. SY values were recalculated after mathematical errors were discovered in calculations for some aquifer systems. RAM (2008) values supercede RAM (1990) values.
RAM + Updated Information	Sustainable Yield Values calculated by inputting updated information from revised RAM D/I values, recharge area corrections to exclude caprock, recharge estimates based on published studies and values into the 1990 Robust Analytical Model. Sources of the update recharge values are provided below by island:
RAM2 + Updated Information	Sustainable Yield Values calculated by inputting updated information from revised RAM D/I values, recharge area corrections to exclude caprock, recharge estimates based on published studies and values into the 2007 Robust Analytical Model 2. Sources of the update recharge values are provided below by island:

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

References	
Hawai'i	*Izuka, S., Engott, J., Bassiouni, M., Johnson, A., Miller, L., Rotzoll, K., and Mair, A, 2016, Volcanic Aquifers of Hawaii - Hydrogeology, Water budgets, and conceptual models, Scientific Investigations Report 2015-5164, 158pp*
	Engott, John, 2014, Special scenario based on 2011: A Water-Budget Model and Assessment of Groundwater Recharge for the Island of Hawai, U.S. Geological Survey Water-Resources Investigation Report 2011-5078, 68pp.
	Engott, John, 2011, A Water-Budget Model and Assessment of Groundwater Recharge for the Island of Hawai, U.S. Geological Survey Water-Resources Investigation Report 2011-5078, 68pp.
	Oki, D.S., 2002, Reassessment of ground-water recharge and Simulated ground-water availability for the Hawi Area of North Kohala, Hawai'i: U.S. Geological Survey Water-Resources Investigations Report 02-4006, 62pp. (Hawi)
	Oki, D.S., 1999, Geohydrology and numerical simulation of the ground-water flow system of Kona, Island of Hawai'i: U.S. Geological Survey Water-Resources Investigations Report 99-4073, 70pp. (Manuka, Kaapuna, Kealakekua, Keauhou)
	Shade, P.J., 1995, Water Budget for the Kohala Area, Island of Hawaii, Prepared in cooperation with the County of Hawaii Department of Water Supply, U.S. Geological Survey, Water-Resources Investigations Report 95-4114, 24pp.
	Izuka, S., Engott, J., Bassiouni, M., Johnson, A., Miller, L., Rotzoll, K., and Mair, A, 2016, Volcanic Aquifers of Hawaii - Hydrogeology, Water budgets, and conceptual models, Scientific Investigations Report 2015-5164, 158pp (as corrected in print)

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

References	
Kaua'i	*Izuka, S., 2006, Effects of Irrigation, Drought, and Ground-Water Withdrawals on Ground-Water Levels in the Southern Līhu'e Basin, Kauai, Prepared in cooperation with the County of Kauai Department of Water U.S. Geological Survey Water-Resources Scientific Investigations Report 2006-5291, 52pp.*
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	Izuka, Oki, and Chen, 2005, Effects of Irrigation and Rainfall Reduction on Ground-Water Recharge in the Līhu'e Basin, Kauai, Hawaii.U.S. Prepared in cooperation with the County of Kauai Department of Water U.S. Geological Survey Water-Resources Scientific Investigations Report 2005-5146. 57pp.
	Izuka, Gingerich, 1998, Ground Water in The Southern Līhu'e Basin, Kauai, Hawaii, Prepared in cooperation with the County of Kauai Department of Water U.S. Geological Survey Water-Resources Scientific Investigations Report 98-4031. 76pp.
	Shade, P.J., 1995, Water Budget for the Island of Kauai, Hawai'i: U.S. Geological Survey Water-Resources Investigations Report 95-4128, 25pp.
Lanai	*Hardy, W.R., 1996, A numerical ground-water model for the Island of Lanai, Hawai'i: Commission on Water Resource Management, Department of Land and Natural Resources, State of Hawai'i, 126pp.*
	Mink, John, 1983, Lanai Water Supply, 62 pp.

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

References	
Maui	*Izuka, S., Engott, J., Bassiouni, M., Johnson, A., Miller, L., Rotzoll, K., and Mair, A, 2016, Volcanic Aquifers of Hawaii - Hydrogeology, Water budgets, and conceptual models, Scientific Investigations Report 2015-5164, 158pp (as corrected in print)*
	Engott, J.A., Johnson 2014, Spatially Distributed Groundwater Recharge Estimated Using a Water-Budget Model for the Island of Maui, Hawaii, 1978-2007, Prepared in cooperation with the County of Maui Department of Water Supply and the State Commission on Water Resource Management, U.S. Geological Survey Water-Resources Scientific Investigations Report 2014-5168. 53pp. (as corrected in print)
	Gingerich, S.B., Engott, J.A.,2012, Groundwater Availability in the Lahaina District, West Maui, Hawaii: Prepared in cooperation with the County of Maui Department of Water Supply, U.S. Geological Survey Scientific Investigations Report 2012-5010, 104pp.
	Engott, J.A., 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in Central and West Maui, Hawai'i, 1926-2004: Prepared in cooperation with the County of Maui Department of Water Supply, U.S. Geological Survey Scientific Investigations Report 2007-5103, 69pp. (Scenario 'C' Waikapu through Ukumehame; Scenario 'D' Kahului through Kamaole)
	Shade, P.J., 1999, Water budget of East Maui, Hawai'i: U.S. Geological Survey Water-Resources Investigations Report 97-4159, 36pp. (Haiku through Lualailua)
	Shade, P.J., 1997, Water Budget for The Iao Area, Island Of Maui, Hawaii, Prepared in cooperation with the County of Maui Department of Water Supply, U.S. Geologic Survey Water-Resources Investigations Report 97-4244, 29pp
Moloka'i	*Shade, P.J., 1997, Water budget for the Island of Molokai, Hawai'i: U.S. Geologic Survey Water-Resources Investigations Report 97-4155, 20pp.*

Table F-10 (continued)
Comparison of Predicted Sustainable Yields Considered by CWRM
Sustainable Yield (SY) in Million Gallons Per Day (MGD)

References	
O'ahu	*Izuka, S., Engott, J., Bassiouni, M., Johnson, A., Miller, L., Rotzoll, K., and Mair, A, 2016, Volcanic Aquifers of Hawaii - Hydrogeology, Water budgets, and conceptual models, Scientific Investigations Report 2015-5164, 158pp (as corrected in print)*
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	Rotzoll, K. and A.I. El-Kadi, 2007, Numerical Ground-Water Flow Simulation for Red Hill Fuel Storage Facilities, NAVFAC Pacific, Oahu,
	Todd Engineeers, 2005, Development of a Groundwater Management Model, Honolulu Area of the Southern Oahu Groundwater system,
	Shade, P.J., and W.D. Nichols, 1996, Water budget and the effects of land-use changes on ground-water recharge, Oahu, Hawai'i: U.S. Geological Survey Professional Paper 1412-C, 38pp.
	Mink & Yuen Inc., 1998 A Study on The Sustainable Yield of The Ewa-Kunia Aquifer System, prepared for Campbel Estate, 49 pp.
	Mink & Yuen Inc., 1998, A Study on The Pearl Harbor Aquifer System, Waipahu-Waiawa And Waimalu, 54 pp.
	George Yuen & Associates (Mink, J.), 1988, Review and Re-Evaluation of Groundwater Conditions in The Pearl Harbor Groundwater
	Mink, J.F., 1980, State of The Groundwater Resources of Southern Oahu, 83 pp.
RAM 2	Sustainable Yield values calculated using the Robust Analytical Model 2. Sources by Aquifer System are provided below: *Liu, C.C.K., 2006, Analytical Groundwater Flow and Transport Modeling for the Estimation of the Sustainable Yield of Pearl Harbor Aquifer: University of Hawai'i Water Resources Research Center, Project Report PR-2006-06, 53pp. (Waimalu, Waipahu-Waiawa, 'Ewa-Kunia)*
	Liu, C.C.K., 2007, RAM2 Modeling and the Determination of Sustainable Yields of Hawai'i Basal Aquifers: University of Hawai'i Water Resources Research Center, Project Report PR-2008-06, 81pp. (Maui-Iao, Molokai-Kualapuu; Oahu-Palolo, Nuuanu, Kalihi, Moanalua)

Table F-11 Aquifer Notes

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Kohala	Hāwī	80101	**11**	The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water. This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.
Kohala	Waimanu	80102	**110**	This Aquifer System contains ground water as basal, perched, and high level, with no reported ground water use.
Kohala	Māhukona	80103	**10**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the high level followed by basal zone. Staff is considering amending the boundary between Waimea and Māhukona Aquifer System Areas based on observed behavior of existing wells within those areas. Changes in boundary conditions amongst these areas will affect and change recharge analysis and quantities; therefore, the SY estimates in this version of the plan are preliminary until further confirmation.
E. Mauna Kea	Honokaʻa	80201	**29**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the high level, followed by basal zone, and with lesser amounts removed from perched.
E. Mauna Kea	Paʻauilo	80202	**56**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.
E. Mauna Kea	Hakalau	80203	**150**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the basal zone, followed by perched.
E. Mauna Kea	Onomea	80204	**147**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
W. Mauna Kea	Waimea	80301	**16**	This Aquifer System contains ground water as basal and high level; with the majority reported ground water is pumped from the basal zone, followed by high level. Staff is also considering amending the boundaries between Waimea and Māhukona/Anaehoomalu Aquifer System Areas based on observed behavior of existing wells within those areas. Changes in boundary conditions amongst these areas will affect and change recharge analysis and quantities; therefore, the SY estimates in this version of the plan are preliminary until further confirmation.
NE. Mauna Loa	Hilo	80401	**349**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the basal zone, followed by perched, and with lesser amounts removed from high level.
NE. Mauna Loa	Keaʻau	80402	**395**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the basal zone, followed by perched, and with lesser amounts removed from high level.
SE. Mauna Loa	ʻŌlaʻa	80501	**125**	This Aquifer System contains ground water as predominantly high-level ground water with some perched, with no reported ground water use.
SE. Mauna Loa	Kapāpala	80502	**19**	This Aquifer System contains ground water as predominantly high-level ground water, with some perched. There are no wells located in this Aquifer System.
SE. Mauna Loa	Nāʻālehu	80503	**118**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water is pumped from the basal zone, followed by high level.
SE. Mauna Loa	Ka Lae	80504	**31**	This Aquifer System contains ground water as predominantly basal, with no reported ground water use.
SW. Mauna Loa	Manukā	80601	**25**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone.
SW. Mauna Loa	Kaʻapuna	80602	**51**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
SW. Mauna Loa	Kealakekua	80603	**38**	This Aquifer System contains ground water as basal and high level. The majority reported ground water is pumped from the high level, followed by basal zone.
NW. Mauna Loa	Anaehoomalu	80701	**30**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone. Assumes all recharge discharges at the coast between Anaehoomalu and Puako. Possible significant underflow of ground water out of Anaehoomalu into adjacent aquifer system areas was not accounted for in the recharge estimate used to calculate the sustainable yield. Accounting for such underflows may yield a much lower sustainable yield for Anaehoomalu. Staff is also considering amending the boundary between Waimea and Anaehoomalu Aquifer System Areas based on observed behavior of existing wells within those areas. Changes in boundary conditions amongst these areas will affect and change recharge analysis and quantities; therefore, the SY estimates in this version of the plan are preliminary until further confirmation.
Kīlauea	Pahoa	80801	**432**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.
Kīlauea	Kalapana	80802	**158**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone.
Kīlauea	Hilina	80803	**20**	This Aquifer System contains ground water as basal and high level, with no reported ground water use.
Kīlauea	Keaiwa	80804	**17**	This Aquifer System contains ground water as predominantly high-level ground water, with some basal All reported ground water use is pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Hualalai	Keauhou	80901	**38**	This Aquifer System contains ground water as basal and high level. The majority reported ground water is pumped from the basal zone, followed by high level. Ongoing and future studies to determine the extent of connection between significant high-level, thin basal, and deep confined freshwater aquifers and impact of ground water pumpage on nearshore ecosystems
Hualalai	Kīholo	80902	**18**	This Aquifer System contains ground water as basal and high level. The majority reported ground water is pumped from the basal zone, followed a minor amount from the high level. Thin basal resources are sensitive to chlorides, while the high-level resrouce is limited
Līhuʻe	Koloa	20101	**29**	This Aquifer System contains ground water as basal, perched and high level, with the majority of reported ground water pumped from the perched zone. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.
Līhuʻe	Hanamāʻulu	20102	**27**	This Aquifer System contains ground water as basal, perched and high level. The majority reported ground water is pumped from the perched zone followed by the basal, and with little to no ground water removed from high level. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Līhuʻe	Wailua	20103	**51**	This Aquifer System contains ground water as basal, perched and high level. The majority reported ground water is pumped from the basal zone followed by high level, and with lesser amounts removed from perched. (1) Predominantly high-level ground water. (2) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (3) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.
Līhuʻe	Anahola	20104	**21**	This Aquifer System contains ground water as basal, perched and high level. The majority reported ground water is pumped from the high-level zone followed by basal, and with lesser amounts removed from perched. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.
Līhuʻe	Kīlauea	20105	**10**	This Aquifer System contains ground water as basal, perched and high level. The majority reported ground water is pumped from the basal zone followed by perched, and with lesser amounts removed from high level. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Hanalei	Kalihiwai	20201	**16**	This Aquifer System contains ground water as basal and perched, with the all the reported ground water pumped from the basal zone. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.
Hanalei	Hanalei	20202	**35**	This Aquifer System contains ground water as basal, perched and high level. The majority reported ground water is pumped from the basal zone followed by perched. There are no wells located in the high-level zone. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.
Hanalei	Wainiha	20203	**24**	This Aquifer System contains ground water as basal and high level, with all the reported ground water pumped from the basal zone. Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood.
Hanalei	Napali	20204	**20**	There are two wells located in the high-level zone, with no reported pumped quantities. (1) Due to the presence of a discontinuous, unmapped confining layer, the nature and extent of the basal ground water lens is not well understood. (2) Predominantly Basal Ground Water. (3) The recharge value used to calculate the Sustainable Yield INCLUDES return irrigation inputs to ground water.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Waimea	Kekaha	20301	**10**	This Aquifer System contains ground water as basal. The basal lens is protected by a thick sedimentary caprock along the coast; however, no wells utilize the caprock.
Waimea	Waimea	20302	**37**	This Aquifer System contains ground water as basal and high level, with all the reported ground water pumped from the perched zone. There are no wells located in the high-level zone.
Waimea	Makaweli	20303	**26**	This Aquifer System contains ground water as basal and perched, with the all reported ground water pumped from the perched zone.
Waimea	Hanapēpē	20304	**22**	This Aquifer System contains ground water as basal and perched; although there is very likely high-level water located in the higher elevation it is currently not utilized. The majority of reported ground water pumped from the basal zone.
Central	Windward	50101	**3**	Only high-level ground water.
Central	Leeward	50102	**3**	(1) Only high-level ground water. (2) Ground water may be brackish in the PaLāwaʻi Basin area.
Mahana Sector	Hauola	50201	**~**	(1) Ground water is brackish
Mahana Sector	Maunalei	50202	**~**	(1) Ground water is brackish
Mahana Sector	Paoma	50203	**~**	(1) Ground water is brackish
Kaa	Honopū	50301	**~**	(1) Ground water is brackish
Kaa	Kaumalapau	50302	**~**	(1) Ground water is brackish

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Kanao	Lealia	50401	~	(1) Ground water is brackish
Kanao	Manele	50402	~	(1) Ground water is brackish
Wailuku	Waikapu	60101	**3**	This Aquifer System contains ground water as basal and high level; with all of reported ground water use pumped from the basal zone.
Wailuku	Iao	60102	**20**	This Aquifer System contains ground water as basal, alluvial, caprock, and high level, with the majority reported ground water use pumped from the basal zone, followed by high level, with lesser amounts removed from alluvial and caprock wells.
Wailuku	Waihee	60103	**8**	This Aquifer System contains ground water as basal, perched, and high level, with all reported ground water use pumped from the basal zone.
Wailuku	Kahakuloa	60104	**5**	This Aquifer System contains ground water as basal, perched, and high level. There are no wells located in this Aquifer System.
Lahaina	Honokōhau	60201	**9**	This Aquifer System contains ground water as basal, perched, and high level, with no reported ground water use.
Lahaina	Honolua	60202	**8**	This Aquifer System contains ground water as basal and high level, with all reported ground water use pumped from the basal zone.
Lahaina	Honokowai	60203	**6**	This Aquifer System contains ground water as basal and high level, with all reported ground water use pumped from the basal zone.
Lahaina	Launiupoko	60204	**7**	This Aquifer System contains ground water as basal and high level, with all reported ground water use pumped from the basal zone.
Lahaina	Olowalu	60205	**2**	This Aquifer System contains ground water as basal and high level, with all reported ground water use pumped from the basal zone.
Lahaina	Ukumehame	60206	**2**	This Aquifer System contains ground water as basal and high level, with all reported ground water use pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Central	Kahului	60301	**1**	(This Aquifer System contains ground water as basal and caprock. Sustainable Yield ignores significant importation of surface water (return irrigation) into Kahului from outside the aquifer system area. This explains the ability to withdraw freshwater from the aquifer at significantly higher rates than the sustainable yield without apparent negative impacts (i.e. rising chloride concentrations or decreasing water levels). The majority of reported ground water use pumped from the basal zone.
Central	Paia	60302	**7**	This Aquifer System contains ground water only as basal ground water. The sustainable Yield ignores significant importation of surface water into Paia from outside the aquifer system area. This explains the ability to withdraw freshwater from the aquifer at significantly higher rates than the sustainable yield without apparent negative impacts (i.e. rising chloride concentrations or decreasing water levels). All reported ground water use pumped from the basal zone.
Central	Makawao	60303	**7**	This Aquifer System contains ground water as basal and high level, with the majority of reported ground water use pumped from the basal zone.
Central	Kamaole	60304	**11**	This Aquifer System contains ground water as basal, perched, and high level. The majority reported ground water use is pumped from the basal zone and with lesser amounts removed from perched.
Koolau	Haiku	60401	**24**	This Aquifer System contains ground water as basal, perched, and high level with the majority reported ground water use pumped from the basal zone, with lesser amount removed from high level wells.
Koolau	Honopou	60402	**16**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.
Koolau	Waikamoi	60403	**37**	This Aquifer System contains ground water as basal, perched, and high level, with no reported ground water use.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Koolau	Keanae	60404	**75**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the basal zone.
Hana	Kuhiwa	60501	**14**	This Aquifer System contains ground water as basal and high level, with no reported ground water use.
Hana	Kawaipapa	60502	**31**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone.
Hana	Waihoi	60503	**18**	This Aquifer System contains ground water as basal, perched, and high level, with no reported ground water use.
Hana	Kipahulu	60504	**15**	This Aquifer System contains ground water as basal, perched, and high level, with the all reported ground water use pumped from the perched zone.
Kahikinui	Kaupo	60601	**13**	This Aquifer System contains ground water as basal and high level, with the all reported ground water use pumped from the basal zone.
Kahikinui	Nakula	60602	**7**	This Aquifer System contains ground water as basal and high level, with no reported ground water use.
Kahikinui	Lualailua	60603	**11**	This Aquifer System contains ground water as basal, with a small area of high level located in the farthest interior. All reported ground water use pumped from the basal zone.
West	Kaluakoi	40101	**2**	This Aquifer System contains ground water as basal which is brackish, with no reported ground water use.
West	Punakou	40102	**2**	This Aquifer System contains ground water as basal which is brackish, with no reported ground water use.
Central	Hoolehua	40201	**2**	This Aquifer System contains ground water as basal which is brackish, with no reported ground water use.
Central	Palaau	40202	**2**	This Aquifer System contains ground water as basal, and there is partially effective caprock. Reported ground water use is pumped mainly from the basal zone, with lesser quantities from the caprock.
Central	Kualapuu	40203	**5**	This Aquifer System contains ground water as basal and high level, with the all reported ground water pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Southeast	Kamiloloa	40301	**3**	This Aquifer System contains ground water as basal, with a small area of high level near the crest of the mountains. All the reported ground water usage is from the basal zone.
Southeast	Kawela	40302	**5**	This Aquifer System contains ground water as basal, with an area of high level. All the reported ground water usage is pumped from the basal zone.
Southeast	Ualapue	40303	**8**	This Aquifer System contains ground water as basal, caprock, and a small area of high level. Reported ground water use is pumped mainly from the basal zone, with lesser quantity from the caprock.
Southeast	Waialua	40304	**6**	This Aquifer System contains ground water as basal and a small area of high level. All reported ground water use is pumped from the basal zone.
Northeast	Kalaupapa	40401	**2**	Ground water occurs predominantly as high-level ground water with minor amounts of basal. There are no wells located in this Aquifer System.
Northeast	Kahanui	40402	**3**	Ground water occurs predominantly as high-level ground water. All reported ground water use is pumped from the high-level zone.
Northeast	Waikolu	40403	**5**	Ground water occurs predominantly as high-level ground water. All reported ground water use is pumped from the high-level zone.
Northeast	Haupu	40404	**2**	Ground water occurs predominantly as high-level ground water. There are no wells located in this Aquifer System.
Northeast	Pelekunu	40405	**9**	Ground water occurs predominantly as high-level ground water with some basal along the coast. There are no wells located in this Aquifer System.
Northeast	Wailau	40406	**15**	Ground water occurs predominantly as high-level ground water. There are no wells located in this Aquifer System.
Northeast	Halawa	40407	**8**	This Aquifer System contains ground water as basal, perched and high level. There are no wells located in this Aquifer System.
Honolulu	Palolo	30101	**5**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. The majority reported ground water use is pumped from the caprock followed by the basal zone and with lesser amounts removed from the high level.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Honolulu	Nuuanu	30102	**14**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. The majority reported ground water use is pumped from the basal followed by the caprock and with lesser amounts removed from the high level.
Honolulu	Kalihi	30103	**9**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. All reported ground water use is pumped from the basal zone.
Honolulu	Moanalua	30104	**16**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. All reported ground water use is pumped from the basal zone.
Honolulu	Waialae-West	30105	**2**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. All reported ground water use is pumped from the basal zone.
Honolulu	Waialae-East	30106	**2**	This Aquifer System contains ground water as basal, perched and high level in addition there is a thick effective caprock. The majority reported ground water use is pumped from the caprock followed by the basal zone.
Pearl Harbor	Waimalu	30201	**45**	This Aquifer System contains predominately ground water as basal and high level in addition there is a caprock. All reported ground water use is pumped from the basal zone and high level. The lowest model-predicted sustainable yield is 47 MGD. However, due to exisiting salinity issues in wells in this aquifer system, CWRM elected to maintain the sustainable yield at 45 MGD. A higher sustainable yield may be possible if well placement and pumping are optimized.
Pearl Harbor	Waipahu-Waiawa	30203	**105**	This Aquifer System contains predominately ground water as basal in addition there is a caprock. All reported ground water use is pumped from the basal zone. The recharge value used in the Sustainable Yield calculation includes spillover of ground water from the Wahiawa Aquifer System area.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
Pearl Harbor	ʻEwa-Kunia	30204	**16**	This Aquifer System contains predominately ground water as basal in addition there is a caprock. All reported ground water use is pumped from the basal zone. The recharge value used in the Sustainable Yield calculation includes spillover of ground water from the Wahiawa Aquifer System area.
Pearl Harbor	Makaiwa	30205	**~**	This Aquifer System contains predominately ground water as basal in addition there is a caprock. All reported ground water use is pumped from the basal zone.
Central	Wahiawā	30501	**23**	This Aquifer System contains ground water entirely of high level. Spillover from this Aquifer Sector supplements the Mokuleia, Wailua, Kawailoa, Ewa-Kunia, and Waipahu-Waiawa Aquifer Systems.
Waianae	Nānākuli	30301	**1**	This Aquifer System contains ground water as basal and high level in addition there is a caprock, with no reported ground water use.
Waianae	Lualualei	30302	**3**	This Aquifer System contains ground water as basal and high level, in addition there is a caprock. The reported ground water use is pumped from the caprock and basal zones.
Waianae	Waiʻanae	30303	**3**	This Aquifer System contains ground water as basal, alluvial, and high level, in addition there is a caprock. The reported ground water use is pumped from the high level and basal zones.
Waianae	Mākaha	30304	**3**	This Aquifer System contains ground water as basal, perched, alluvial, and high level, in addition there is a caprock. The majority reported ground water use is pumped from the high level, followed by the perched, alluvial, and cap rock.
Waianae	Keaʻau	30305	**3**	This Aquifer System contains ground water as basal and high level, in addition there is a caprock. All reported ground water use is pumped from the basal zone.

Table F-11 Aquifer Notes (continued)

Aquifer Sector	Aquifer System	Aquifer Code	Sustainable Yield (2019)	Comments
North	Mokulēʻia	30401	**17**	This Aquifer System contains ground water as basal, in addition there is a thick effective caprock. All reported ground water use is pumped from the basal zone. The recharge value used in the Sustainable Yield calculation includes spillover of ground water from the Wahiawa Aquifer System area.
North	Waialua	30402	**17**	This Aquifer System contains ground water as basal, in addition there is a thick effective caprock. All reported ground water use is pumped from the basal zone. The recharge value used in the Sustainable Yield calculation includes spillover of ground water from the Wahiawa Aquifer System area.
North	Kawailoa	30403	**22**	This Aquifer System contains ground water as basal and perched but lacks an effective caprock. The majority of reported ground water use is pumped from the basal zone. The recharge value used in the Sustainable Yield calculation includes spillover of ground water from the Wahiawa Aquifer System area.
Windward	Koʻolauloa	30601	**35**	This Aquifer System is predominantly basal ground water.
Windward	Kahana	30602	**15**	This Aquifer System contains ground water as basal, alluvial, and high level, in addition there is a caprock. All reported ground water use is pumped from high level.
Windward	Koʻolaupoko	30603	**28**	This Aquifer System contains ground water as basal and high level, in addition there is a caprock. The majority reported ground water use is pumped from high level. Ground water removed from the aquifer system area by the Waiāhole Tunnel was subtracted from the total recharge value used to calculate sustainable yield.
Windward	Waimānalo	30604	**9**	This Aquifer System contains ground water as basal and high level, in addition there is a caprock. All reported ground water use is pumped from high level.
Waiahole Ditch	Waiahole Ditch	30701	**15**	From Waiahole contested case hearing CCH-OA95-1. Water available for leeward distribution from Waiahole Ditch System (not a true aquifer system area); otherwise, unused portions remain in windward streams.

Table F-12 Sustainable Yield Values for Hawai‘i Caprock Aquifers

Sustainable Yield = Miligrams Per Liter (mg/L) Sodium

Aquifer Sector Area	Aquifer System Area	Code	Sustainable Yield
O‘ahu			
‘Ewa Caprock	Malakole	30207	NA
‘Ewa Caprock	Kapolei	30208	1000
‘Ewa Caprock	Puuloa	30209	1000

F.4.4.2 Future Sustainable Yield Selection Criteria

As the WRPP is a living document, sustainable yields will be re-estimated continually based on the best information available as new information is acquired with time. In general, the best information that is scientifically sound and CWRM-vetted for aquifer-specific hydrologic, geologic, or other data will be used for future sustainable yield revisions on case-by-case basis. Revisions shall be consistent with the following criteria:

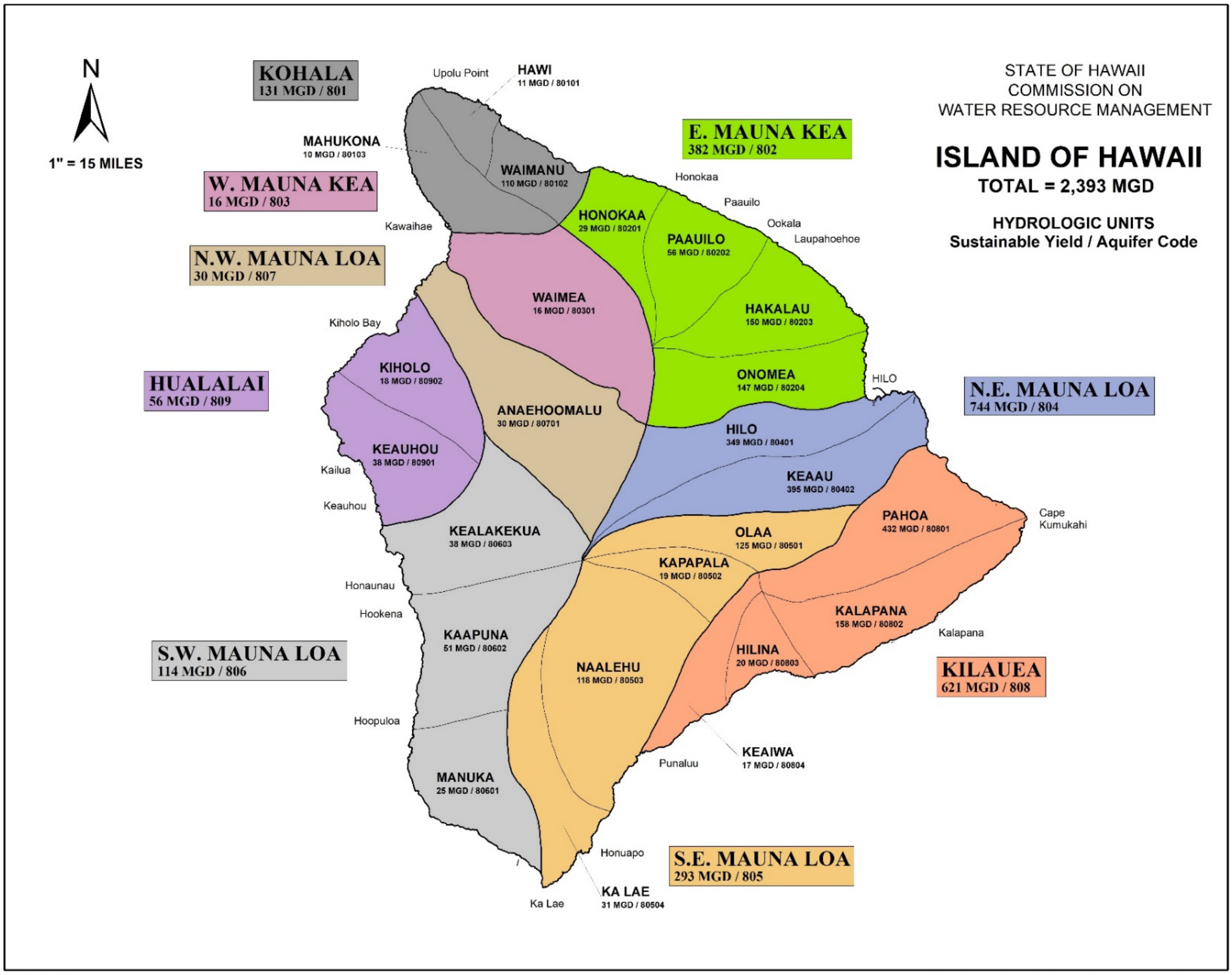
For Aquifer Systems with predominantly basal resources:

- Presence of an operational deep monitor well and other publicly available hydrogeologic data, such as:
  - Recharge studies that follow the convention of **Section F.4.3.1**;
  - Complete and significant record of historical pumpage, chloride, and water-level data;
  - Numerical model studies for establishing infrastructure safe yields; or
  - Other hydrologic and geologic studies reviewed and accepted by CWRM staff.
- Ground water inputs from adjacent aquifers.

For Aquifer Systems with predominantly high-level resources:

- Presence of an operational ground water-level monitoring network and a stream monitoring network, where applicable, to ensure compliance with instream flow standards and other publicly available hydrogeologic data, such as:
  - Recharge studies that follow the convention of **Section F.4.3.1**;
  - Complete and significant record of historical pumpage, chloride, and water-level data;
  - Numerical model studies for establishing infrastructure safe yields; or
  - Other hydrologic and geologic studies reviewed and accepted by CWRM staff.
- Ground water spill-over from adjacent aquifers.

Figure F-17 Island of Hawai‘i Ground Water Hydrologic Units and 2019 Sustainable Yields



06/20/2018

Map Projection: Universal Transverse Mercator

Figure F-18 Island of Kaua'i Ground Water Hydrologic Units and 2019 Sustainable Yields

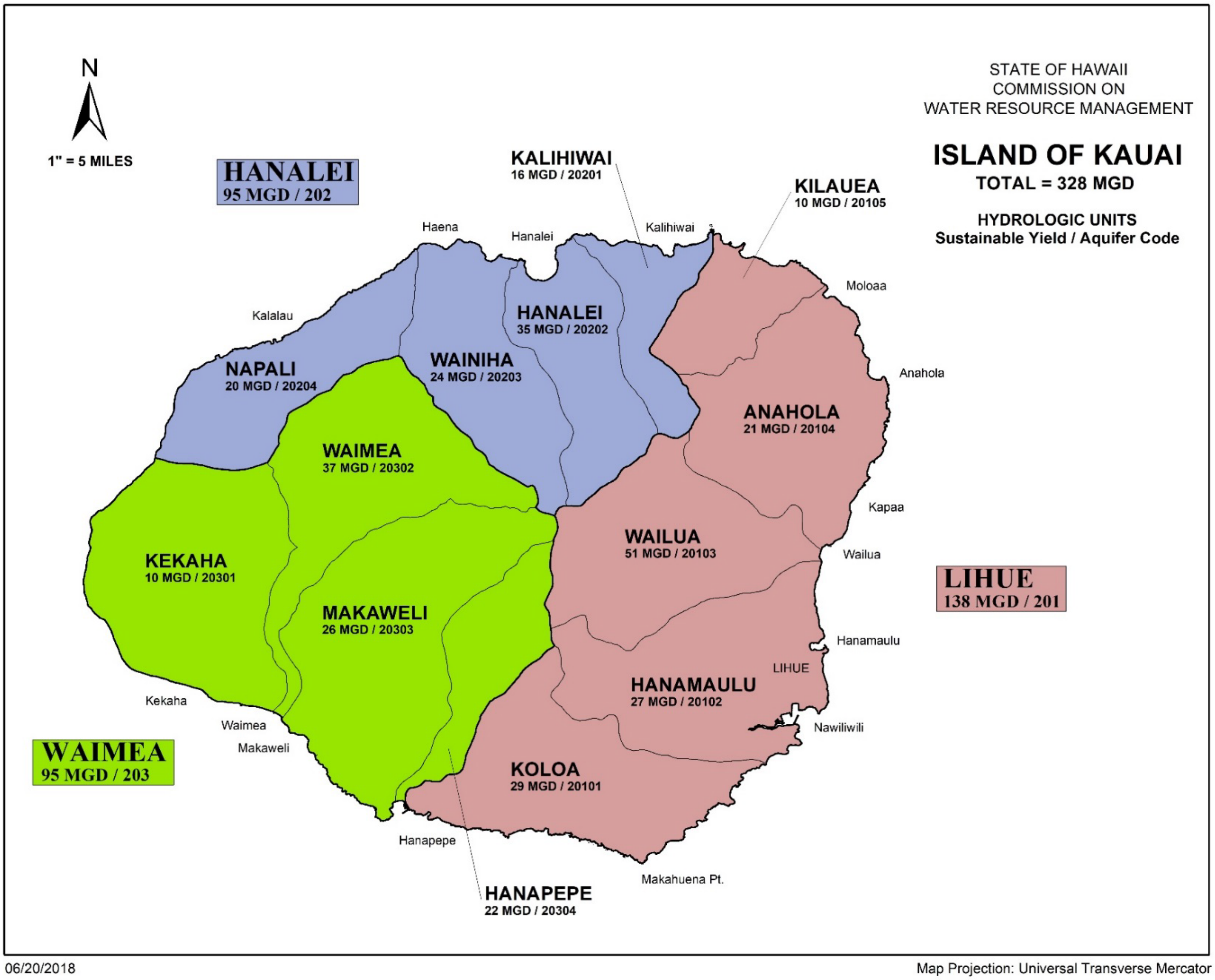


Figure F-19 Island of Lānaʻi Ground Water Hydrologic Units and 2019 Sustainable Yields

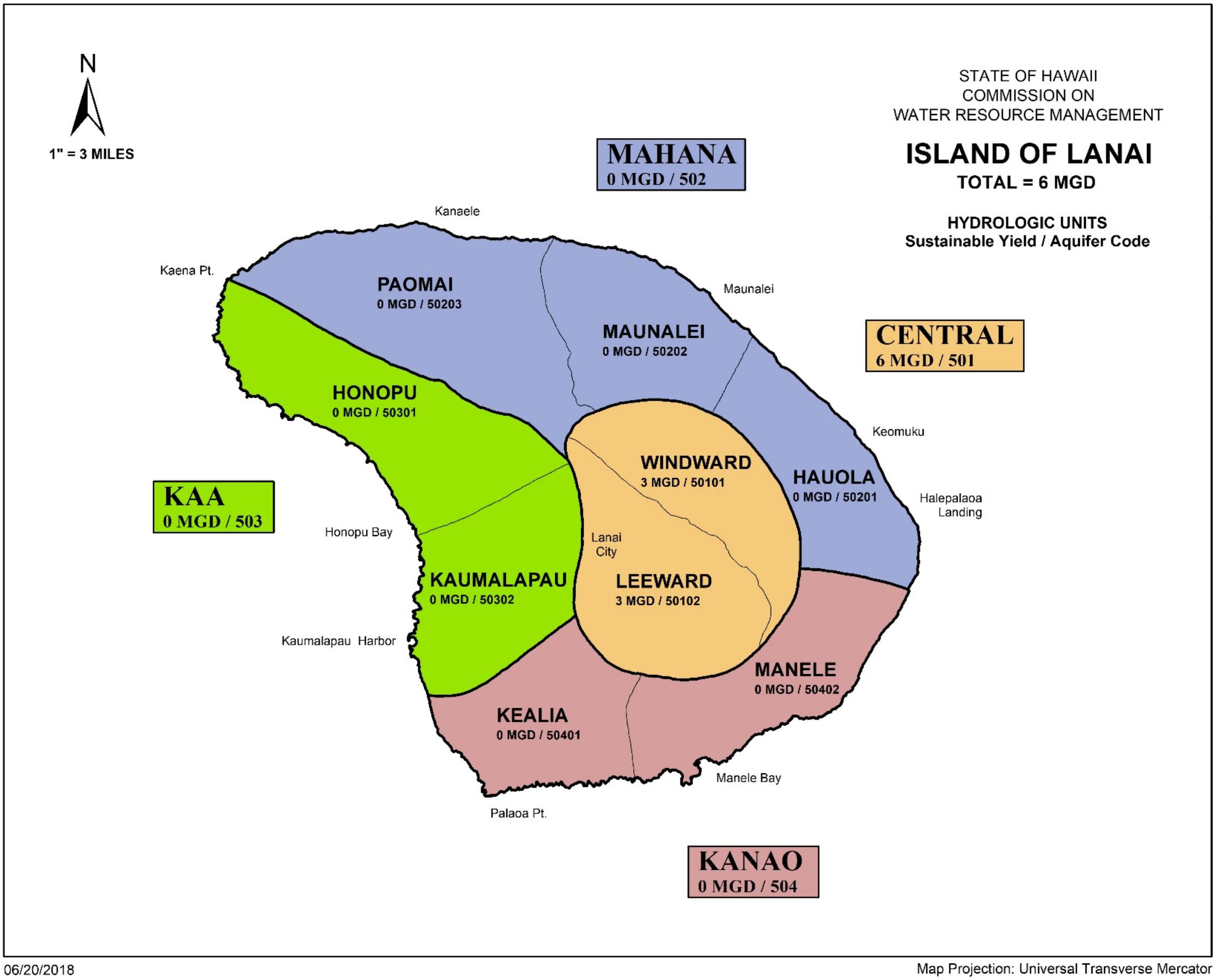


Figure F-20 Island of Maui Ground Water Hydrologic Units and 2019 Sustainable Yields

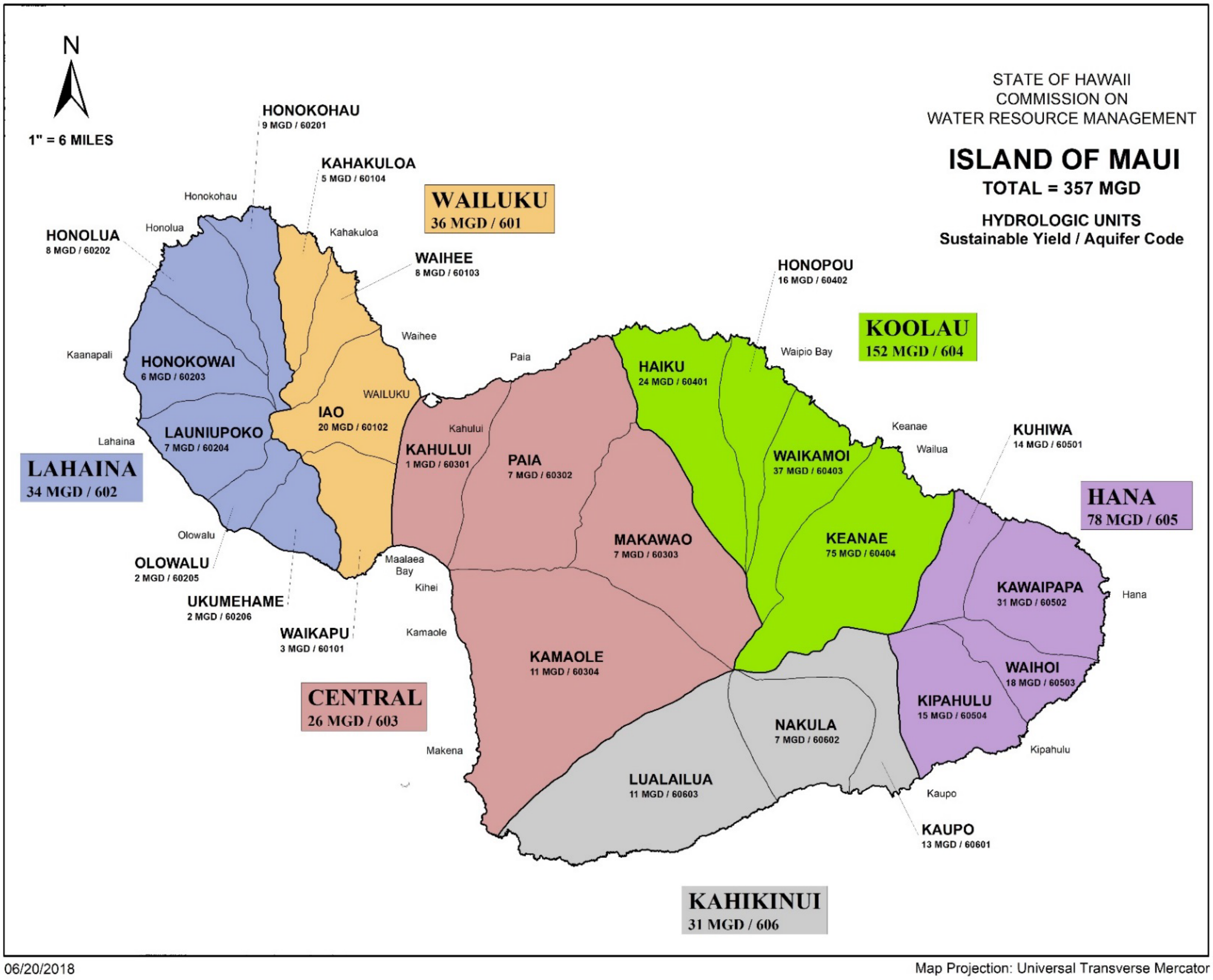
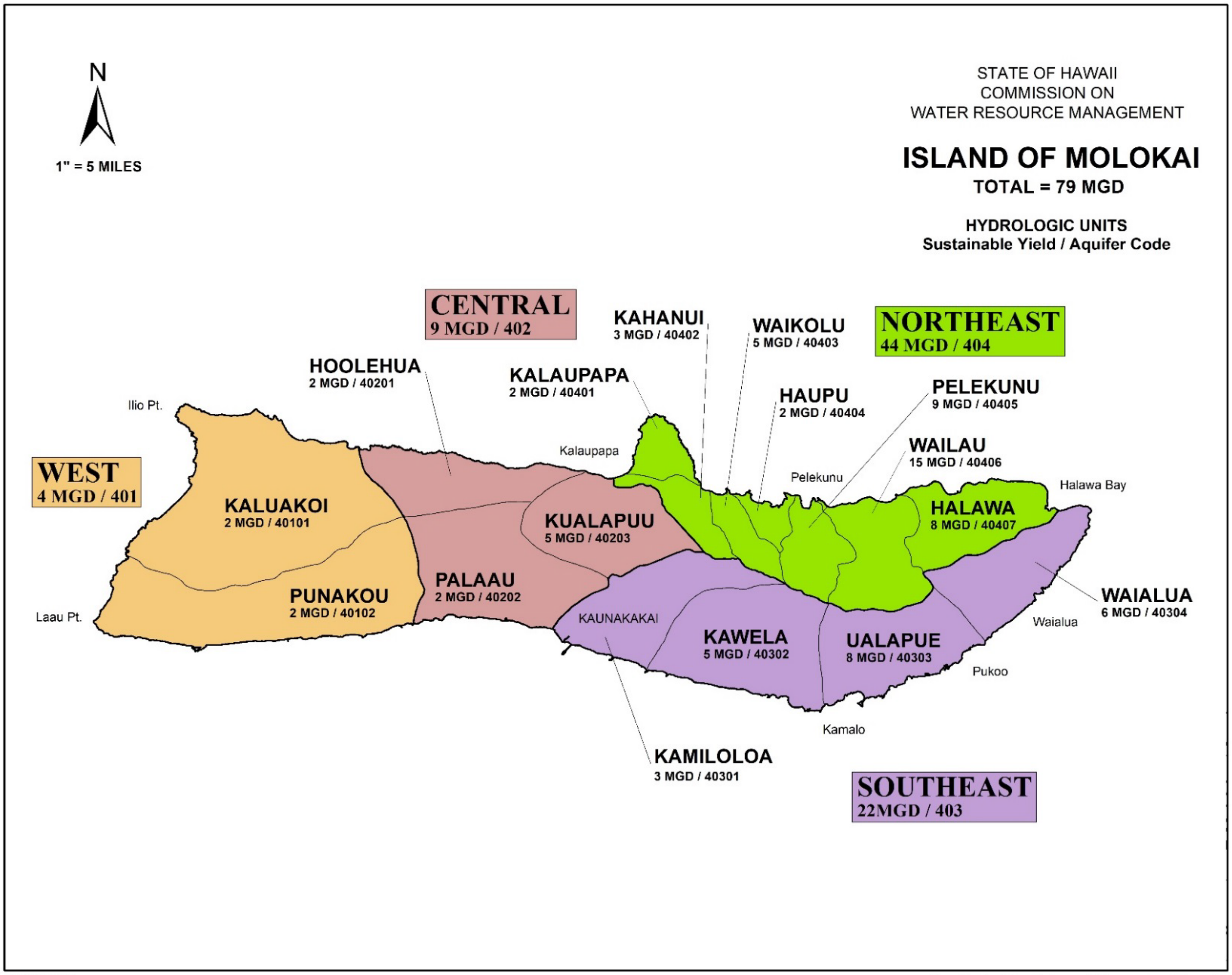
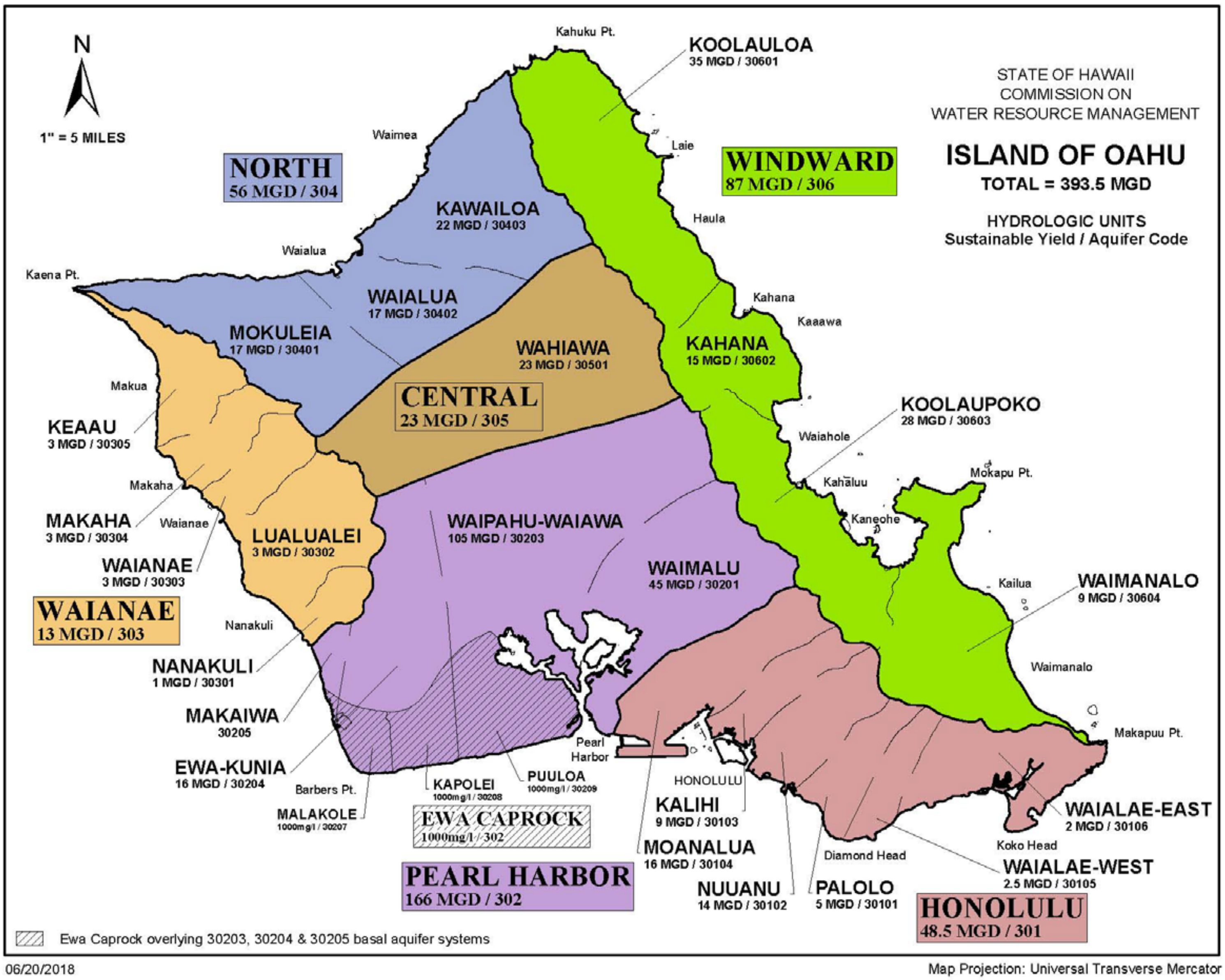


Figure F-21 Island of Moloka‘i Ground Water Hydrologic Units and 2019 Sustainable Yields



06/20/2018
Map Projection: Universal Transverse Mercator

Figure F-22 Island of Oʻahu Ground Water Hydrologic Units and 2019 Sustainable Yields



F.5 Nature and Occurrence of Surface Water

Early in its history, CWRM recognized the need for a broad-based collection of existing information on Hawaiʻi's surface water resources to enable sensible water management and decision making. As a result, CWRM and the U.S. National Park Service (USNPS) undertook a cooperative project that produced the 1990 document entitled *Hawaii Stream Assessment: A Preliminary Appraisal of Hawaii's Stream Resources* (HSA). This document continues to serve as a key reference for stream-related research in Hawaiʻi. To provide the general public with an introduction to Hawaiʻi's surface water resources, CWRM and the USGS cooperated to develop the *Surface Water in Hawaii* information brochure published in 2003. The brochure includes information on basic surface water characteristics, system components and behavior, and natural and human-related impacts. The information in this section adapts CWRM's collaborative work with the USNPS and the USGS to provide a basic overview of the nature and occurrence of surface water in Hawaiʻi and implications for surface water management through instream flow standards.

F.5.1 Surface Water Occurrence

The State Water Code defines surface water as consisting of both contained surface water and diffused surface water. Contained surface water exists upon the surface of the earth in naturally or artificially created water bodies such as streams, man-made watercourses, lakes, reservoirs, and coastal waters. Diffused surface water includes all other waters on the surface of the earth that are not contained within waterbodies.

Surface water occurs in areas that, due to topographic slope, contribute to surface water drainage systems that typically manifest as streams or rivers. These drainage areas are confined by topographic divides and are generally referred to as watersheds. Watersheds are sometimes called drainage basins or catchments. Hawaiʻi watersheds are consistently small in comparison to mainland systems, however, watershed profiles vary widely across the main islands. For example, watersheds on the geologically young island of Hawaiʻi tend to be short in length, have fairly shallow channels, exhibit simple stream networks with few tributaries, and may sometimes terminate in a waterfall at the ocean. On the older island of Kauai, watershed systems exhibit eroded features, such as deeper incised channels, complex stream networks with many tributary branches, and large riverine estuaries at the ocean interface.

Watersheds are influenced by human alterations to natural stream systems that affect both surface water hydrology, stream biota, and water quality. Infrastructure significantly changes the path and flow of water. Ditches and canals, even storm drain systems, are built to convey water from one area to another, while reservoirs are used to store water on and off stream systems. Stream channel alterations also influence watershed processes. Channel alterations may include hardened channel linings and embankments, retention basins, culverts, drainage inlets and outlets, and channel realignments.

Within a watershed, surface water resources occur in various settings, both natural and altered. Streams, springs, ditches and canals, and reservoirs are the most common surface water settings in Hawaiʻi. These are described in the sections below.

F.5.1.1 Streams

Streams originating in mauka rainfall belts are the principle drainage features of Hawaiʻi watersheds. The USGS defines the term "stream" as follows:

> *Stream – a general term for a body of flowing water; natural water course containing water at least part of the year. In hydrology, it is generally applied to the water flowing in a natural channel as distinct from a canal.*

Streamflow consists of five components: 1) Direct runoff of rainfall in the form of overland flow and subsurface flow, which rapidly returns infiltrated water to the stream; 2) Water returned from bank storage; 3) Ground water discharge in the form of base flow, where the stream intersects the water table; 4) Rain that falls directly on streams; and 5) any additional water, including excess irrigation water, discharged to the stream by humans.[39]

Direct runoff occurs during and immediately following a period of rainfall when the capacity of the soil to accept and store water is exceeded, causing water to run off in a sheet of overland flow. Water may also enter the stream as subsurface flow when rainfall infiltrates the ground surface and moves laterally in the near-surface soils. Subsurface flow is generally slower and may continue for days after a rainfall event but may also occur quickly if water is able to move through preferential pathways. Similarly, during a period of high rainfall, water may be absorbed into the banks of the stream as bank storage. This water can be returned to the stream to contribute to total streamflow.

Water that infiltrates the ground surface may also recharge ground water bodies such as perched aquifers or dike compartments, which subsequently discharge water to streams. This ground water discharge to the stream, referred to as base flow, may occur during extended dry periods as well as during rainfall events. Base flow contributions occur where the stream intersects the ground water table and where the ground water body is above the water level in the stream. Since ground water levels vary with time, base flow also varies with time. However, variations in base flow are much smaller than variations in direct runoff.

Perennial Streams: A perennial stream is defined as a stream which flows continuously throughout the year. Some streams flow perennially throughout their entire course, while others flow perennially over parts of their course. Streams in Hawaiʻi are commonly perennial in mountainous interior areas, where streams gain water from dike-impounded ground water systems and where rainfall is persistent. Perennial flow is also common in lower stream reaches

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[39] Oki, D.S., 2004, Trends in Streamflow Characteristics in Hawaii, 1913-2003: U.S. Geological Survey Fact Sheet 2004-3104, 4 p.

near the coast where streams gain water from freshwater-lens systems. Where a vertically extensive freshwater-lens system exists, streams may gain water and flow perennially at higher altitudes inland from the coast.[40]

The HSA provided a listing of 376 perennial streams which were defined using data from various sources. The authors acknowledged that, although over one third of the streams on the list did not flow continuously from their headwaters to the ocean, these streams have perennial sections. This list of streams is used by CWRM to make preliminary determinations in regulatory permitting, though streams must often be assessed on a case-by-case basis.

Intermittent Streams: A stream or part of a stream is considered intermittent when it only flows at certain times of the year. Flow generally occurs for several weeks or months in response to seasonal precipitation and subsequent ground water discharge. An intermittent stream may also exist where a perched ground water body contributes to streamflow during certain times of the year. Intermittent streams are often able to support small communities of native freshwater species, either due to upstream or downstream perennial reaches or the persistence of pool habitats between flowing stream segments.

Ephemeral Streams: Ephemeral streams usually manifest in dry gulches on the leeward side of mountain ranges, where there is little or no ground water influence. Ephemeral streams only flow in direct response to rainfall, which indicates that the stream channel is not in contact with the water table. In general, flows last but a few hours or days following a single storm event.

F.5.1.2 Springs

Springs occur where ground water discharges naturally from the ground surface at a more or less continuous rate. Springs are largely dependent upon the permeability of rock layers, the position of the water table, and surface topography.

F.5.1.3 Ditches and Canals

The ditches and canals that traverse the Hawaiian landscape are largely a result of the sugar industry's need to transport water for cane cultivation in the late 1800s. By 1884, there were a total of 90 sugar planters, plantations, and mills. Extensive irrigation systems often consisted of concrete-lined or unlined channels, tunnels, and flumes that moved water from wet, windward areas to arable plains in dry, leeward areas. By 1920, an estimated 800 million gallons of surface water, in addition to almost 400 million gallons of pumped ground water, was consumed by the sugar industry daily.

[40] Izuka, S.K., and Gingerich, S.B., 1998, Ground water in the southern Lihue basin, Kauai, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 98-4031, 71 p.

The demise of the sugar industry towards the end of the 20th Century brought the closure of large-scale plantations and the conversion of plantation fields to diversified agriculture. Associated changes also occurred in irrigation practices and agricultural water consumption. Many of the irrigation systems that once served plantation agriculture still continue to divert water, however, most systems do not function as efficiently as they once did. System maintenance, which was executed by the plantations, is no longer coordinated and many new owners of former plantation lands do not have the means or desire to carry out refurbishment and repair projects. These irrigation systems are significant in that, not only do they contribute to the viability of agriculture, they impact the surface water hydrology of diverted streams; they impact the hydrology of the streams they pass via leakage, overflows, and controlled releases (for maintenance); and they impact the ground water hydrology of the area receiving irrigation.

F.5.1.4 Reservoirs

A reservoir is generally an artificial basin created for the purpose of collecting, storing, and regulating water. Reservoirs are usually created by damming the downstream end of a drainage basin. In Hawaiʻi, there are very few natural lakes, so these man-made reservoirs often serve as recreational boating and fishing lakes. Many of the reservoirs that dot the landscape were constructed to serve the sugar and pineapple industries, while others were built for flood control or as impoundment reservoirs for drinking water prior to treatment. Reservoirs can influence local climatological patterns, habitat conditions for stream organisms, water quality, and ground water infiltration. **Appendix J Resource Conservation and Augmentation** contains additional discussion on dams and reservoirs.

F.5.2 Surface Water Hydrologic Units

Surface water hydrologic units have been established by CWRM to provide a consistent basis for managing surface water resources. A surface water hydrologic unit coding system is used to reference and describe the units delineated by CWRM. This section describes the coding system and lists all surface water hydrologic units by island. Maps illustrating the hydrologic unit boundaries are included in **Section F.5.2.3 Surface Water Hydrologic Coding System**.

F.5.2.1 Purpose of Surface Water Hydrologic Unit Coding

As described earlier in **Section F.5.1**, surface water occurs in variable settings throughout Hawaiʻi. The surface water hydrologic unit coding system described herein was established to provide a consistent method by which to reference and describe surface water resources and to assist in various water planning efforts. The coding system is an important first-step towards improving the organization and management of surface water information that CWRM collects and maintains.

The primary goal of the coding system is to provide standard surface water hydrologic unit delineations for the coordination of data, information, and resource management practices. Key objectives of CWRM Surface Water Hydrologic Units include the following:

- Define and delineate unique units that can accommodate the relational requirements in a database environment, while providing a system that can be easily understood by the general public;
- Develop an information management system which utilizes a coding system to relate surface water permits and other resource information to a given unit;
- Define hydrologic units to be considered in the analysis and development of instream flow standards;
- Provide a reference system that promotes better information management of other resource inventories;
- Promote the sharing and collection of surface water resource data between government agencies, the public, private entities, and community organizations; and
- Improve the overall coordination of monitoring, data collection, and field investigation efforts.

F.5.2.2 Basis for Surface Water Hydrologic Unit Delineations

The State Water Code mandates that the WRPP shall include:

> *"…Hydrologic units and their characteristics, including the quantity and quality of available resource, requirements for beneficial instream uses and environmental protection, desirable uses worthy of preservation by permit, and undesirable uses for which permits may be denied."*[41]

The State Water Code defines a hydrologic unit as "[a] surface drainage area or a ground water basin or a combination of the two."[42]

Ground water hydrologic units were established by CWRM under the 1990 WRPP. For surface water units, however, the 1990 WRPP only suggests a complex classification scheme.

In 2005, CWRM adopted surface water hydrologic units and the coding system described below. In developing CWRM Surface Water Hydrologic Units, it was necessary to review the HSA, *State Delineation of Watersheds* (1994), and *Refinement of Hawaii Watershed Delineations* (1999) reports to arrive at a coding system that could meet the requirements for organizing and managing surface water information.

[41] HRS §174C-31(d)(2).

[42] HRS §174C-3.

The naming convention for surface water hydrologic units indicates regional and sub-regional divisions as follows:

Island division = Island
Regional division = Surface Water Hydrologic Unit

F.5.2.3 Surface Water Hydrologic Unit Coding System

The surface water hydrologic unit code is a unique combination of four digits. In the *State Definition and Delineation of Watersheds* report, a watershed unit is defined as follows:

> *"A watershed unit is comprised of a drainage basin (or basins) which include both stream and overland flow, whose runoff either enters the ocean along an identified segment of coastline (coastal segment) or enters an internal, landlocked drainage basin. The watershed units for an island are defined so that all segments of coastline are assigned to a unique watershed unit and so that all areas of an island are assigned to one, and only one, watershed unit."*

The surface water hydrologic unit coding system is based on a hierarchy in which the island is the largest component and the surface water hydrologic unit is the regional component. The island is identified by a single-digit number. Each surface water hydrologic unit is identified by a three-digit number and a Hawaiian geographic name or local geographic term.

Therefore, surface water hydrologic units are assigned a unique code in the four-digit format as follows:

0	**000**
Island	Surface Water Hydrologic Unit

The individual components of the coding system are described below.

ISLAND: <u>0</u>000

The first digit represents the eight main Hawaiian Islands using a unique number assigned by CWRM. The Island Code is the same 1-digit number used in the Hawaii Stream Assessment. The islands of Niihau, Kahoolawe and Lanai did not appear in the HSA database because these islands do not have perennial streams, however they have been included in the coding system as part of a more comprehensive surface water management scheme.

SURFACE WATER HYDROLOGIC UNIT SYSTEM: 0**<u>000</u>**

The last three digits are sequentially assigned, generally beginning in the north and continuing around each island in a clockwise manner. This method is similar to previous coding efforts.

There are a total of 558 Surface Water Hydrologic Units statewide. **Table F-13** to **Table F-20** below list all units by island and are accompanied by maps showing the unit boundaries (see **Figure F-23** to **Figure F-30**). For the majority of hydrologic units, unit boundaries closely match drainage basin boundaries. Individual stream systems are contained entirely within the hydrologic unit boundaries (from the headwater to the mouth). However, in a few instances, streams were found to cross hydrologic unit boundaries, and in these cases, drainage basins were refined to more accurately determine the natural flow of water based on elevation gradients. In these instances, the hydrologic unit boundaries were evaluated together with the drainage basin and redrawn through on-screen digitizing using ArcGIS software.

Table F-13 Niʻihau (1) Surface Water Hydrologic Units

1001	Kaaukuu	1008	Mauuloa
1002	Kooeaukani	1009	Nonopapa
1003	Kaʻailana	1010	Puuwai
1004	Nomilu	1011	Kaumuhonu
1005	Kalaoa	1012	Keanauhi
1006	Honuaula	1013	Keawanui
1007	Halaii		

Table F-14 Kauaʻi (2) Surface Water Hydrologic Units

2001	Awaʻawapuhi	2038	Moikeha
2002	Honopū	2039	Waikaea
2003	Nakeikionaiwi	2040	Wailua
2004	Kalalau	2041	Kawailoa
2005	Pōhakuao	2042	Hanamāʻulu
2006	Waiolaa	2043	Līhuʻe Airport
2007	Hanakoa	2044	Nāwiliwili
2008	Waiahuakua	2045	Puali
2009	Hoʻolulu	2046	Huleia
2010	Hanakāpīʻai	2047	Kipu Kai
2011	Maunapuluo	2048	Mahaulepu
2012	Limahuli	2049	Waikomo
2013	Mānoa	2050	Aepo
2014	Wainiha	2051	Lāwaʻi
2015	Lumahaʻi	2052	Kalāheo
2016	Waikoko	2053	Wahiawa
2017	Waipā	2054	Hanapēpē
2018	Waiʻoli	2055	Kukamahu
2019	Hanalei	2056	Kaumakani
2020	Waileia	2057	Mahinauli
2021	ʻAnini	2058	Aʻakukui
2022	Kalihikai West	2059	Waipao
2023	Kalihikai Center	2060	Waimea
2024	Kalihikai East	2061	Kapilimao
2025	Kalihiwai	2062	Paua
2026	Puʻukumu	2063	Hoea
2027	Kauapea	2064	Niu
2028	Kīlauea	2065	Kaawaloa
2029	Kulihaili	2066	Nahomalu
2030	Pīlaʻa	2067	Kaulaula
2031	Waipake	2068	Haeleele
2032	Moloaʻa	2069	Hikimoe
2033	Pāpaʻa	2070	Kaaweiki
2034	Aliomanu	2071	Kauhao
2035	Anahola	2072	Makaha
2036	Kumukumu	2073	Milolii
2037	Kapaʻa	2074	Nualolo

Table F-15 Oʻahu (3) Surface Water Hydrologic Units

3001	Kālunawaikaʻala	3045	Niu
3002	Pakulena	3046	Wailupe
3003	Paumalu	3047	Waialaenui
3004	Kawela	3048	Diamond Head
3005	Oio	3049	Ala Wai
3006	Malaekahana	3050	Nuuanu
3007	Kahawainui	3051	Kapalama
3008	Wailele	3052	Kalihi
3009	Koloa	3053	Moanalua
3010	Kaipapau	3054	Keehi
3011	Maakua	3055	Manuwai
3012	Waipuhi	3056	Salt Lake
3013	Kaluanui	3057	Halawa
3014	Papaʻakoko	3058	Aiea
3015	Halehaa	3059	Kalauao
3016	Punaluu	3060	Waimalu
3017	Kahana	3061	Waiawa
3018	Makaua	3062	Waipio
3019	Kaʻaʻawa	3063	Kapakahi
3020	Kualoa	3064	Waikele
3021	Hakipuʻu	3065	Honouliuli
3022	Waikane	3066	Kaloi
3023	Waianu	3067	Makaiwa
3024	Waiāhole	3068	Nanakuli
3025	Kaʻalaea	3069	Ulehawa
3026	Haiamoa	3070	Mailiili
3027	Kahaluu	3071	Kaupuni
3028	Heʻeia	3072	Kamaileunu
3029	Keaʻahala	3073	Makaha
3030	Kāneʻohe	3074	Keaau
3031	Kawa	3075	Makua
3032	Puu Hawaiiloa	3076	Kaluakauila
3033	Kawainui	3077	MʻAnini
3034	Kaelepulu	3078	Kawaihapai
3035	Waimanalo	3079	Pahole
3036	Kahawai	3080	Makaleha
3037	Makapuu	3081	Waialua
3038	Koko Crater	3082	Kiikii
3039	Hanauma	3083	Paukauila
3040	Portlock	3084	Anahulu
3041	Kamiloiki	3085	Loko Ea
3042	Kamilonui	3086	Keamanea
3043	Hahaione	3087	Waimea
3044	Kuliouou		

Table F-16 Molokaʻi (4) Surface Water Hydrologic Units

4001	Waihanau	4026	Honouliwai
4002	Waialeia	4027	Waialua
4003	Waikolu	4028	Kainalu
4004	Wainene	4029	Honomūni
4005	Anapuhi	4030	Ahaino
4006	Waiohookalo	4031	Mapulehu
4007	Keawanui	4032	Kaluaʻaha
4008	Kailiili	4033	Kahananui
4009	Pelekunu	4034	Ohia
4010	Waipu	4035	Wawaia
4011	Haloku	4036	Kamalo
4012	Oloupena	4037	Kawela
4013	Puukaoku	4038	Kamiloloa
4014	Wailele	4039	Kaunakakai
4015	Wailau	4040	Kalamaula
4016	Kalaemilo	4041	Manawainui
4017	Waiahookalo	4042	Kaluapeelua
4018	Kahiwa	4043	Waiahewahewa
4019	Kawainui	4044	Kolo
4020	Pipiwai	4045	Hakina
4021	Halawa	4046	Kaunala
4022	Papio	4047	Papohaku
4023	Honowewe	4048	Kaa
4024	Pohakupili	4049	Moʻomomi
4025	Honoulimaloo	4050	Maneopapa

Table F-17 Lanaʻi (5) Surface Water Hydrologic Units

5001	Puumaiekahi	5017	Awehi
5002	Lapaiki	5018	Kapua
5003	Hawaiilanui	5019	Naha
5004	Kahua	5020	Kapoho
5005	Kuahua	5021	Kawaiu
5006	Poaiwa	5022	Mahanalua
5007	Halulu	5023	Manele
5008	Maunalei	5024	Anapuka
5009	Wahane	5025	PaLāwaʻi Basin
5010	Hauola	5026	Ulaula
5011	Nahoko	5027	Kaumalapau
5012	Kaa	5028	Kalamanui
5013	Haua	5029	Kalamaiki
5014	Waiopa	5030	Paliamano
5015	Kahea	5031	Honopū
5016	Lopa	5032	Kaapahu

Table F-18 Maui (6) Surface Water Hydrologic Units

6001	Waikapu	6050	Punalau
6002	Pohakea	6051	Honomanu
6003	Papalaua	6052	Nuaailua
6004	Ukumehame	6053	Piinaau
6005	Olowalu	6054	Ohia
6006	Launiupoko	6055	Waiokamilo
6007	Kauaula	6056	Wailuanui
6008	Kahoma	6057	West Wailuaiki
6009	Wahikuli	6058	East Wailuaiki
6010	Honokowai	6059	Kopiliula
6011	Kahana	6060	Waiohue
6012	Honokahua	6061	Paakea
6013	Honolua	6062	Waiaaka
6014	Honokōhau	6063	Kapaula
6015	Anakaluahine	6064	Hanawi
6016	Poelua	6065	Makapipi
6017	Honanana	6066	Kuhiwa
6018	Kahakuloa	6067	Waihole
6019	Waipili	6068	Manawaikeae
6020	Waiolai	6069	Kahawaihapapa
6021	Makamakaole	6070	Keaaiki
6022	Waihee	6071	Waioni
6023	Waiehu	6072	Lanikele
6024	Iao	6073	Heleleikeoha
6025	Kalialinui	6074	Kawakoe
6026	Kailua Gulch	6075	Honomaele
6027	Maliko	6076	Kawaipapa
6028	Kuiaha	6077	Moomoonui
6029	Kaupakulua	6078	Haneoo
6030	Manawaiiao	6079	Kapia
6031	Uaoa	6080	Waiohonu
6032	Kealii	6081	Papahawahawa
6033	Kakipi	6082	Alaalaula
6034	Honopou	6083	Wailua
6035	Hoolawa	6084	Honolewa
6036	Waipio	6085	Waieli
6037	Hanehoi	6086	Kakiweka
6038	Hoalua	6087	Hahalawe
6039	Hanawana	6088	Puaaluu
6040	Kailua	6089	Oheo
6041	Nailiilihaele	6090	Kalena
6042	Puehu	6091	Koukouai
6043	Oopuola	6092	Opelu
6044	Kaaiea	6093	Kukuiula
6045	Punaluu	6094	Kaapahu

Table F-18 Maui (6) Surface Water Hydrologic Units (continued)

6046	Kolea	6095	Lelekea
6047	Waikamoi	6096	Alelele
6048	Puohokamoa	6097	Kalepa
6049	Haipuaena	6098	Nuanuaaloa
6099	Manawainui	6106	Kipapa
6100	Kaupo	6107	Kanaio
6101	Nuu	6108	Ahihi Kinau
6102	Pahihi	6109	Mooloa
6103	Waiopai	6110	Wailea
6104	Poopoo	6111	Hapapa
6105	Manawainui Gulch	6112	Waiakoa

Table F-19 Kahoolawe (7) Surface Water Hydrologic Units

7001	Lae Paki	7013	Waaiki
7002	Honokoa	7014	Kealia Luna
7003	Makaakae	7015	Hakioawa
7004	Ahupuiki	7016	Oawawahie
7005	Ahupu	7017	Pali o Kalapakea
7006	Kaukamoku	7018	Kaukamaka
7007	Moaulaiki	7019	Lae o Kaka
7008	Olohia	7020	Kamohio
7009	Kuheeia	7021	Kanaloa
7010	Kaulana	7022	Waikahalulu
7011	Papakanui	7023	Honokanaia
7012	Papakaiki	7024	Wai Honu

Table F-20 Hawai‘i (8) Surface Water Hydrologic Units

8001	Kealahewa	8050	Malanahae
8002	Hualua	8051	Honokaia
8003	Kumakua	8052	Kawela
8004	Kapua	8053	Keaakaukau
8005	Ohanaula	8054	Kainapahoa
8006	Hanaula	8055	Nienie
8007	Hapahapai	8056	Papuaa
8008	Pali Akamoa	8057	Ouhi
8009	Wainaia	8058	Kahaupu
8010	Halelua	8059	Kahawailiili
8011	Halawa	8060	Keahua
8012	Aamakao	8061	Kalopa
8013	Niulii	8062	Waikaalulu
8014	Waikama	8063	Kukuilamalamahii
8015	Pololu	8064	Alilipali
8016	Honokane Nui	8065	Kaumoali
8017	Honokane Iki	8066	Pohakuhaku
8018	Kalele	8067	Waipunahina
8019	Waipahi	8068	Waipunalau
8020	Honokea	8069	Paauilo
8021	Kailikaula	8070	Aamanu
8022	Honopūe	8071	Koholalele
8023	Kolealiilii	8072	Kalapahapuu
8024	Ohiahuea	8073	Kukaiau
8025	Nakooko	8074	Puumaile
8026	Waiapuka	8075	Kekualele
8027	Waikaloa	8076	Kaala
8028	Waimaile	8077	Kealakaha
8029	Kukui	8078	Keehia
8030	Paopao	8079	Kupapaulua
8031	Waiaalala	8080	Kaiwiki
8032	Punalulu	8081	Kaula
8033	Kaimu	8082	Kaohaoha
8034	Pae	8083	Kaawalii
8035	Waimanu	8084	Waipunalei
8036	Pukoa	8085	Laupahoehoe
8037	Manuwaikaalio	8086	Kilau
8038	Naluea	8087	Manowaiopae

Table F-20 Hawaiʻi (8) Surface Water Hydrologic Units (continued)

8039	Kahoopuu	8088	Kuwaikahi
8040	Waipāhoehoe	8089	Kihalani
8041	Wailoa/Waipio	8090	Kaiwilahilahi
8042	Kaluahine Falls	8091	Haakoa
8043	Waiulili	8092	Pahale
8044	Waikoekoe	8093	Kapehu Camp
8045	Waipunahoe	8094	Paeohe
8046	Waialeale	8095	Maulua
8047	Waikoloa	8096	Pohakupuka
8048	Kapulena	8097	Kulanakii
8049	Kawaikalia	8098	Ahole
8099	Poupou	8133	Paukaa
8100	Manoloa	8134	Honolii
8101	Ninole	8135	Maili
8102	Kaaheiki	8136	Wainaku
8103	Waikolu	8137	Pukihae
8104	Waikaumalo	8138	Wailuku
8105	Waiehu	8139	Wailoa
8106	Nanue	8140	Kaahakini
8107	Opea	8141	Kīlauea
8108	Peleau	8142	Keauhou Point
8109	Umauma	8143	Kīlauea Crater
8110	Hakalau	8144	Kapāpala
8111	Kolekole	8145	Pahala
8112	Paheehee	8146	Hīlea
8113	Honomū	8147	Nā’ālehu
8114	Laimi	8148	Kiolakaʻa
8115	Kapehu	8149	South Point
8116	Makea	8150	Kauna
8117	Alia	8151	Kiʻilae
8118	Makahanaloa	8152	Kealakekua
8119	Waimaauou	8153	Waiʻaha
8120	Waiaama	8154	Honokōhau
8121	Kawainui	8155	Keahole
8122	Onomea	8156	Kīholo
8123	Alakahi	8157	Pōhakuloa
8124	Hanawi	8158	Kamakoa
8125	Kalaoa	8159	Hāloa
8126	Aleamai	8160	Lamimaumau
8127	Kaieie	8161	Waikoloa
8128	Puuokalepa	8162	Kawaihae
8129	Kaapoko	8163	Honokoa
8130	Papaikou	8164	Keawanui
8131	Kapue	8165	Lapakahi
8132	Pahoehoe	8166	Māhukona

Figure F-23 Niihau Surface Water Hydrologic Units, Unit Codes 1001 to 1013

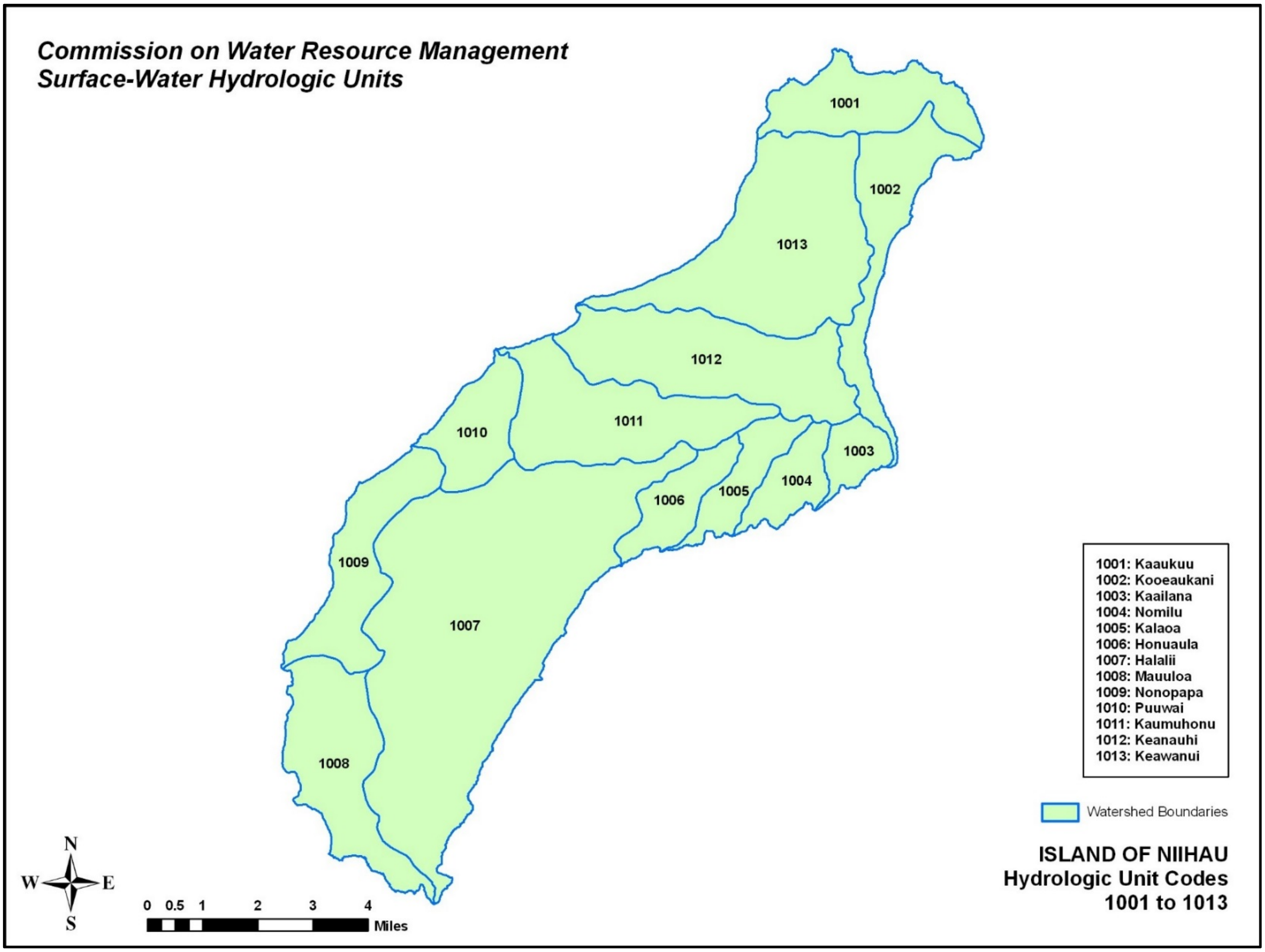


Figure F-24 Kauaʻi Surface Water Hydrologic Units, Unit Codes 2001 to 2074

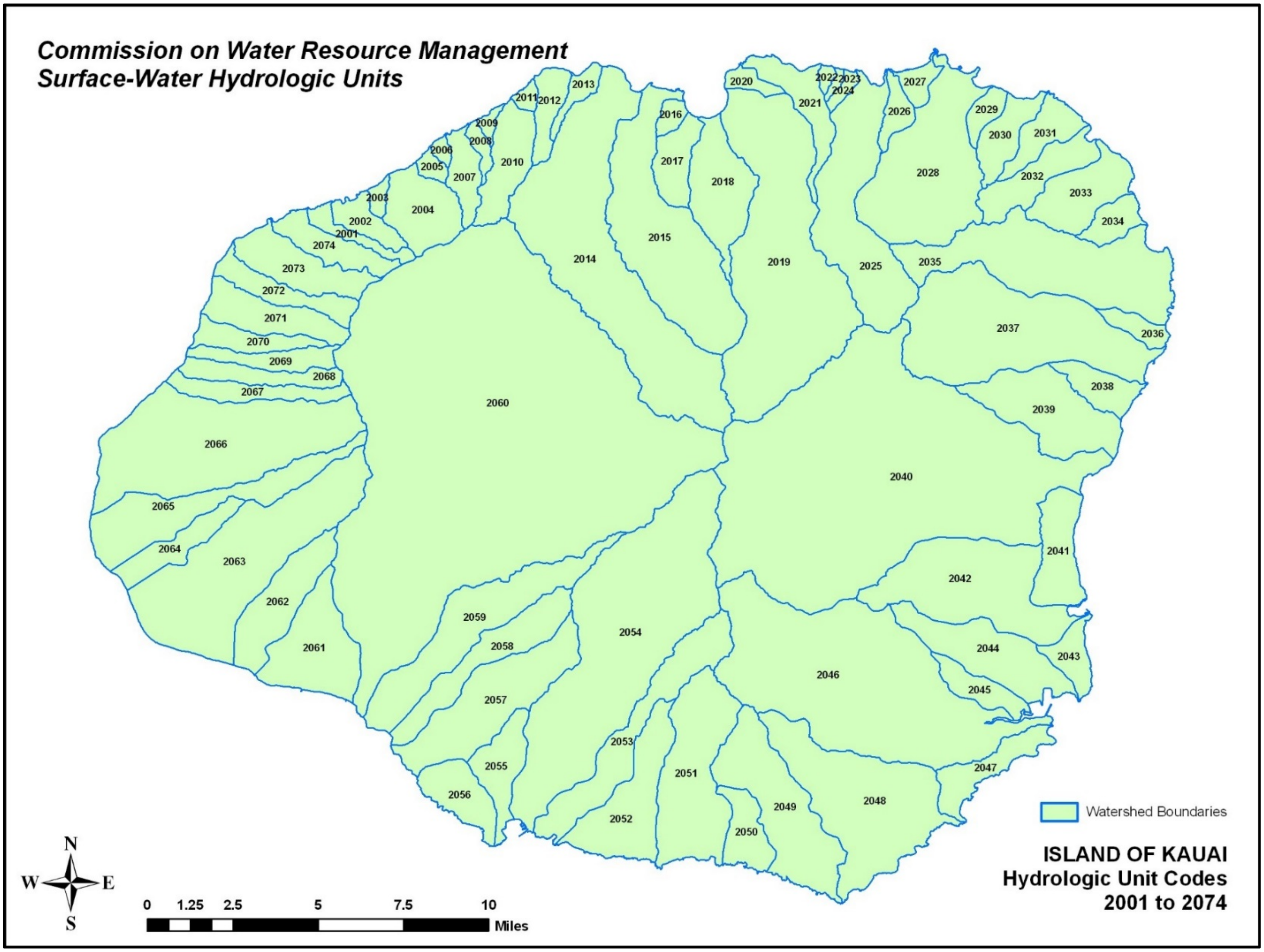


Figure F-24A Kaua‘i Surface Water Hydrologic Units, Unit Codes 2001 to 2013

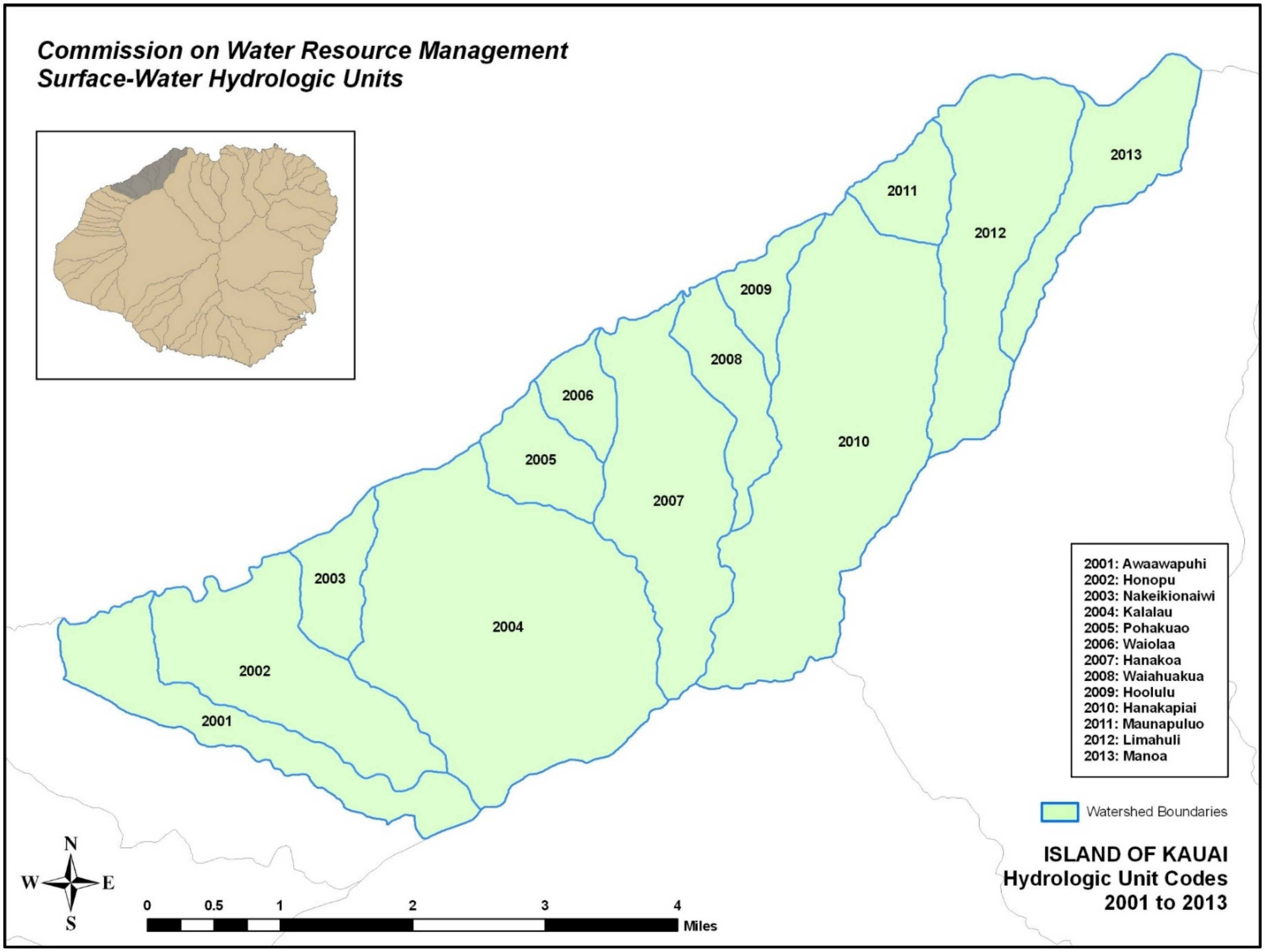


Figure F-24B Kauaʻi Surface Water Hydrologic Units, Unit Codes 2014 to 2026

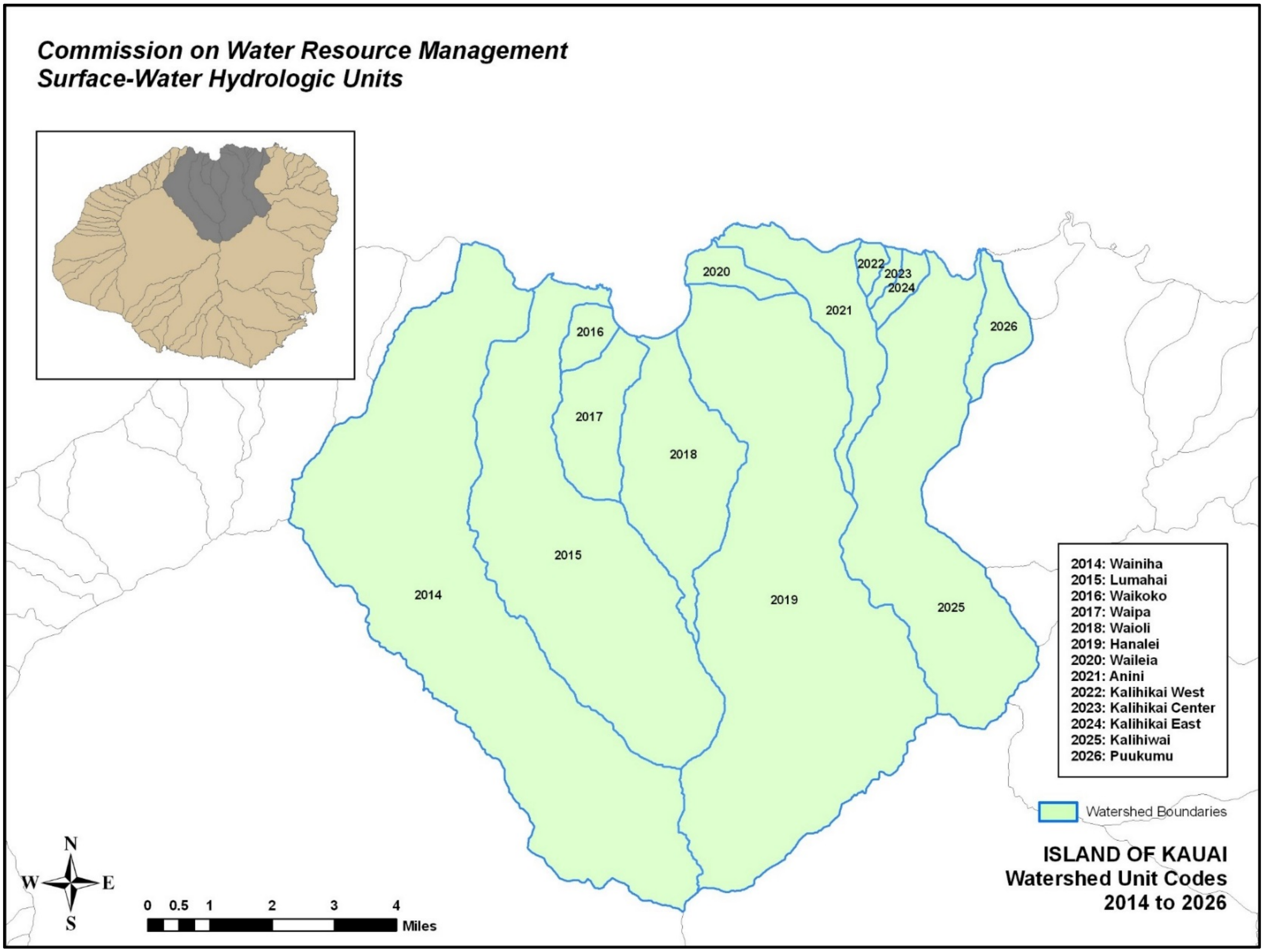


Figure F-24C Kauaʻi Surface Water Hydrologic Units, Unit Codes 2027 to 2039

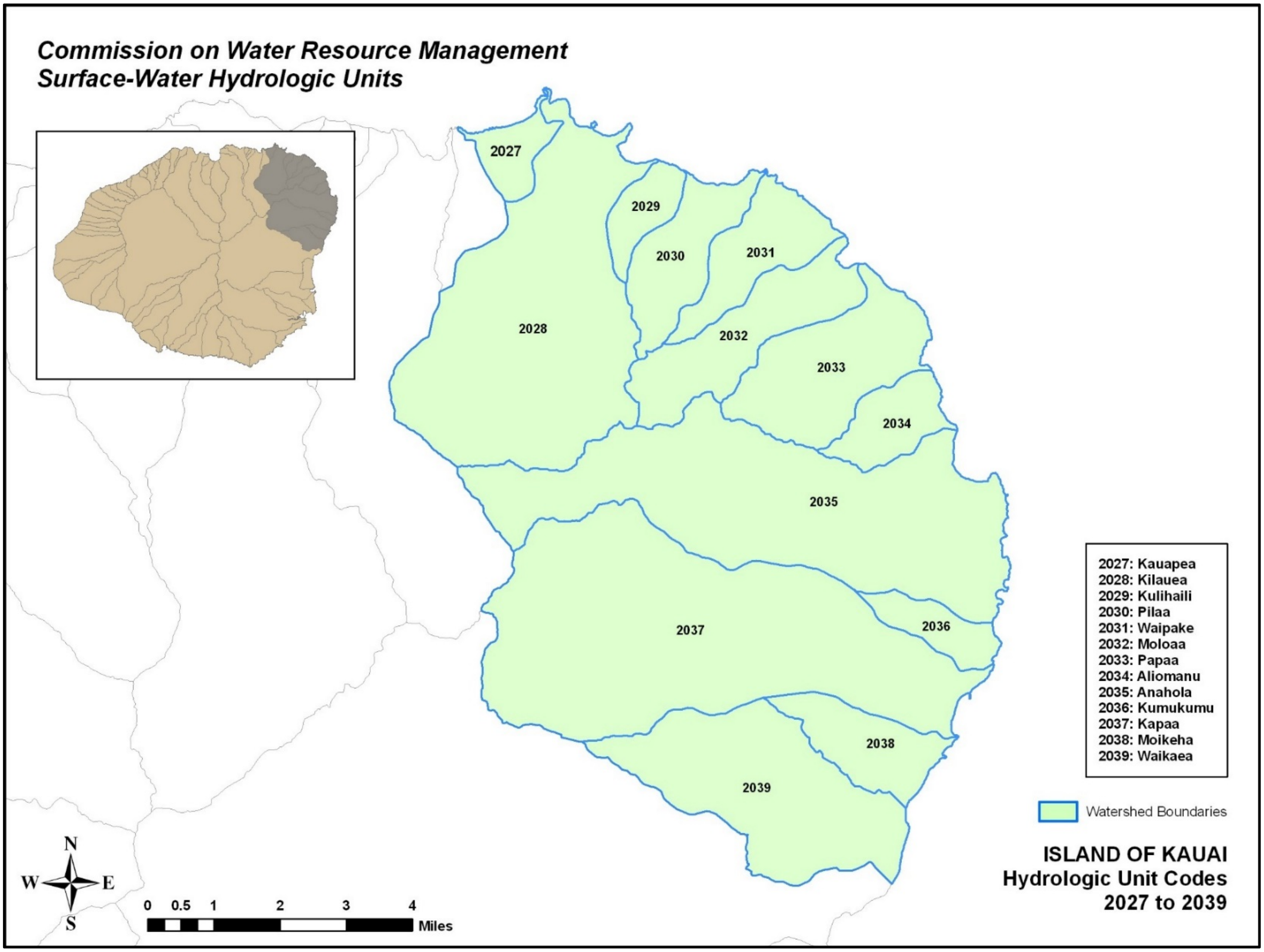


Figure F-24D Kauaʻi Surface Water Hydrologic Units, Unit Codes 2040 to 2052

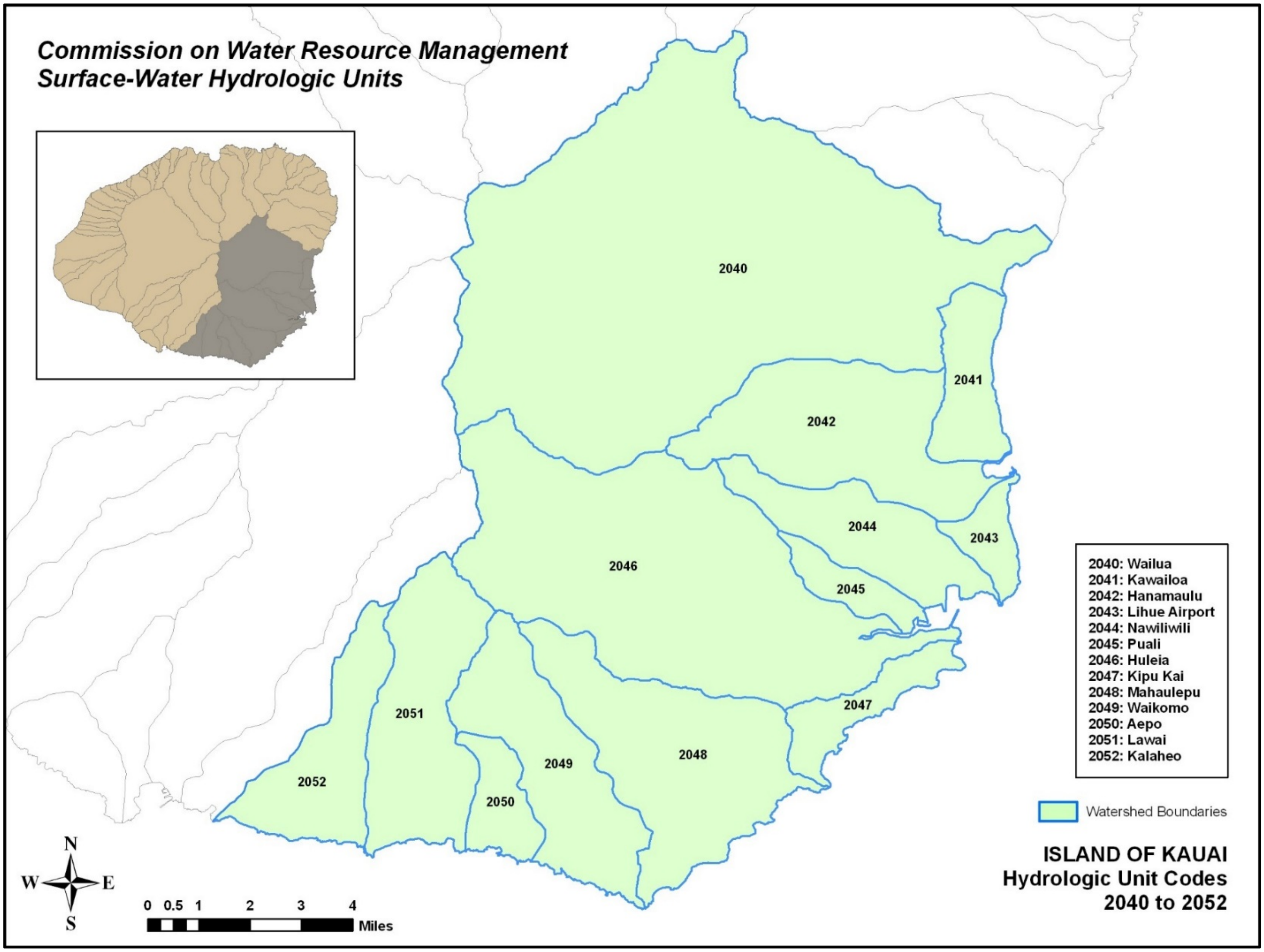


Figure F-24E Kaua'i Surface Water Hydrologic Units, Unit Codes 2053 to 2060

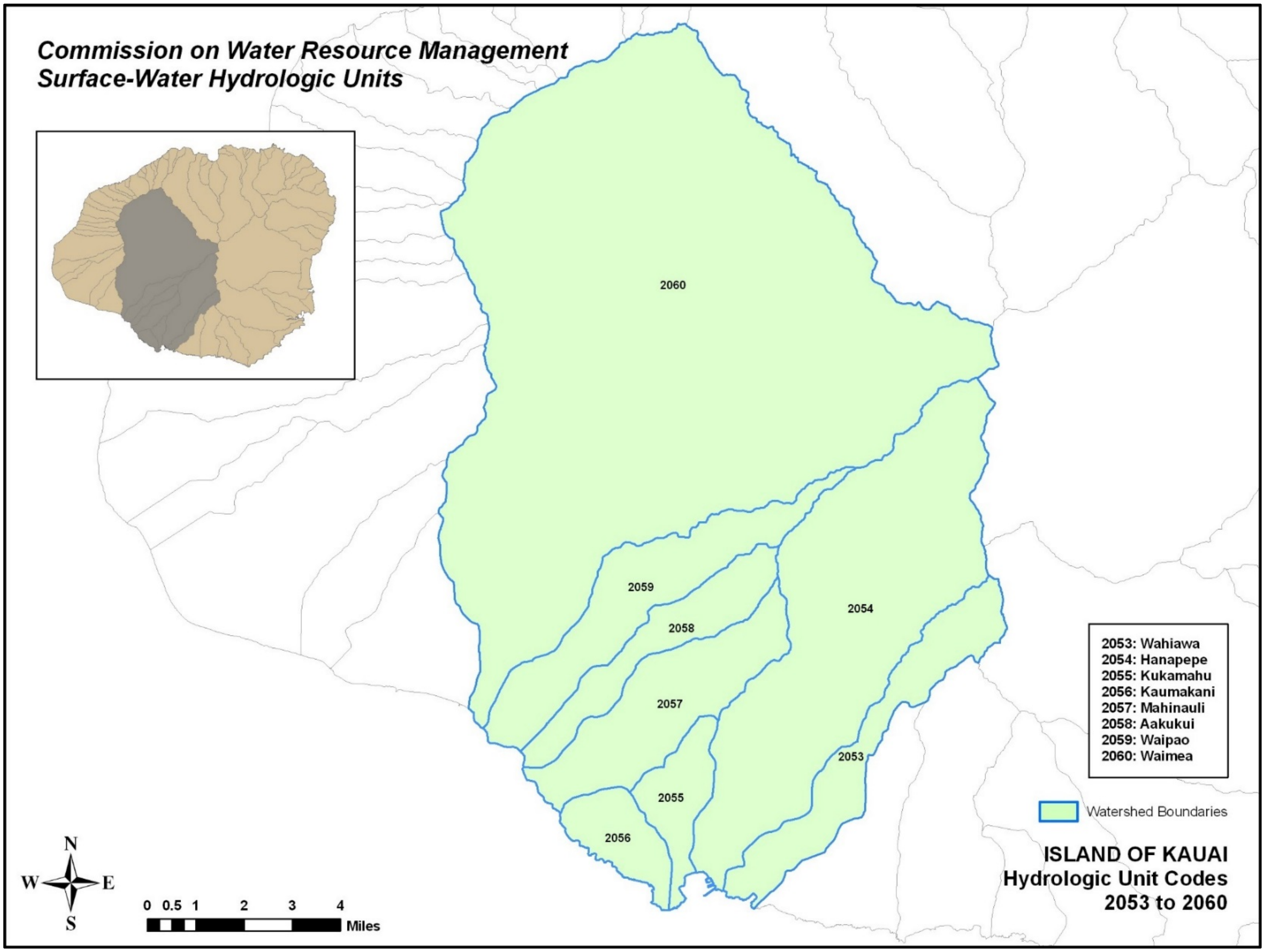


Figure F-24F Kauaʻi Surface Water Hydrologic Units, Unit Codes 2061 to 2074

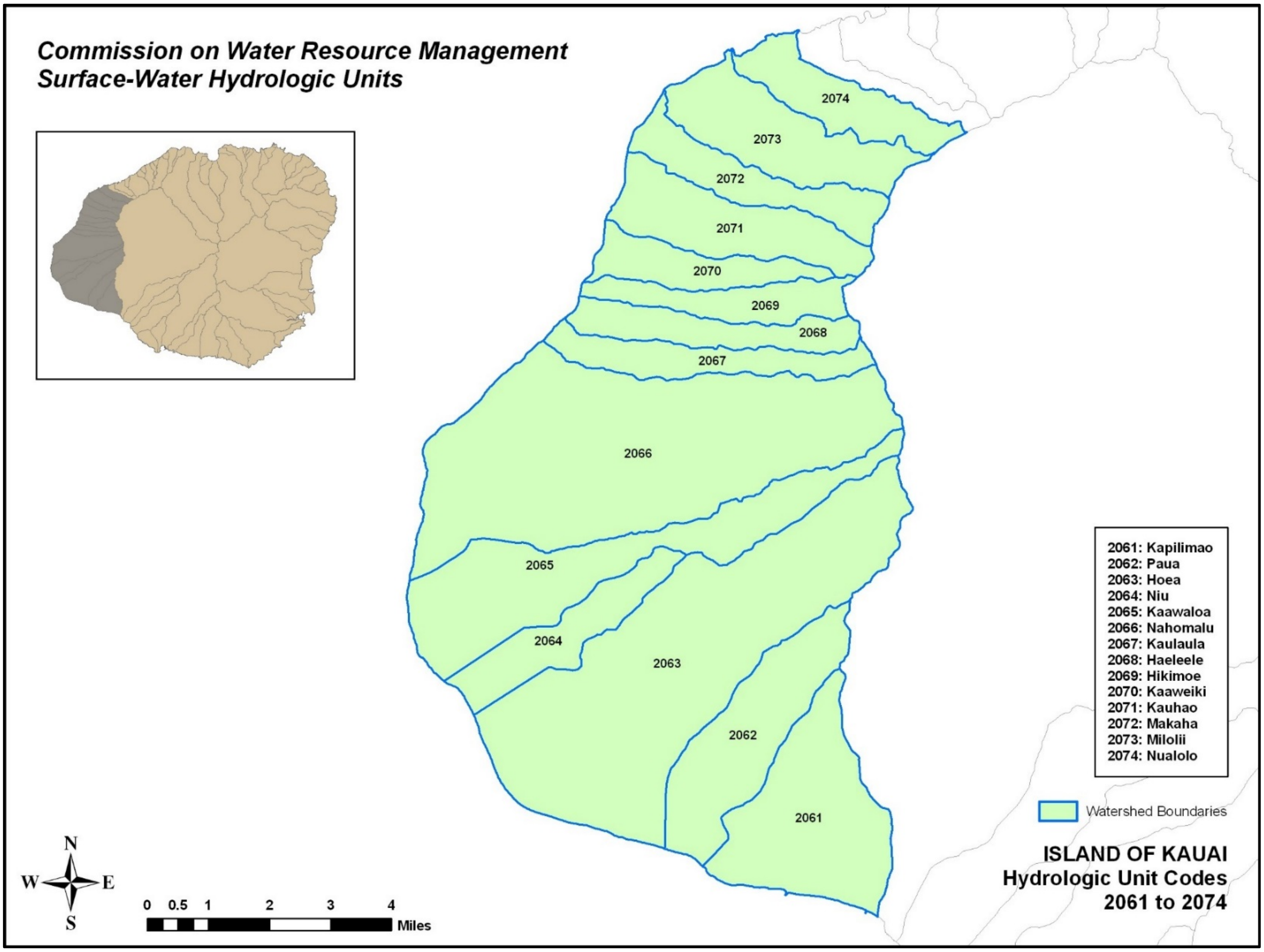


Figure F-25 O‘ahu Surface Water Hydrologic Units, Unit Codes 3001 to 3087

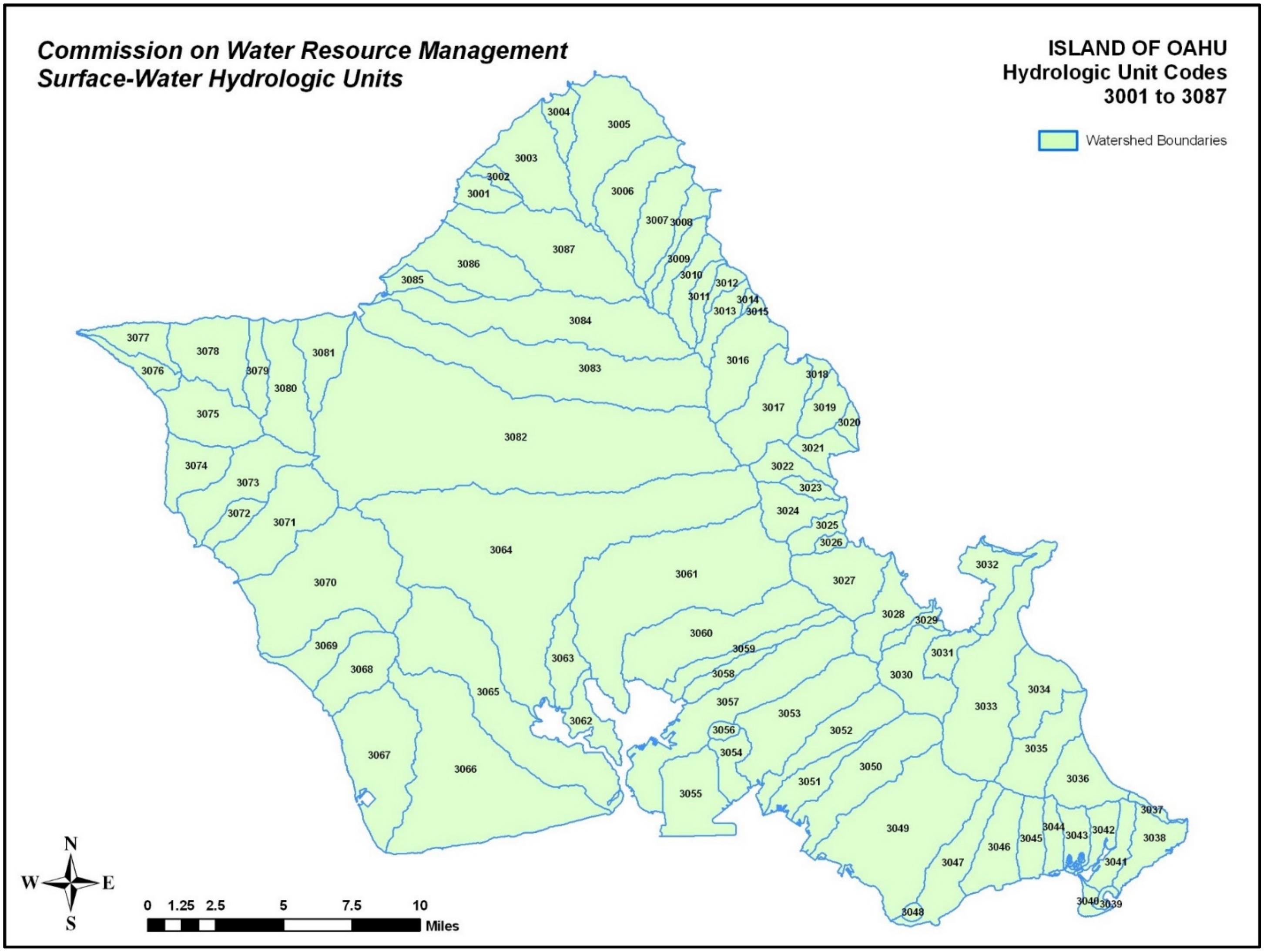


Figure F-25A Oʻahu Surface Water Hydrologic Units, Unit Codes 3001 to 3026

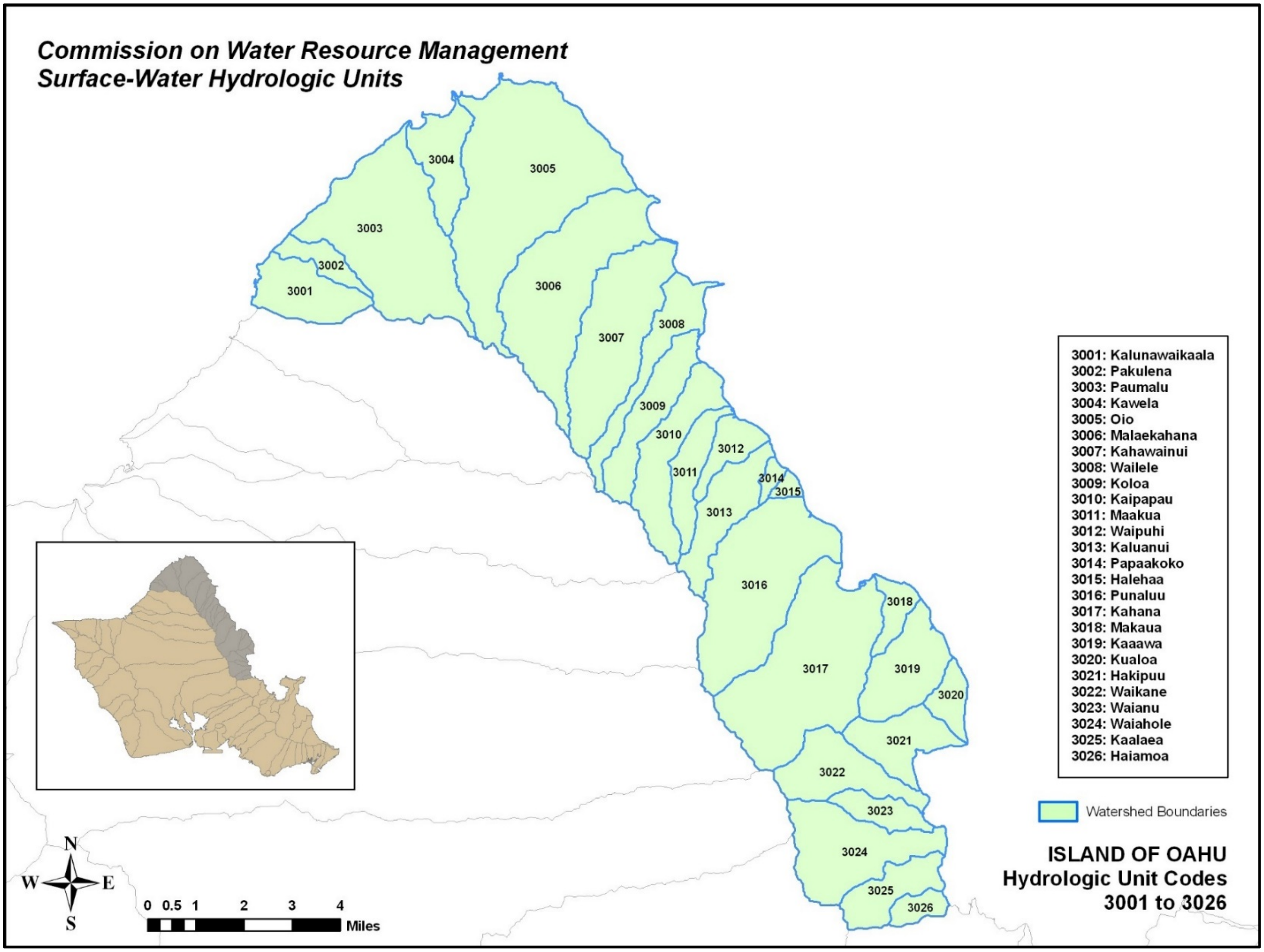


Figure F-25B O‘ahu Surface Water Hydrologic Units, Unit Codes 3027 to 3046

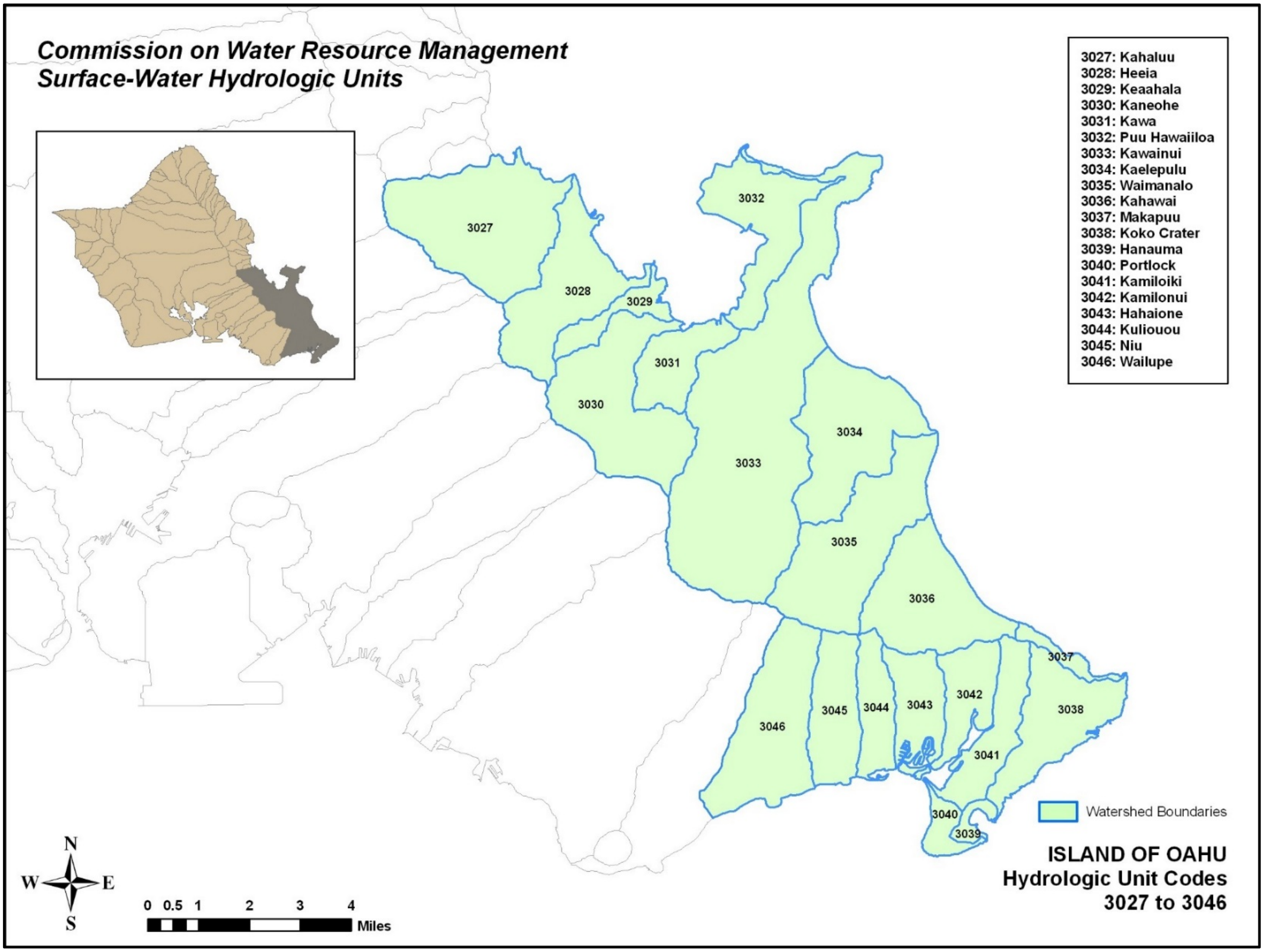


Figure F-25C O‘ahu Surface Water Hydrologic Units, Unit Codes 3047 to 3061

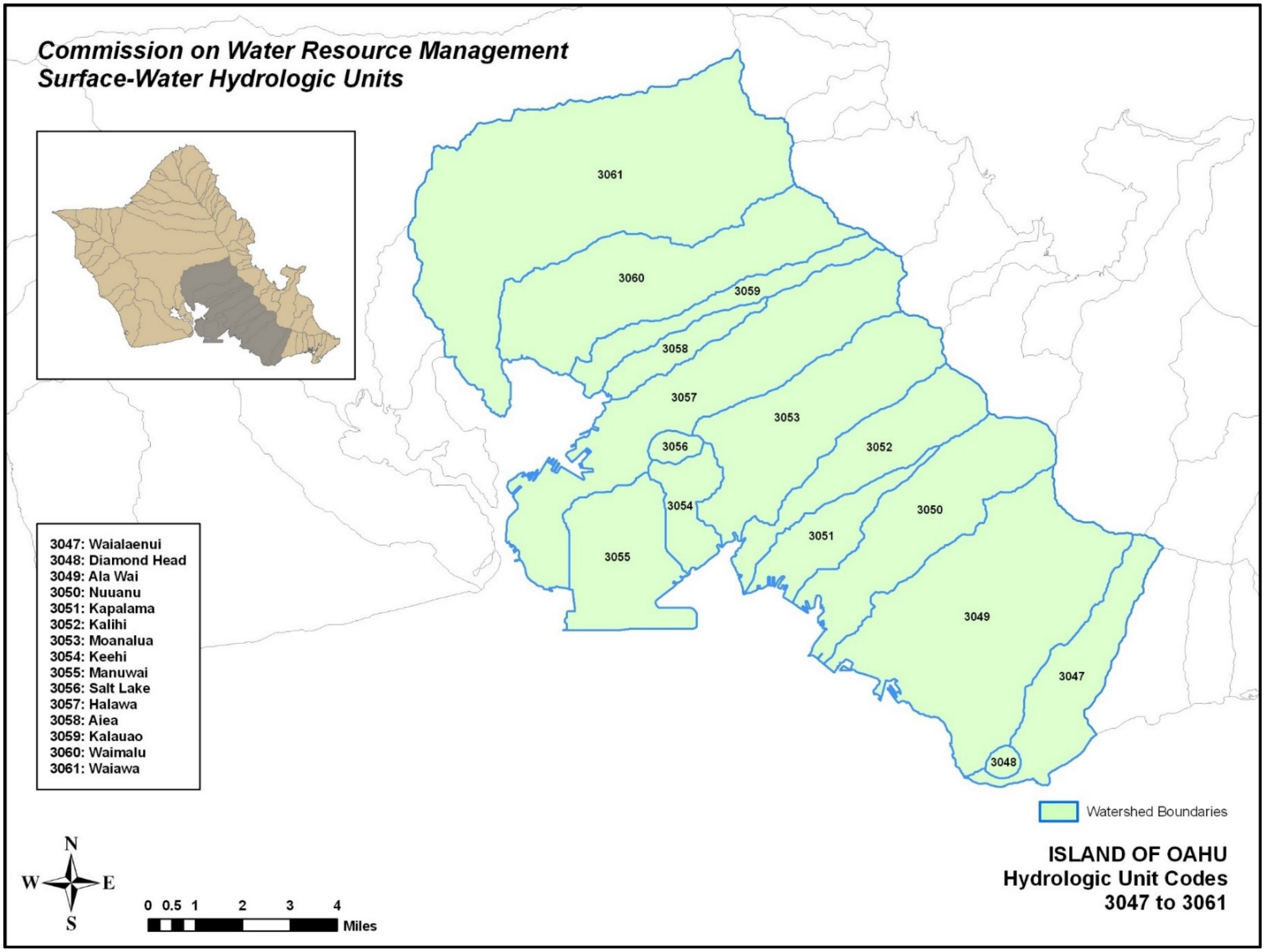


Figure F-25D O‘ahu Surface Water Hydrologic Units, Unit Codes 3062 to 3070

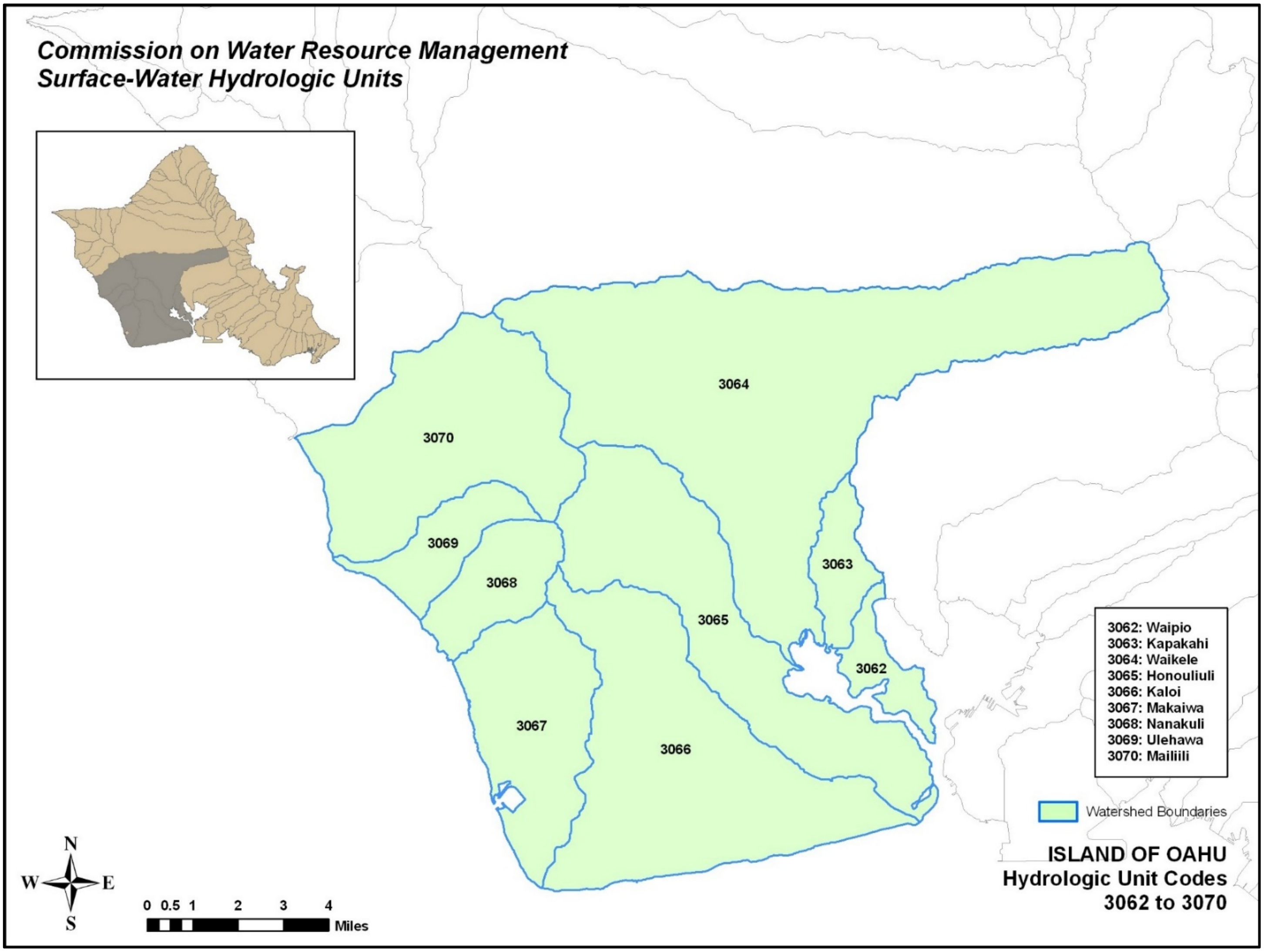


Figure F-25E O‘ahu Surface Water Hydrologic Units, Unit Codes 3071 to 3081

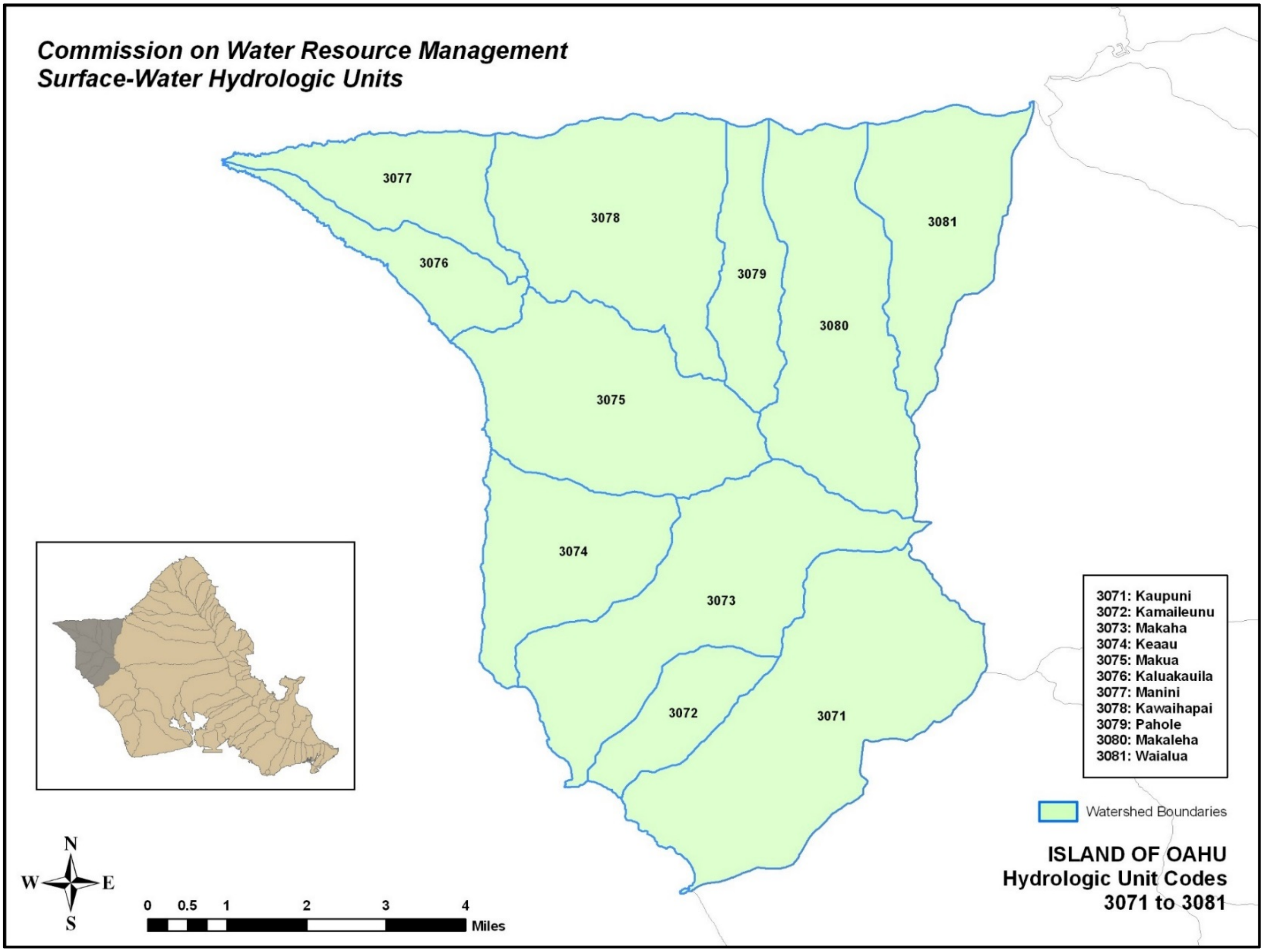


Figure F-25F O‘ahu Surface Water Hydrologic Units, Unit Codes 3082 to 3087

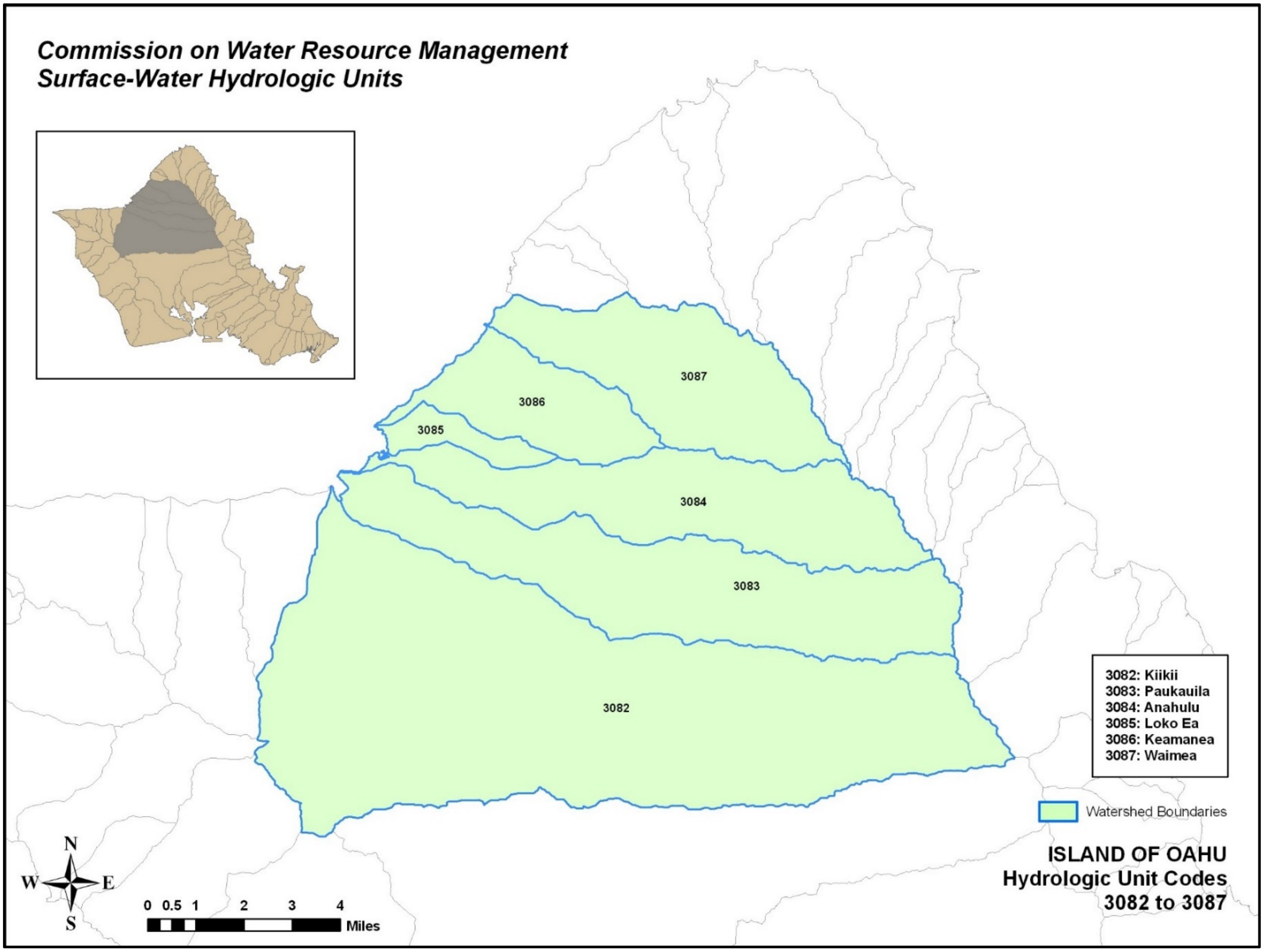


Figure F-26 Moloka‘i Surface Water Hydrologic Units, Unit Codes 4001 to 4050

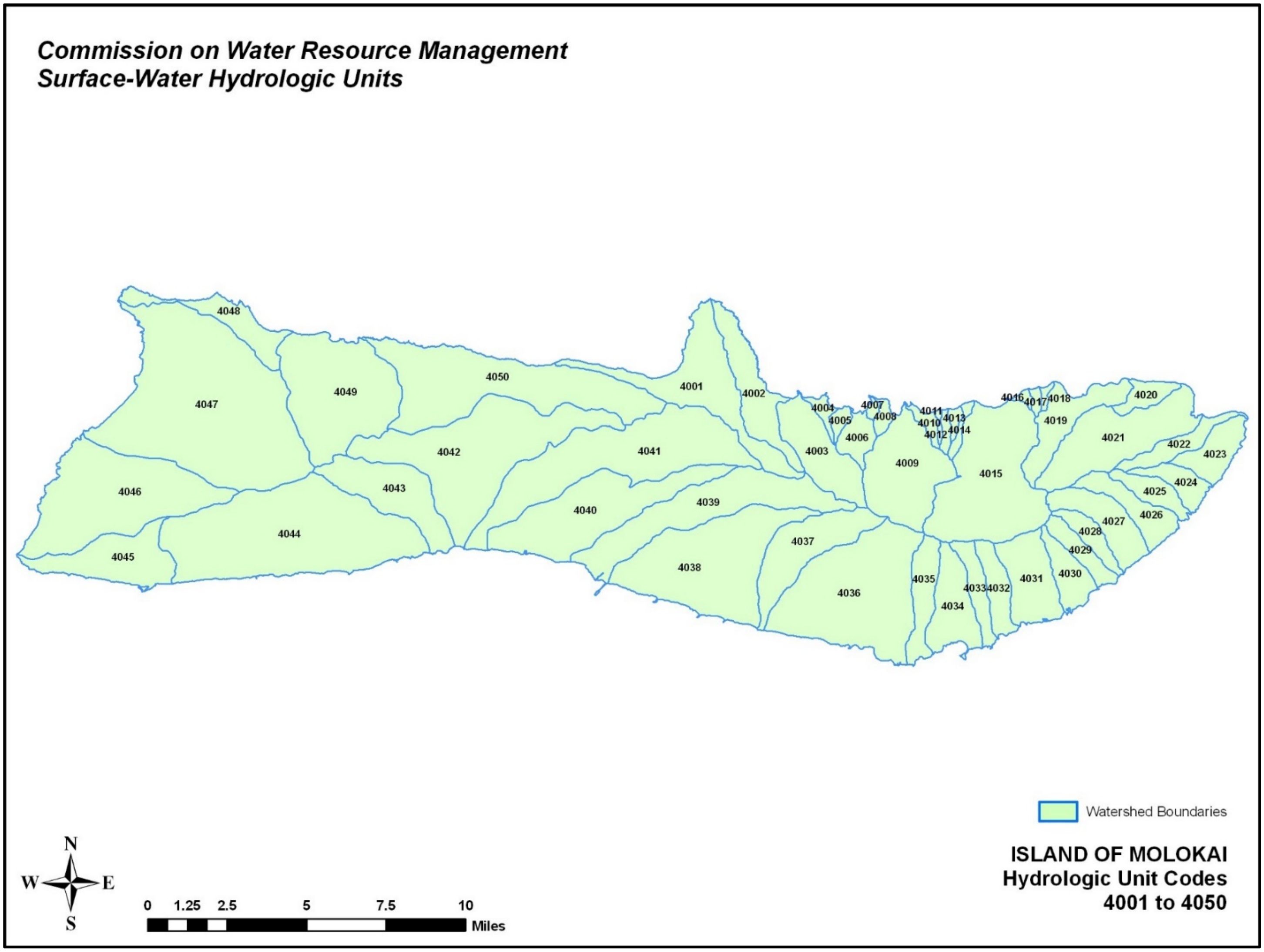


Figure F-26A Moloka'i Surface Water Hydrologic Units, Unit Codes 4001 to 4009

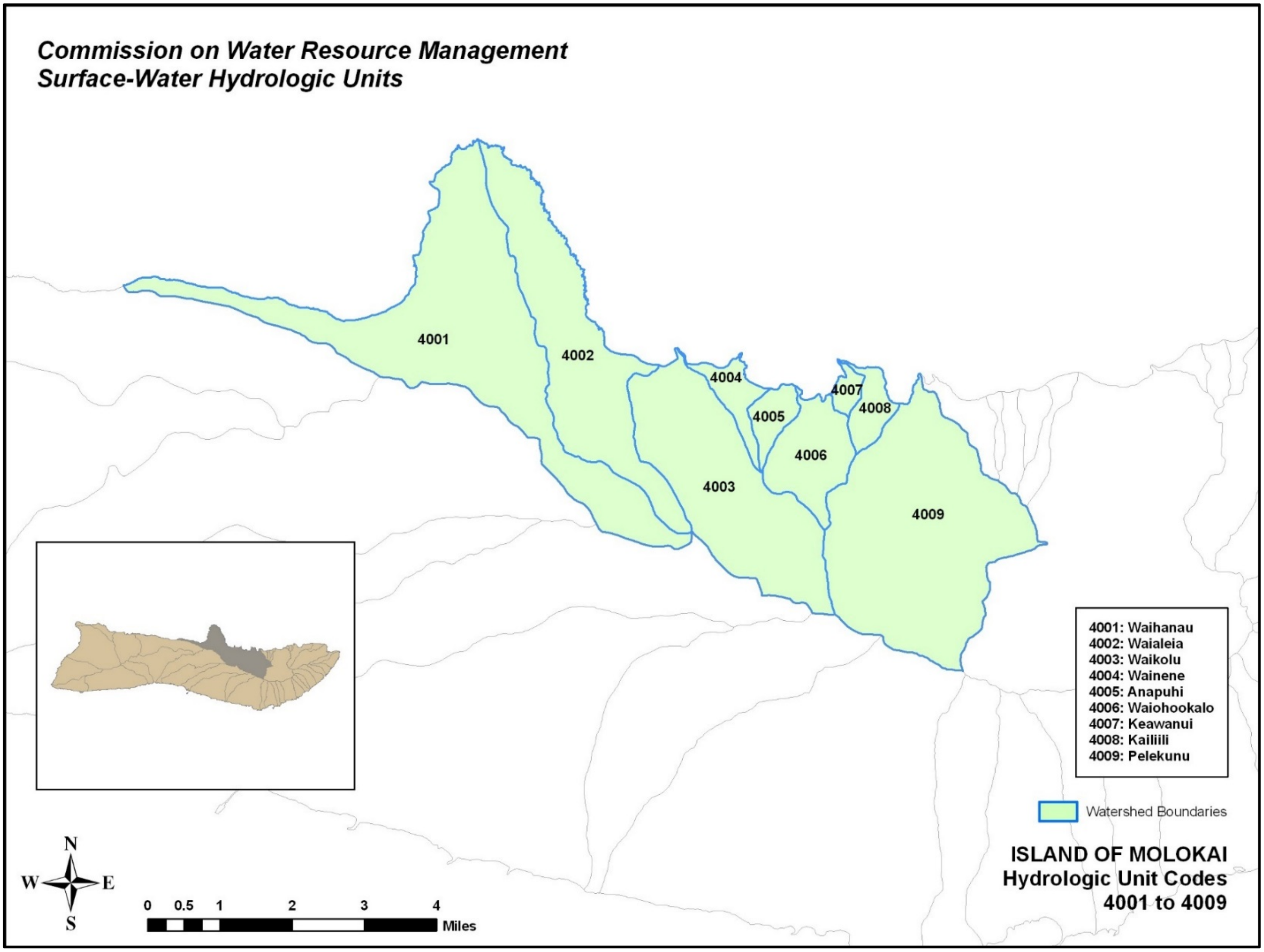


Figure F-26B Moloka'i Surface Water Hydrologic Units, Unit Codes 4010 to 4035

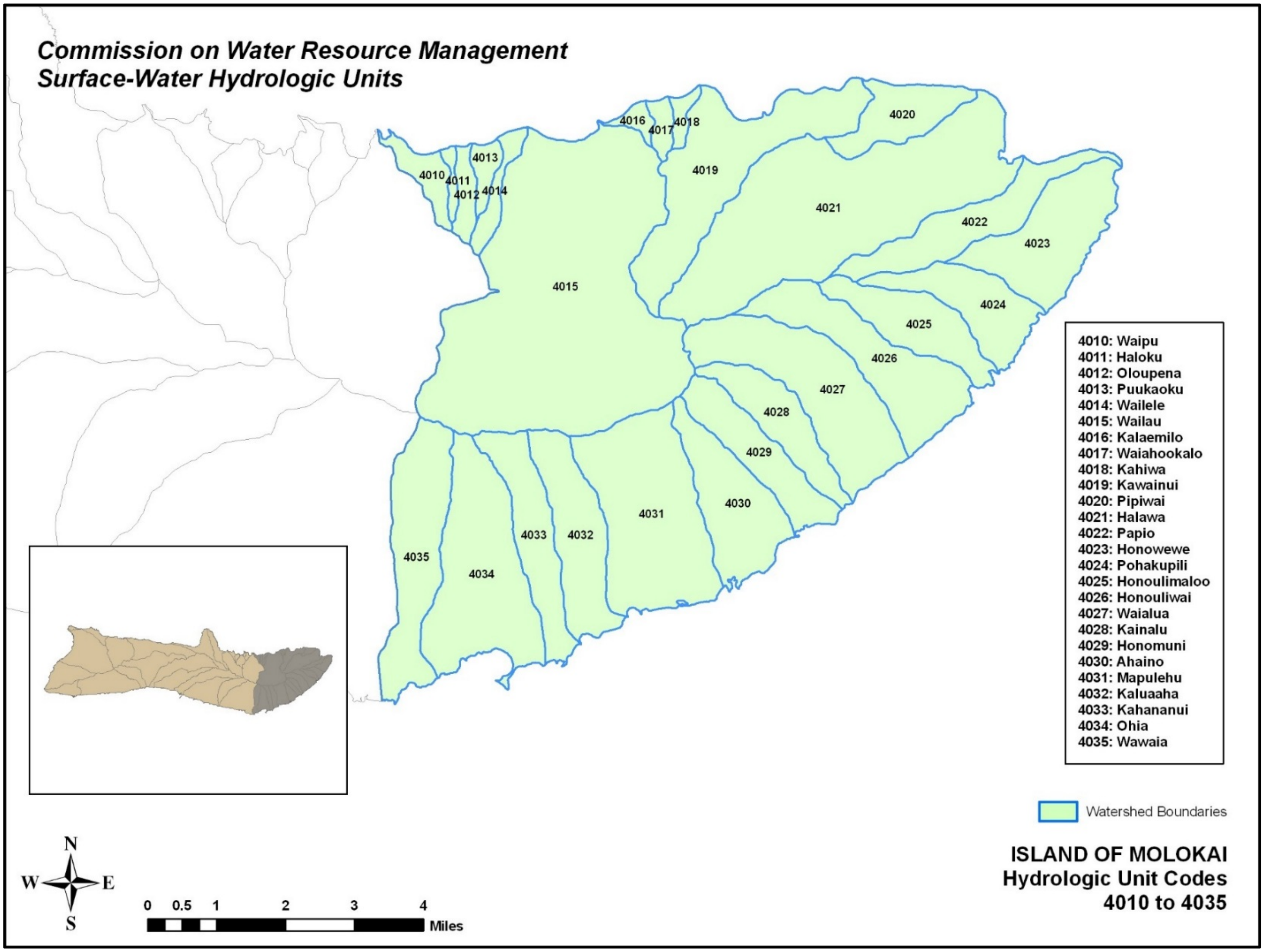


Figure F-26C Moloka‘i Surface Water Hydrologic Units, Unit Codes 4036 to 4041

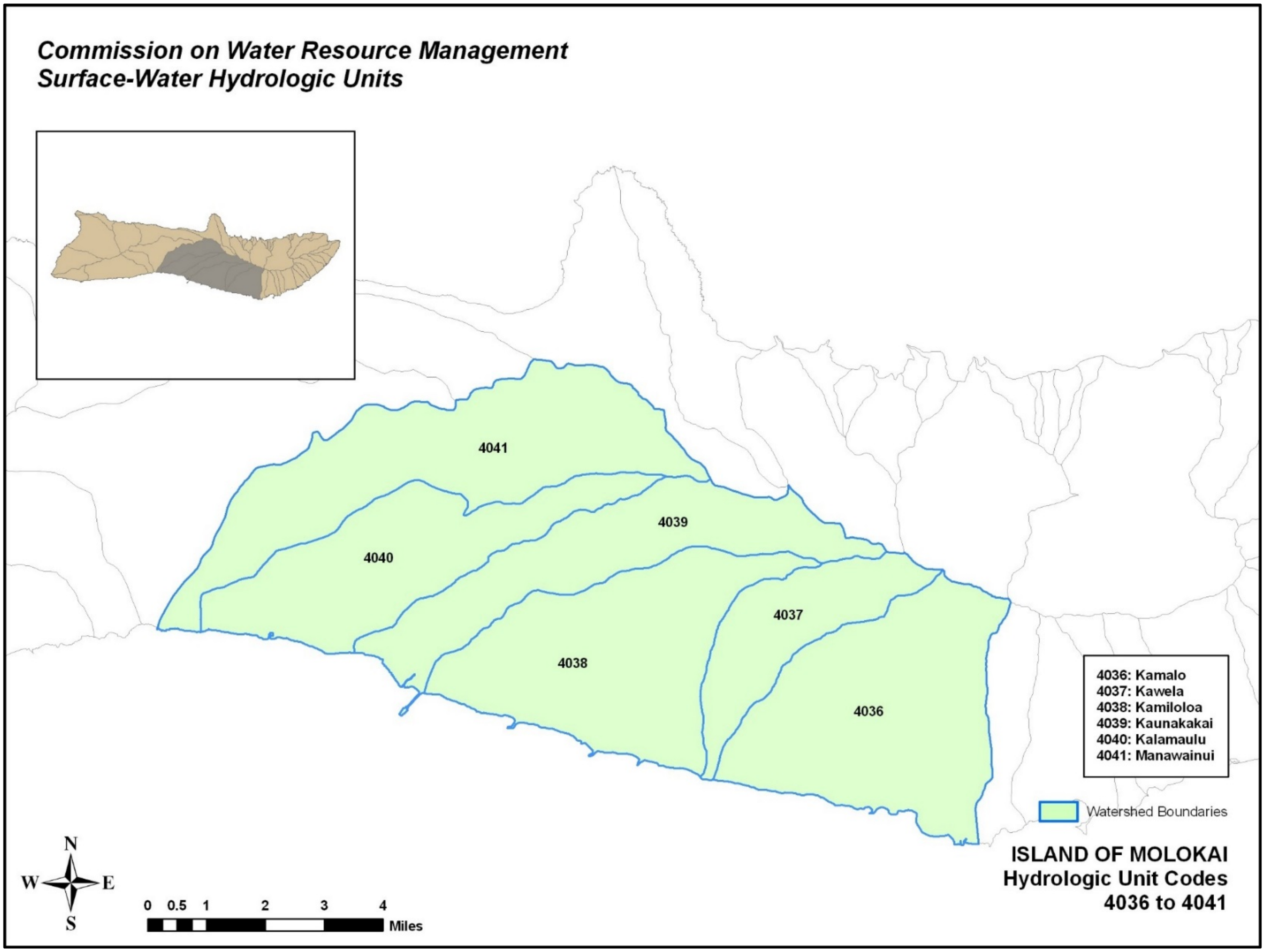


Figure F-26D Moloka‘i Surface Water Hydrologic Units, Unit Codes 4042 to 4050

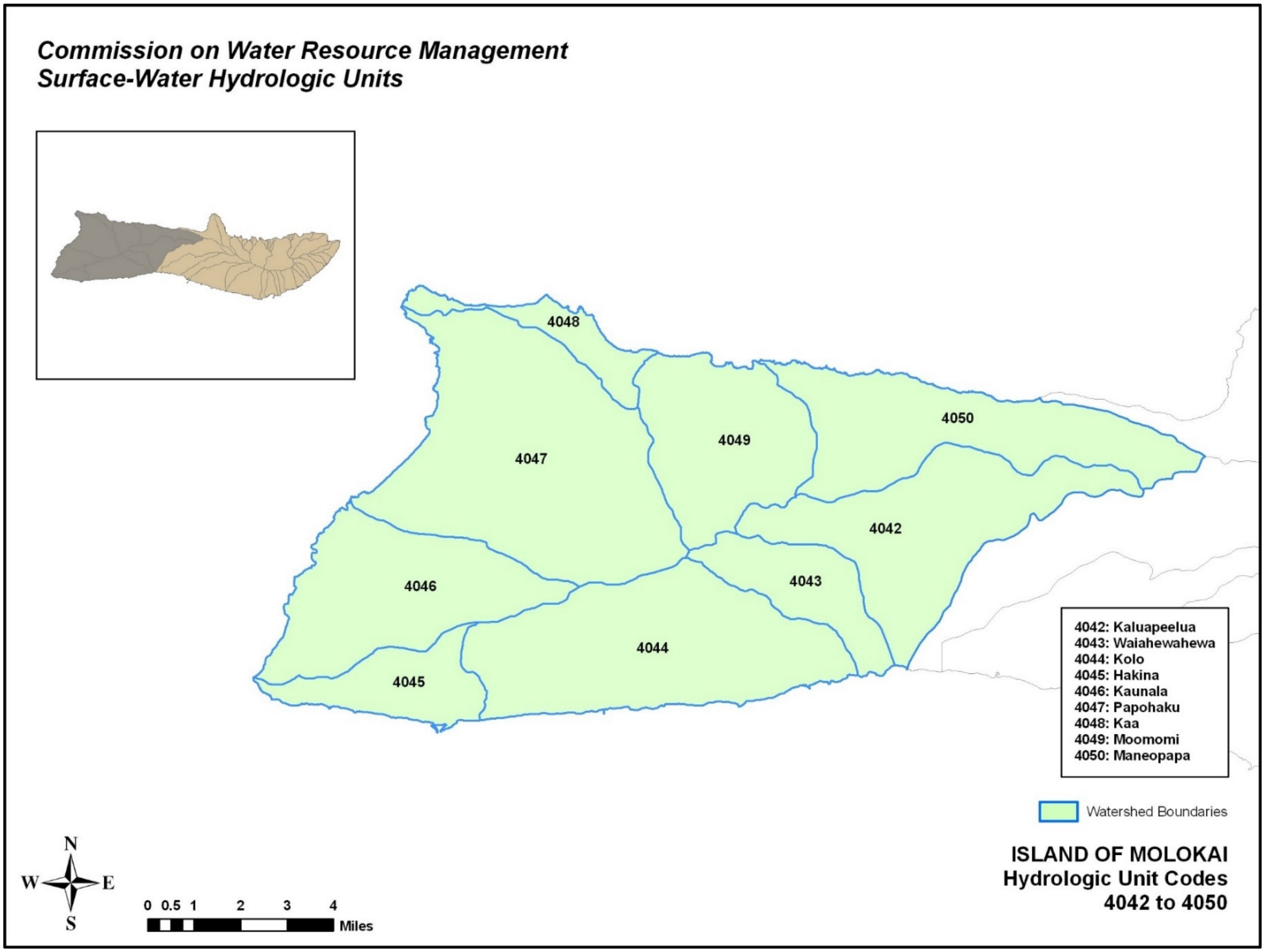


Figure F-27 Lānaʻi Surface Water Hydrologic Units, Unit Codes 5001 to 5032

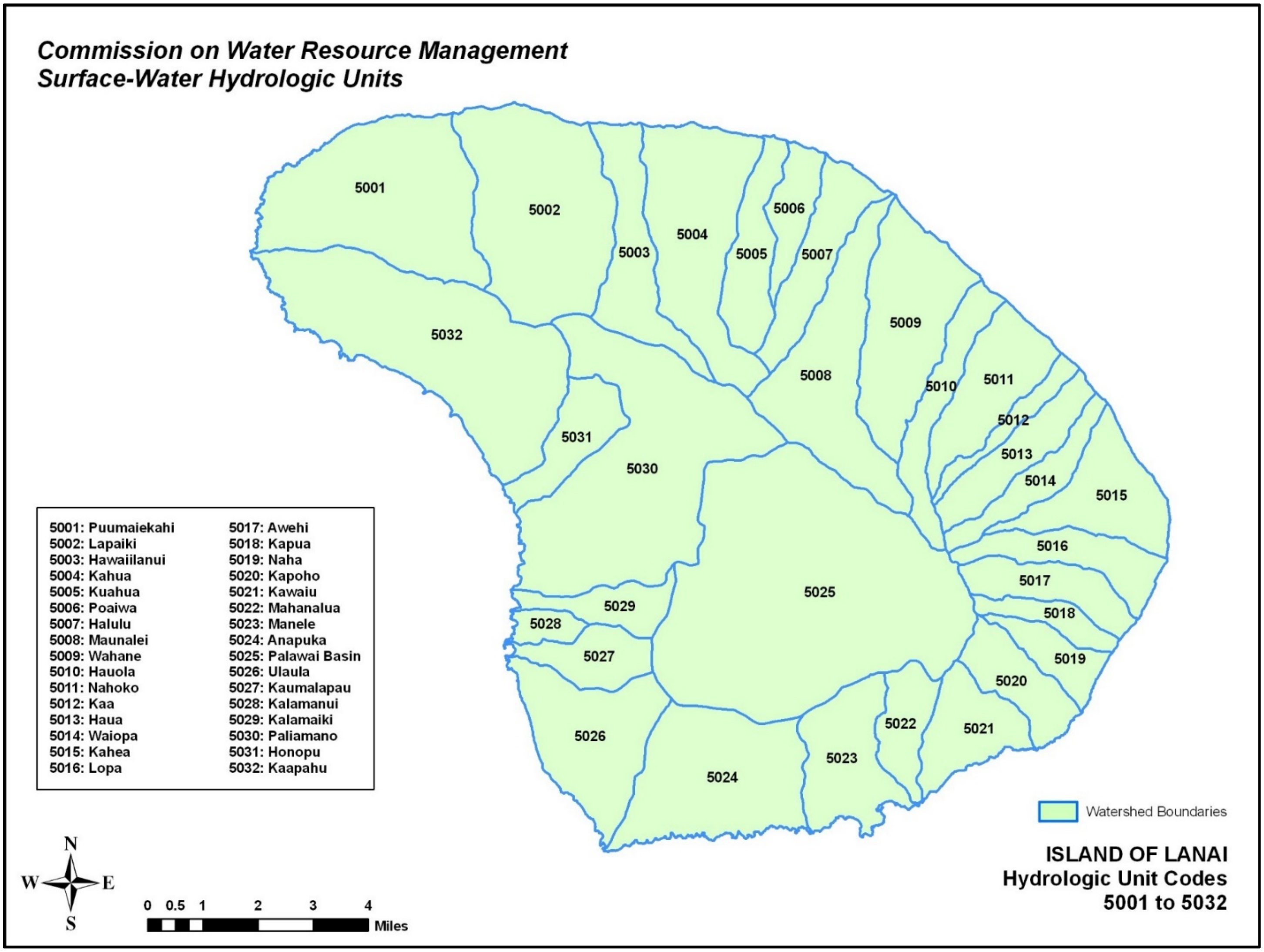


Figure F-28 Maui Surface Water Hydrologic Units, Unit Codes 6001 to 6112

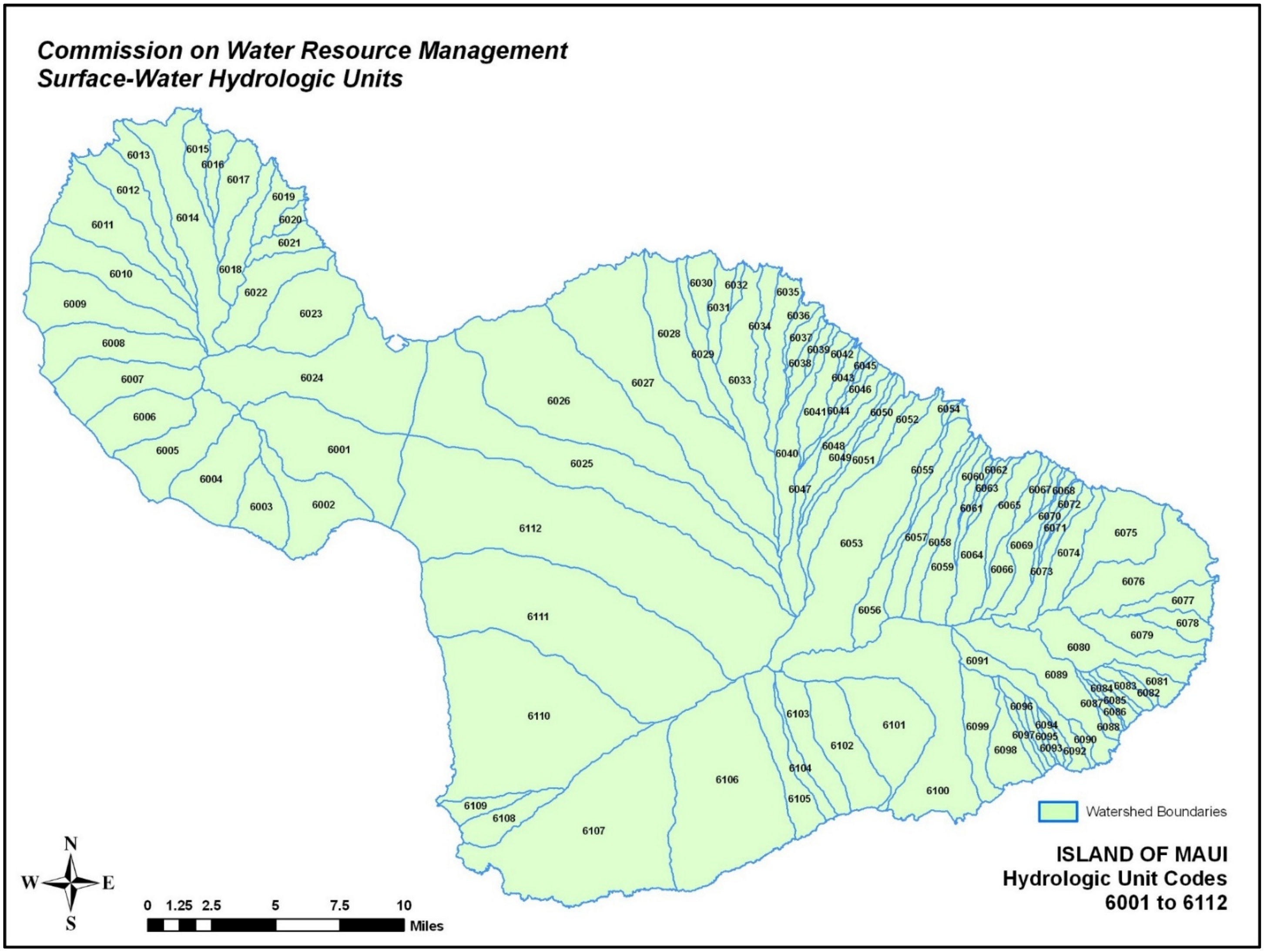


Figure F-28A Maui Surface Water Hydrologic Units, Unit Codes 6001 to 6010

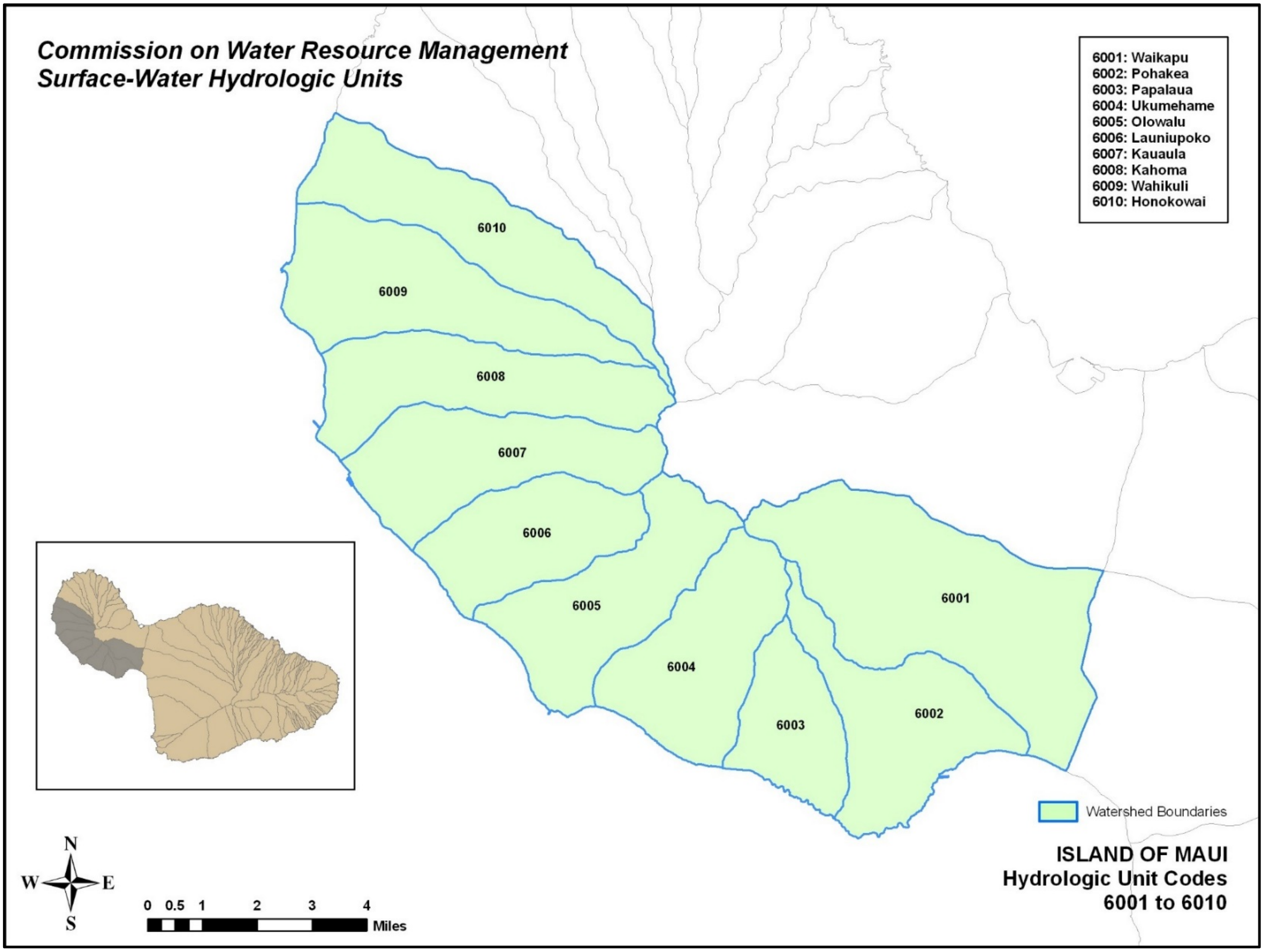


Figure F-28B Maui Surface Water Hydrologic Units, Unit Codes 6011 to 6024

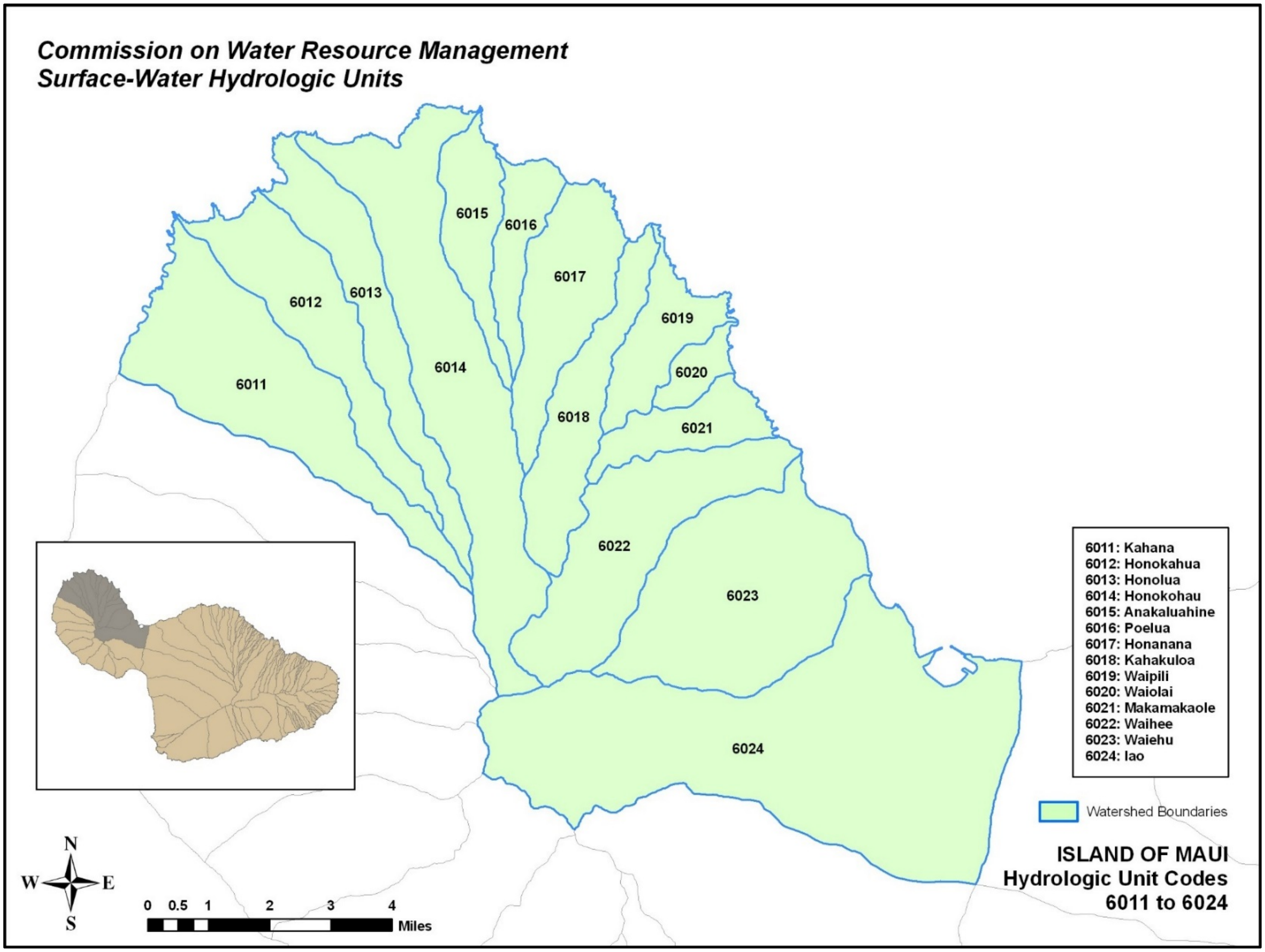


Figure F-28C Maui Surface Water Hydrologic Units, Unit Codes 6025 to 6035

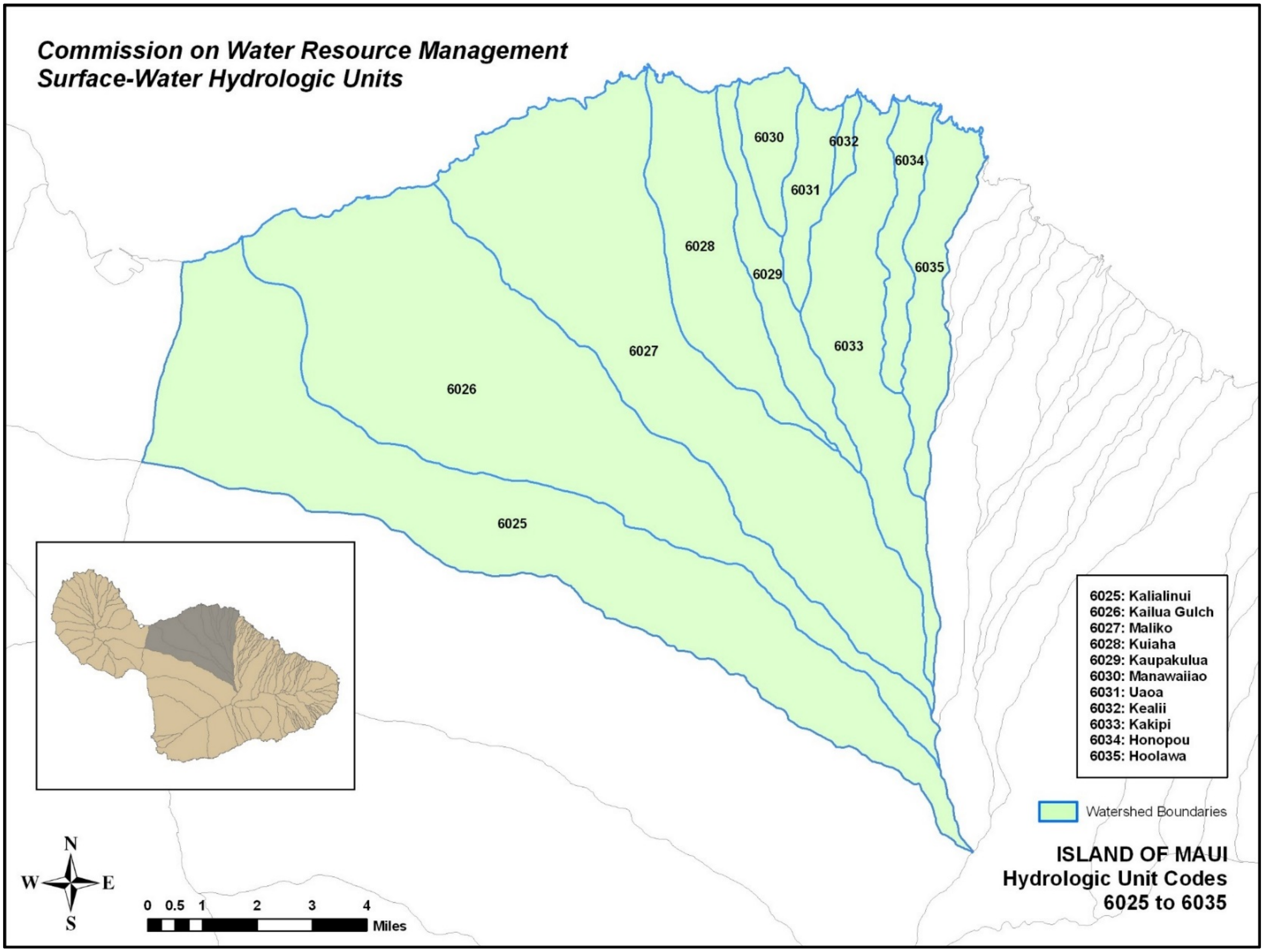


Figure F-28D Maui Surface Water Hydrologic Units, Unit Codes 6036 to 6065

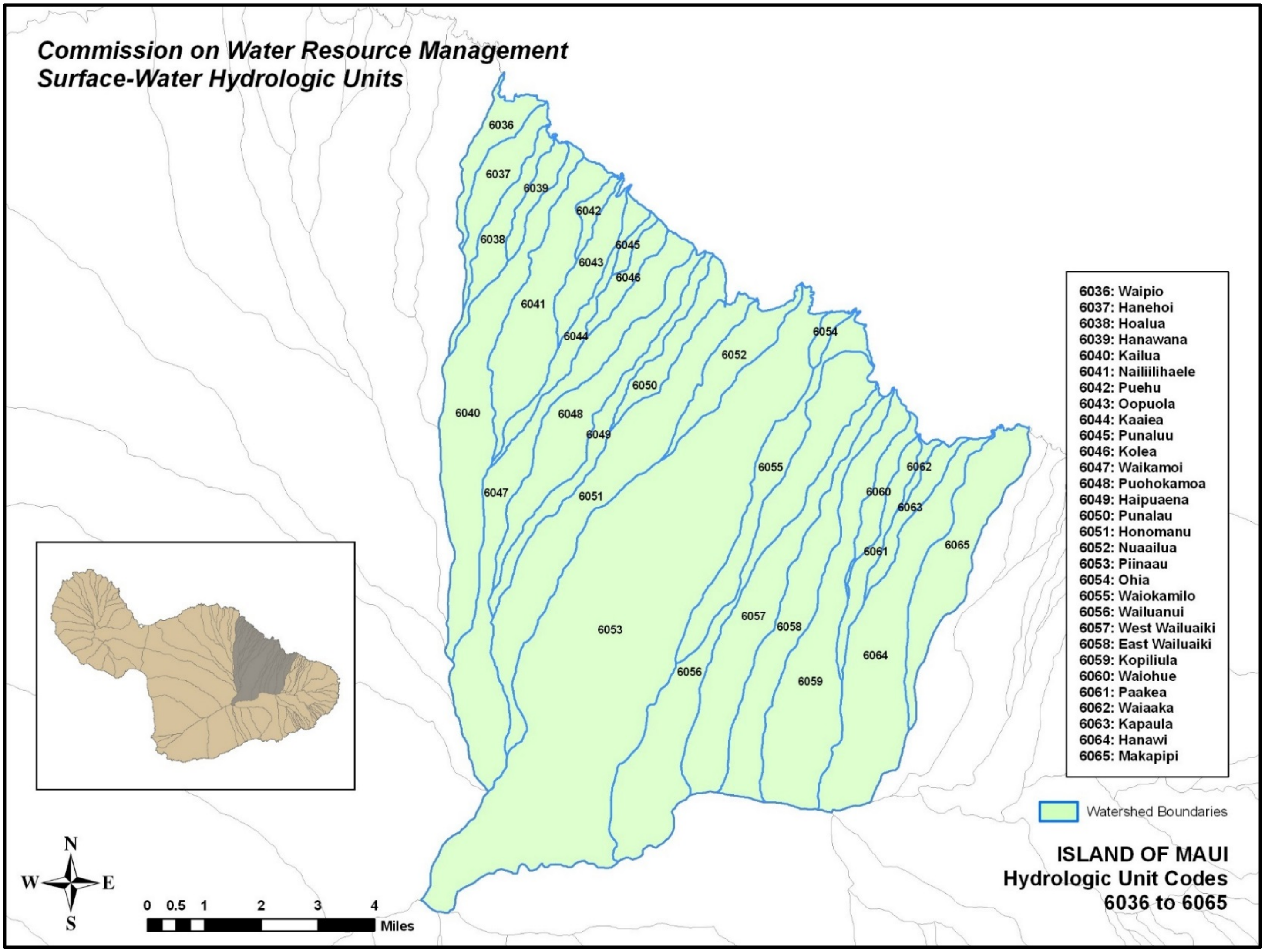


Figure F-28E Maui Surface Water Hydrologic Units, Unit Codes 6066 to 6088

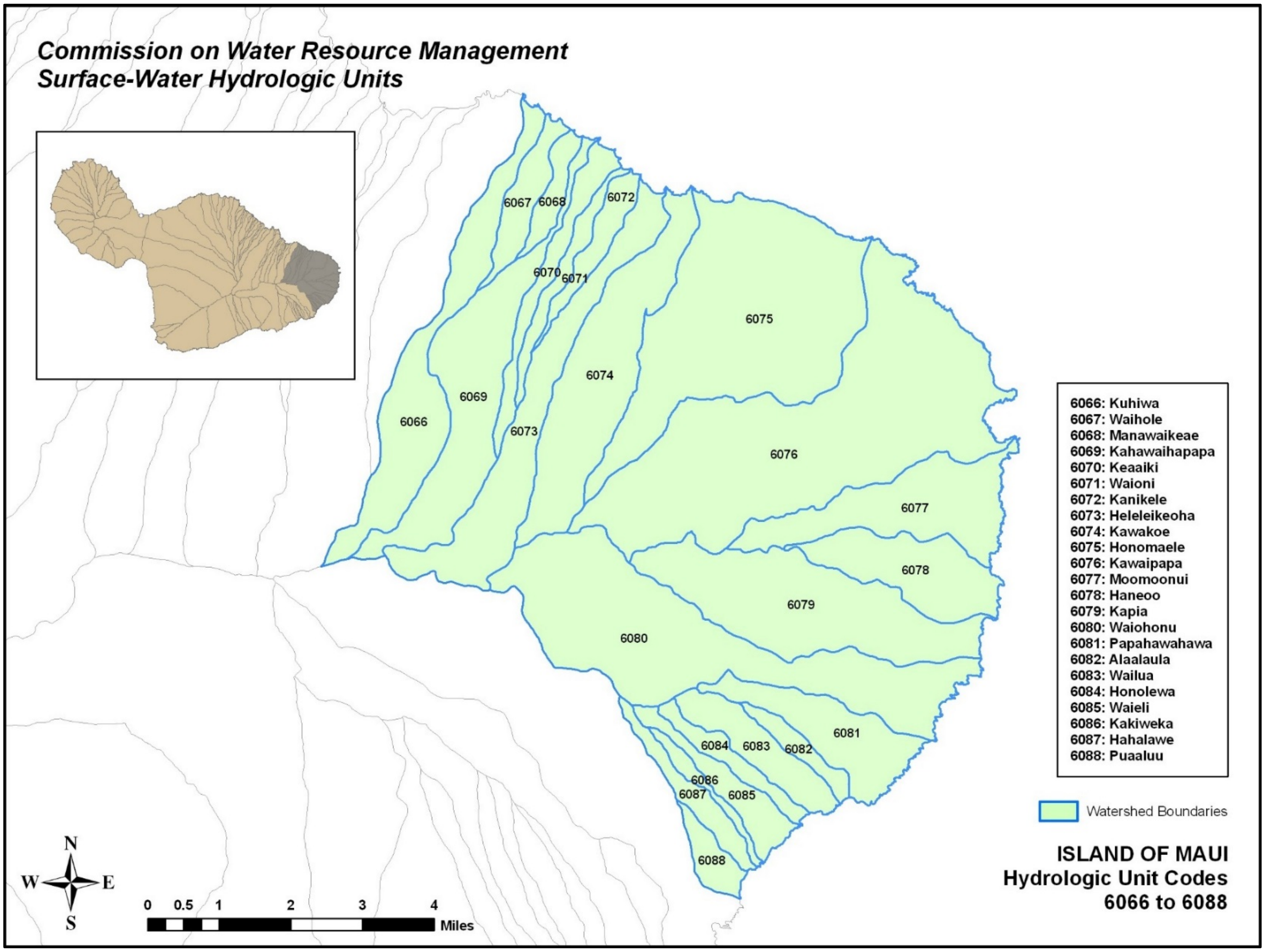


Figure F-28F Maui Surface Water Hydrologic Units, Unit Codes 6089 to 6104

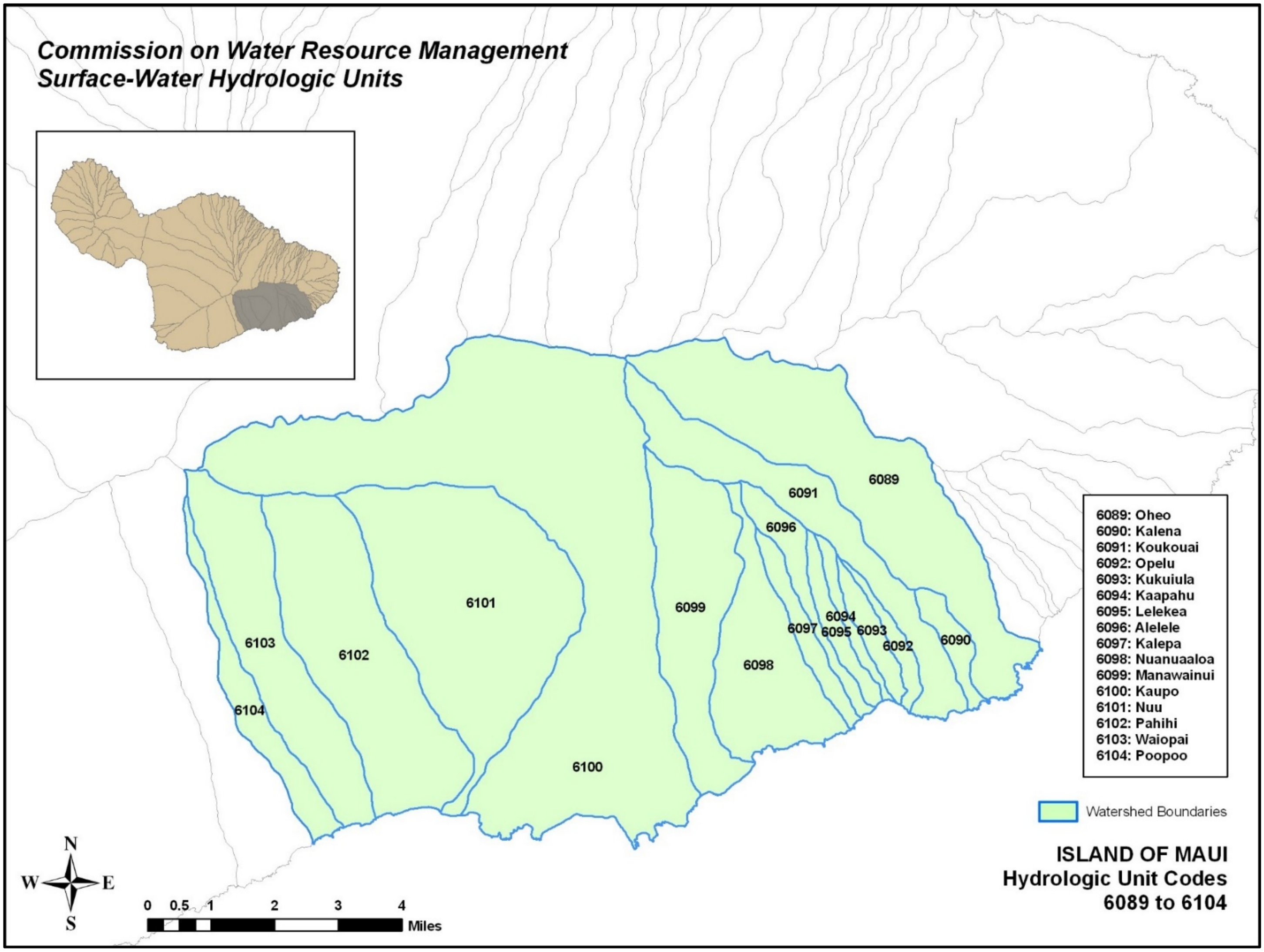


Figure F-28G Maui Surface Water Hydrologic Units, Unit Codes 6105 to 6112

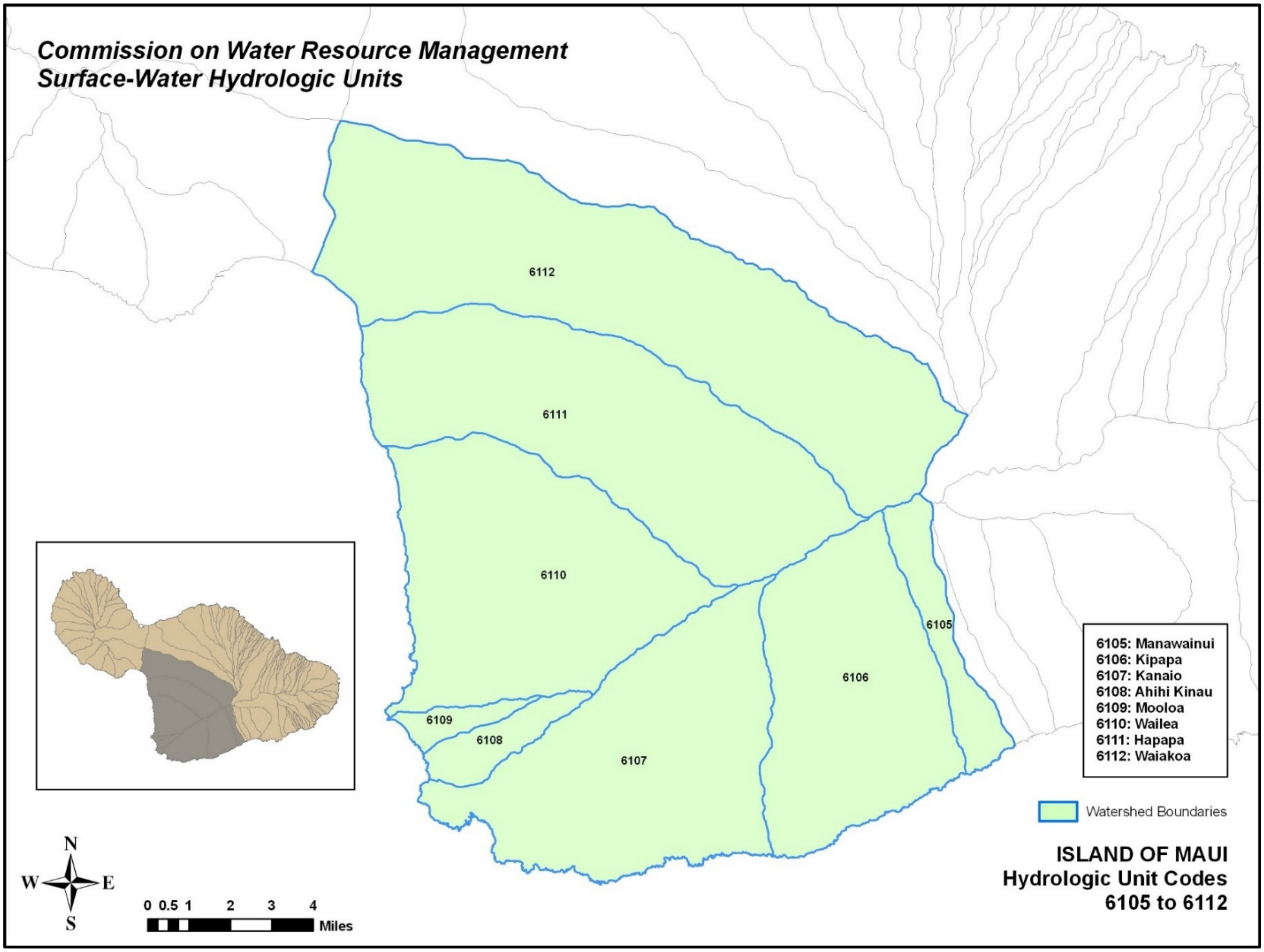


Figure F-29 Kahoʻolawe Surface Water Hydrologic Units, Unit Codes 7001 to 7024

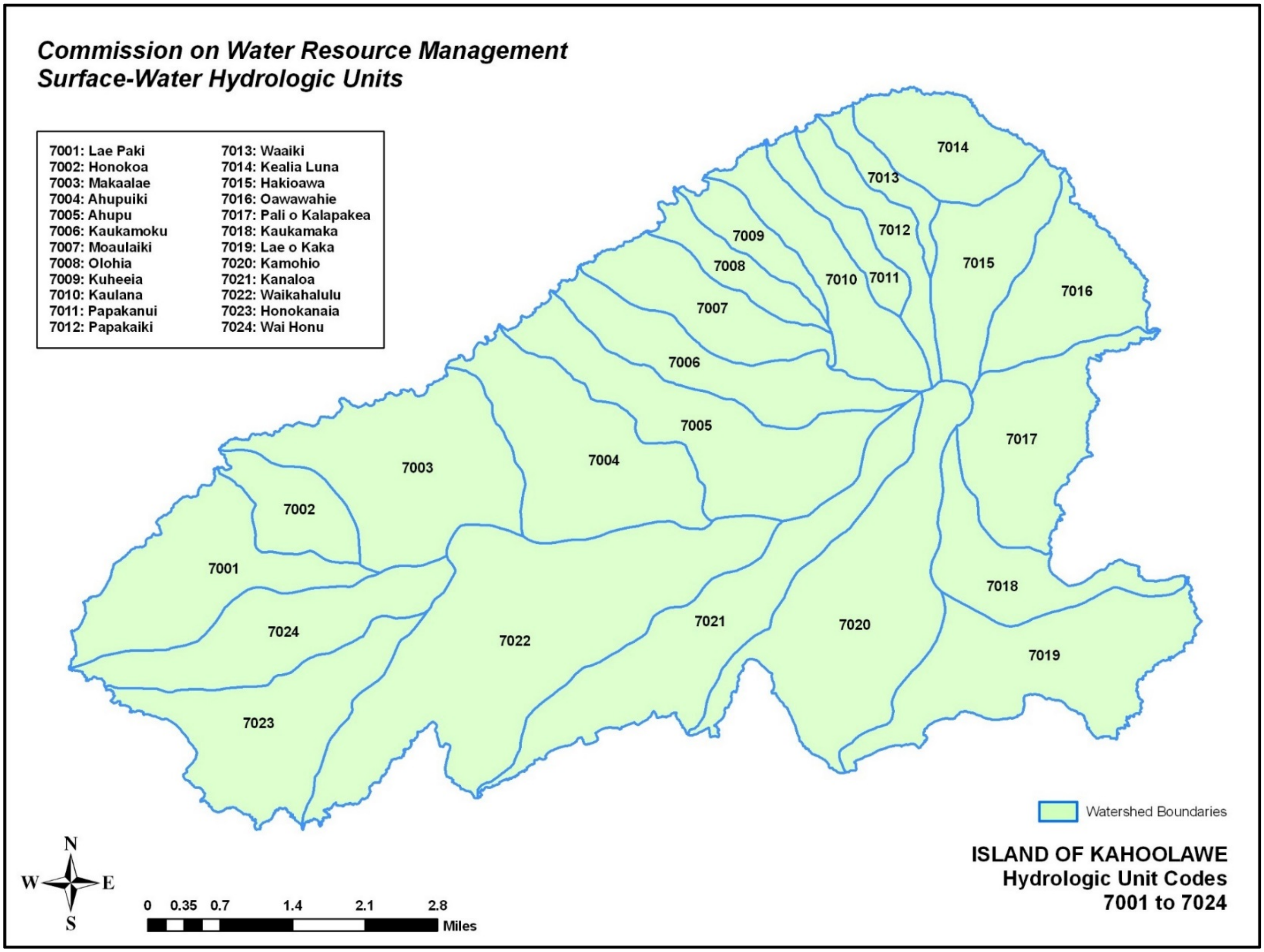


Figure F-30 Hawaiʻi Surface Water Hydrologic Units, Unit Codes 8001 to 8166

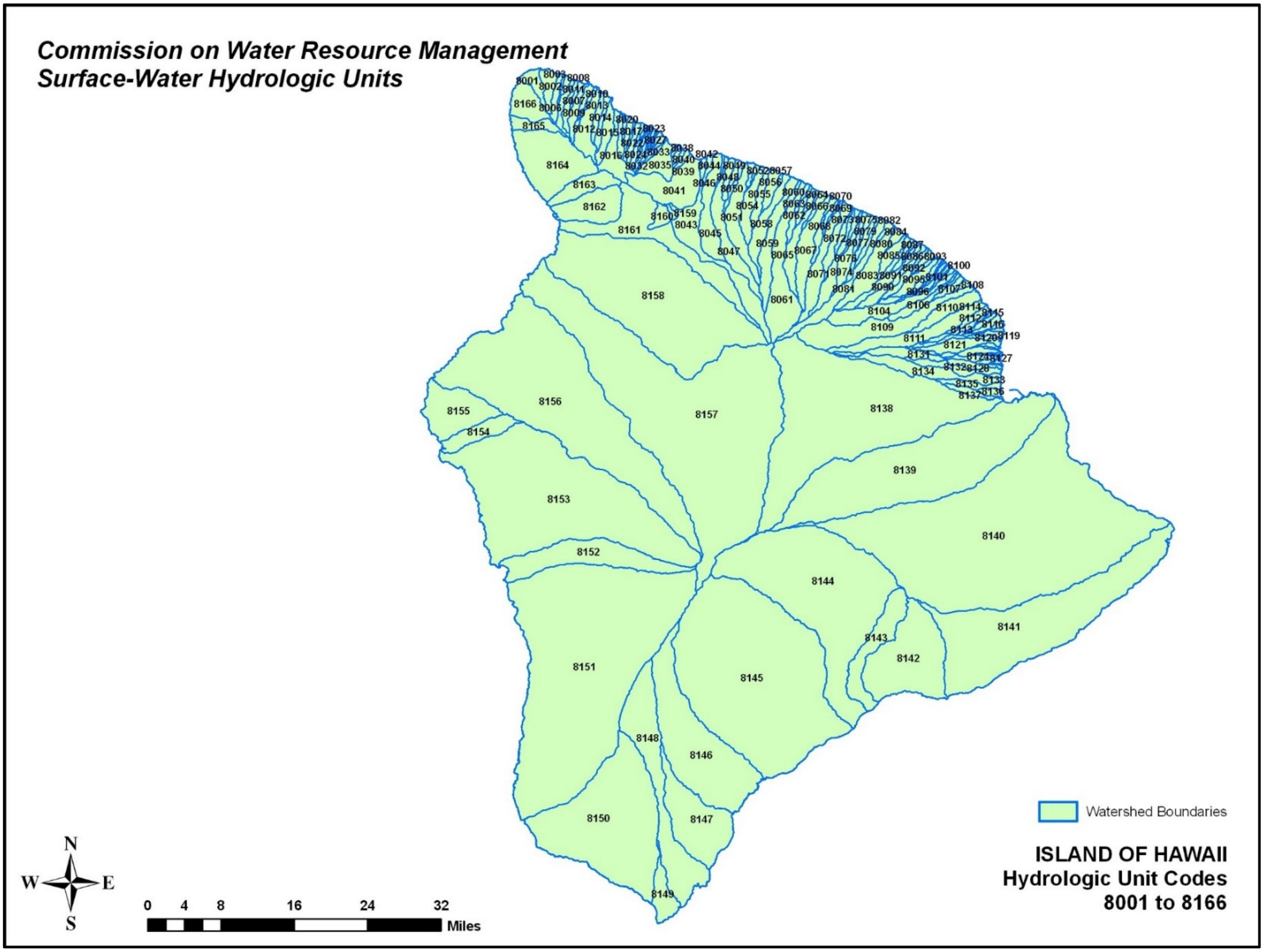


Figure F-30A Hawai‘i Surface Water Hydrologic Units, Unit Codes 8001 to 8022

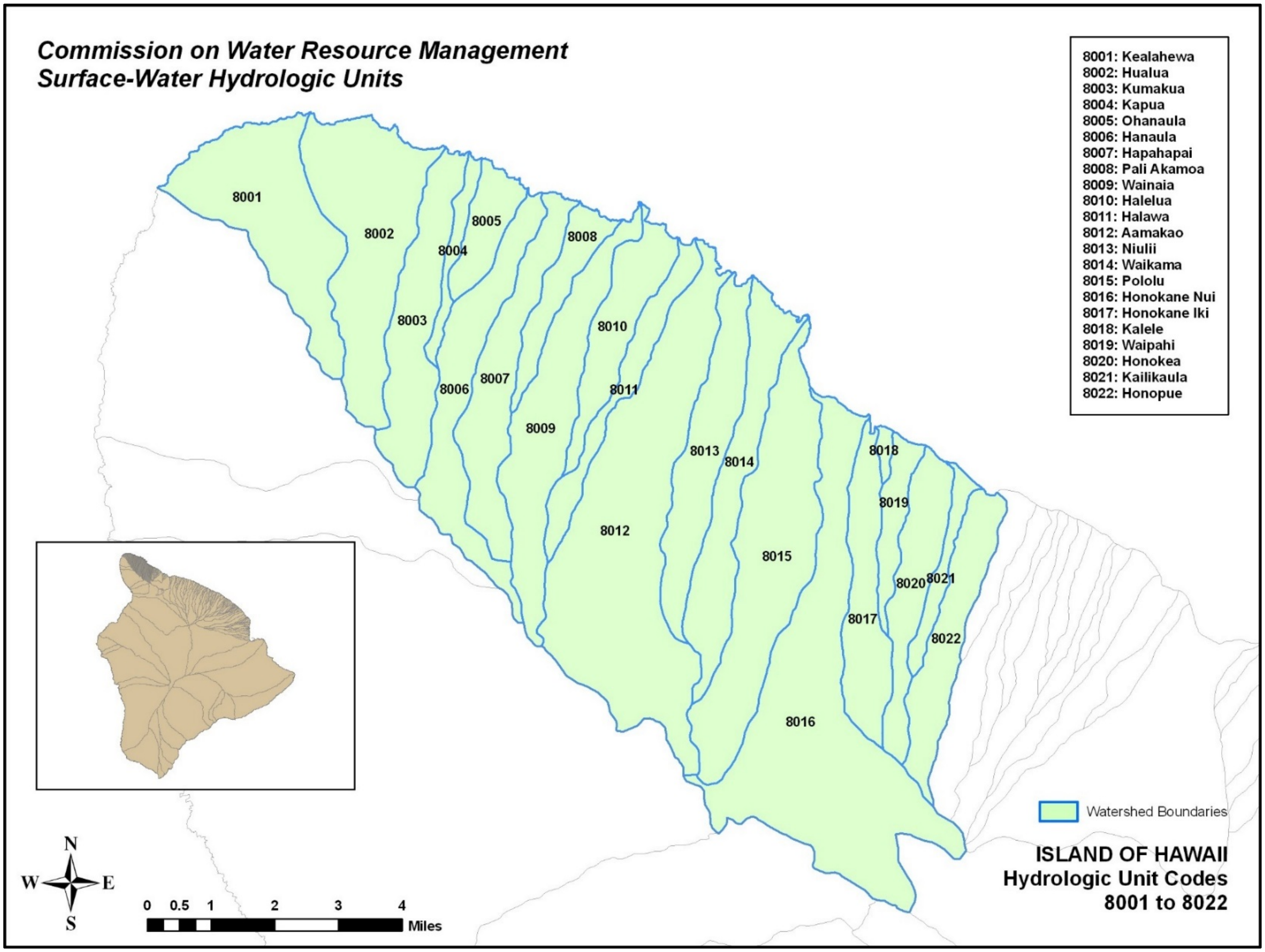


Figure F-30B Hawai‘i Surface Water Hydrologic Units, Unit Codes 8023 to 8042

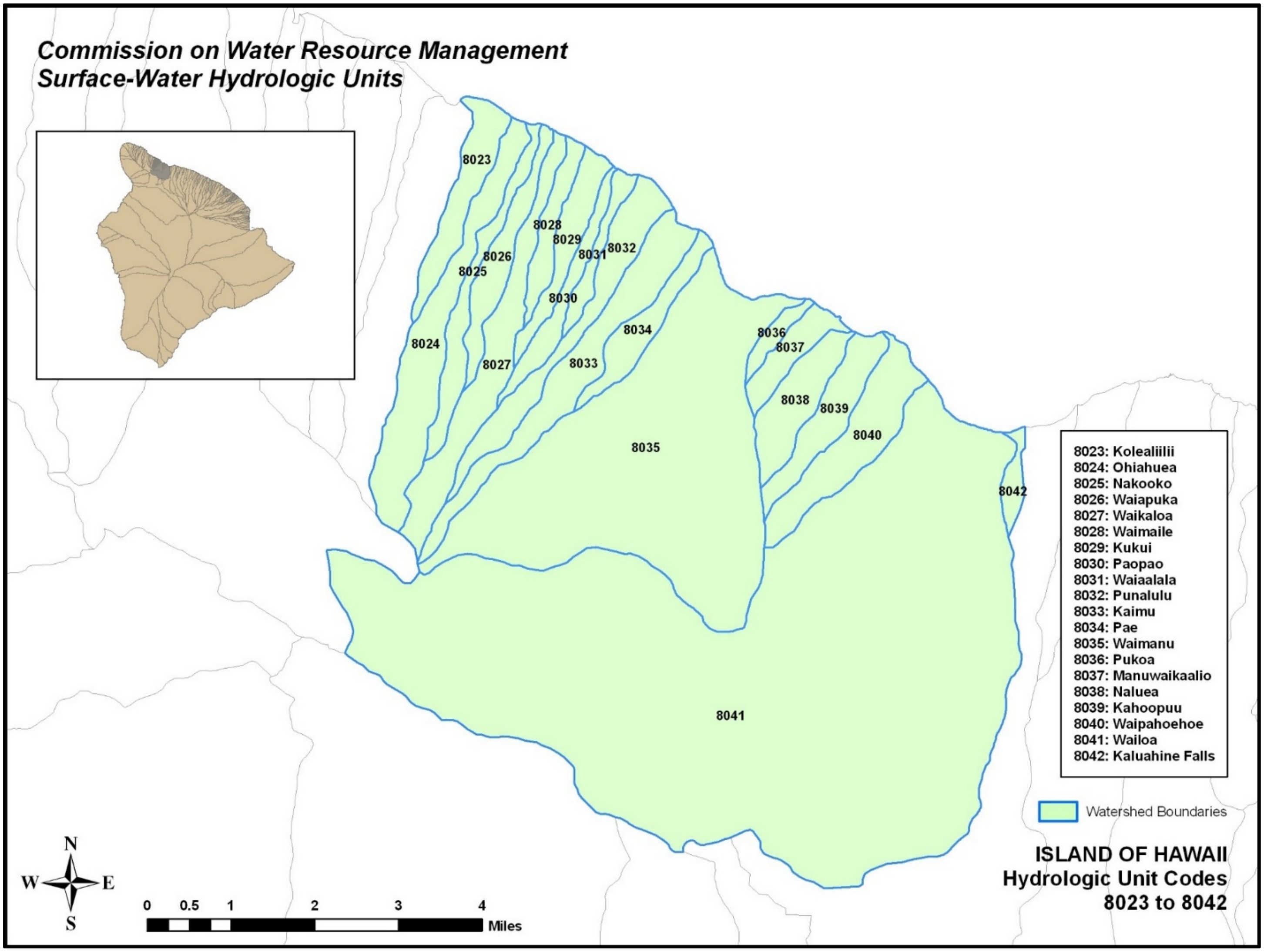


Figure F-30C Hawai‘i Surface Water Hydrologic Units, Unit Codes 8043 to 8066

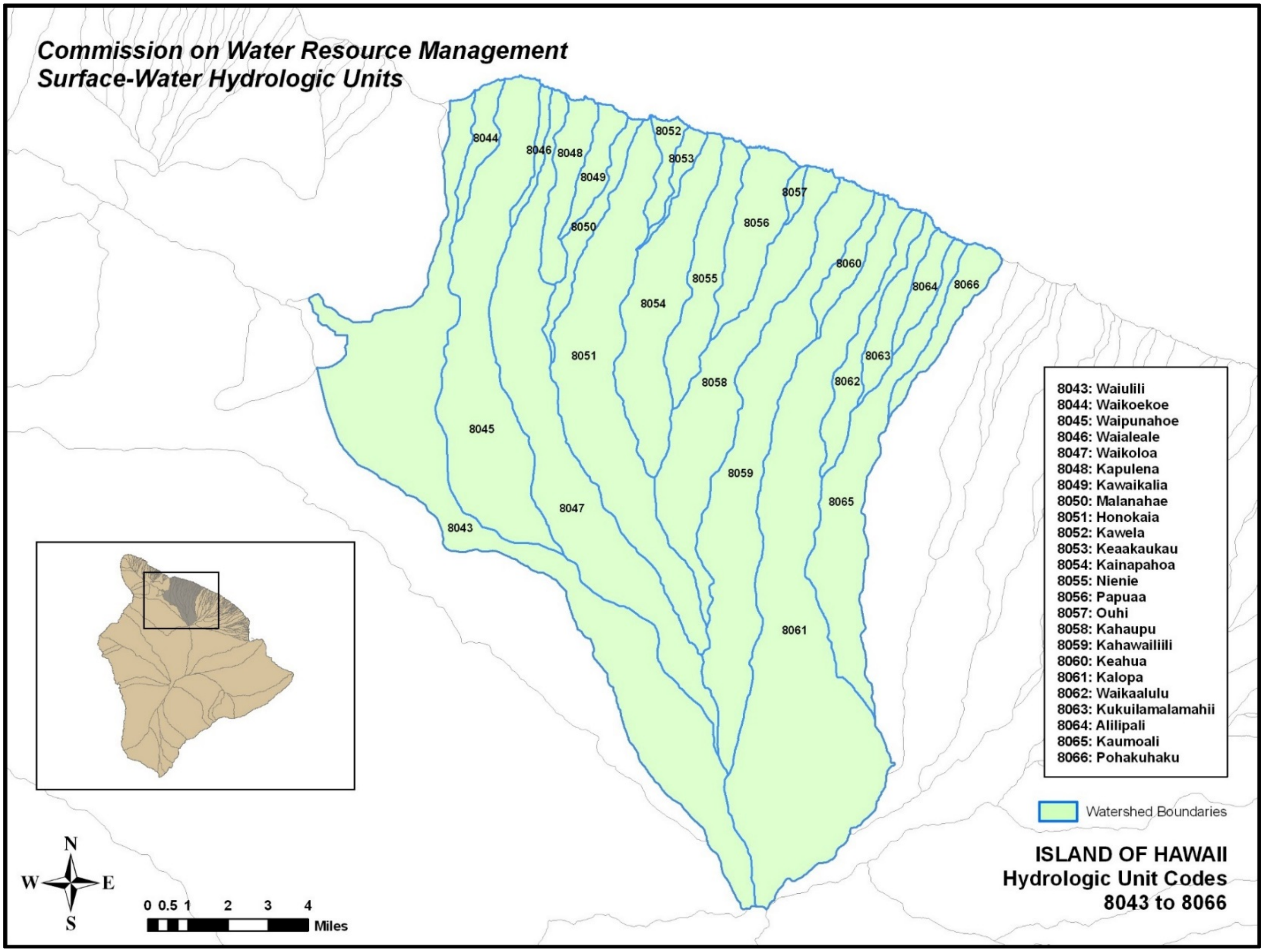


Figure F-30D Hawai‘i Surface Water Hydrologic Units, Unit Codes 8067 to 8083

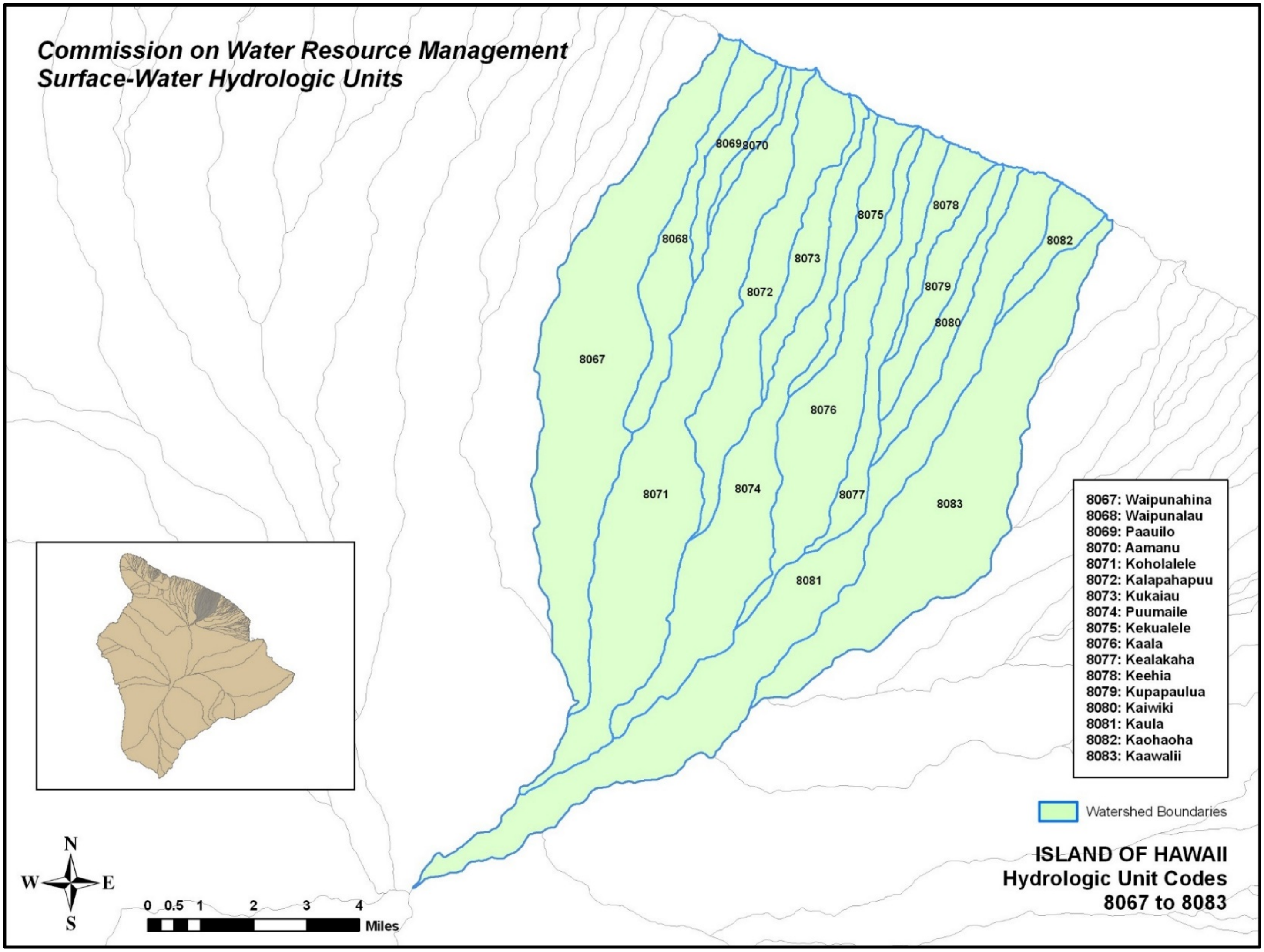


Figure F-30E Hawai‘i Surface Water Hydrologic Units, Unit Codes 8084 to 8107

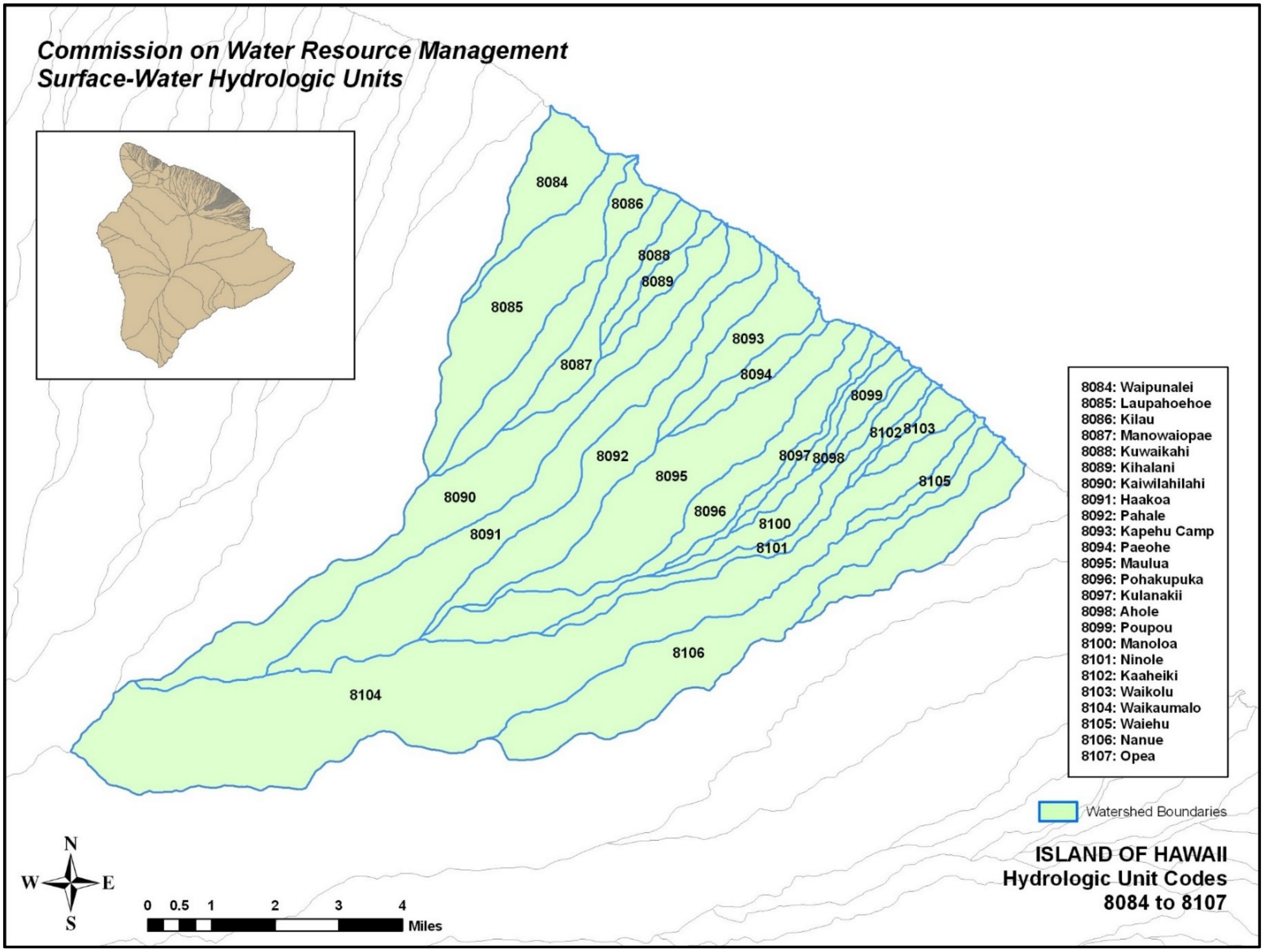


Figure F-30F Hawai‘i Surface Water Hydrologic Units, Unit Codes 8108 to 8113

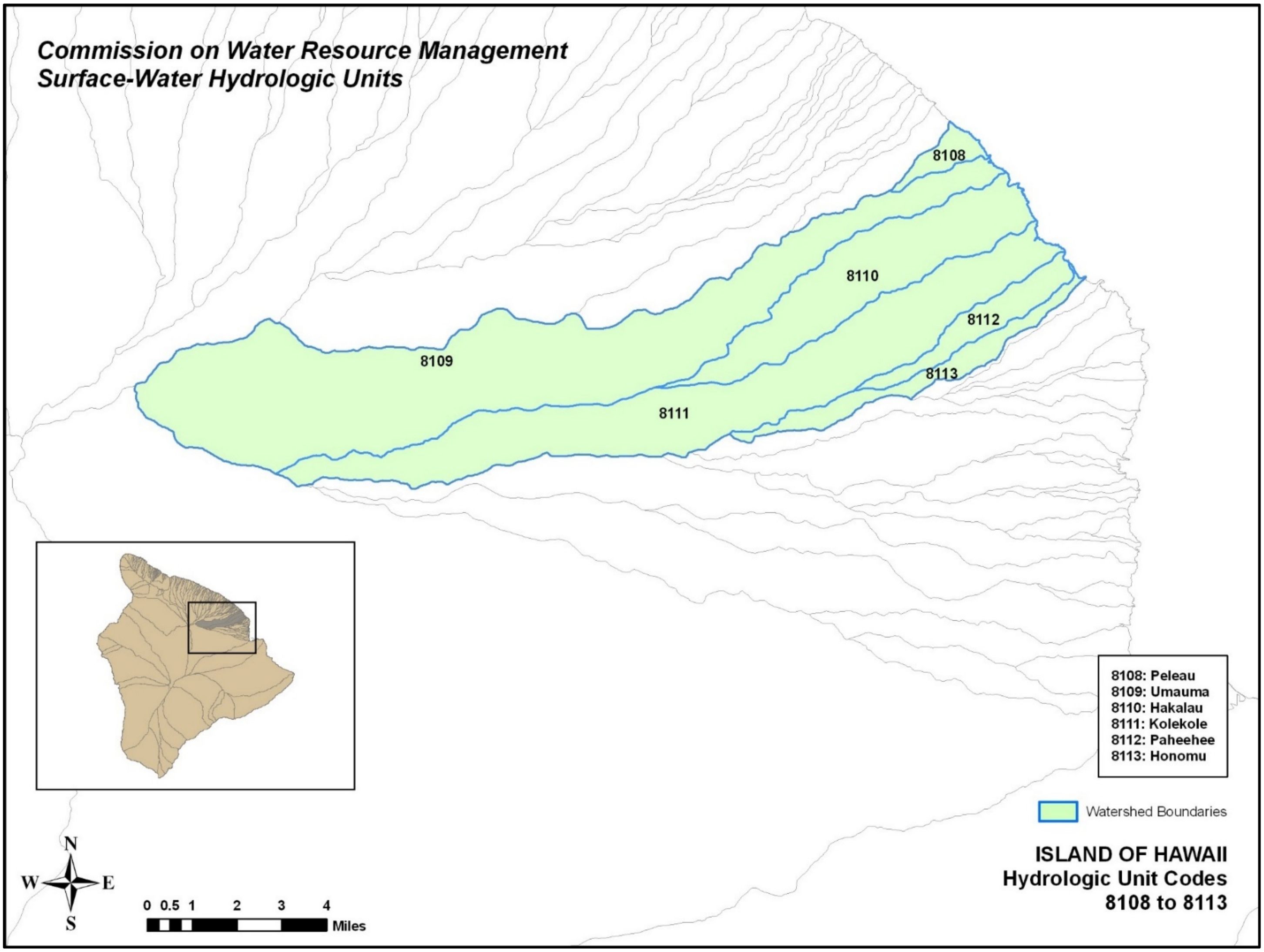


Figure F-30G Hawai‘i Surface Water Hydrologic Units, Unit Codes 8114 to 8137

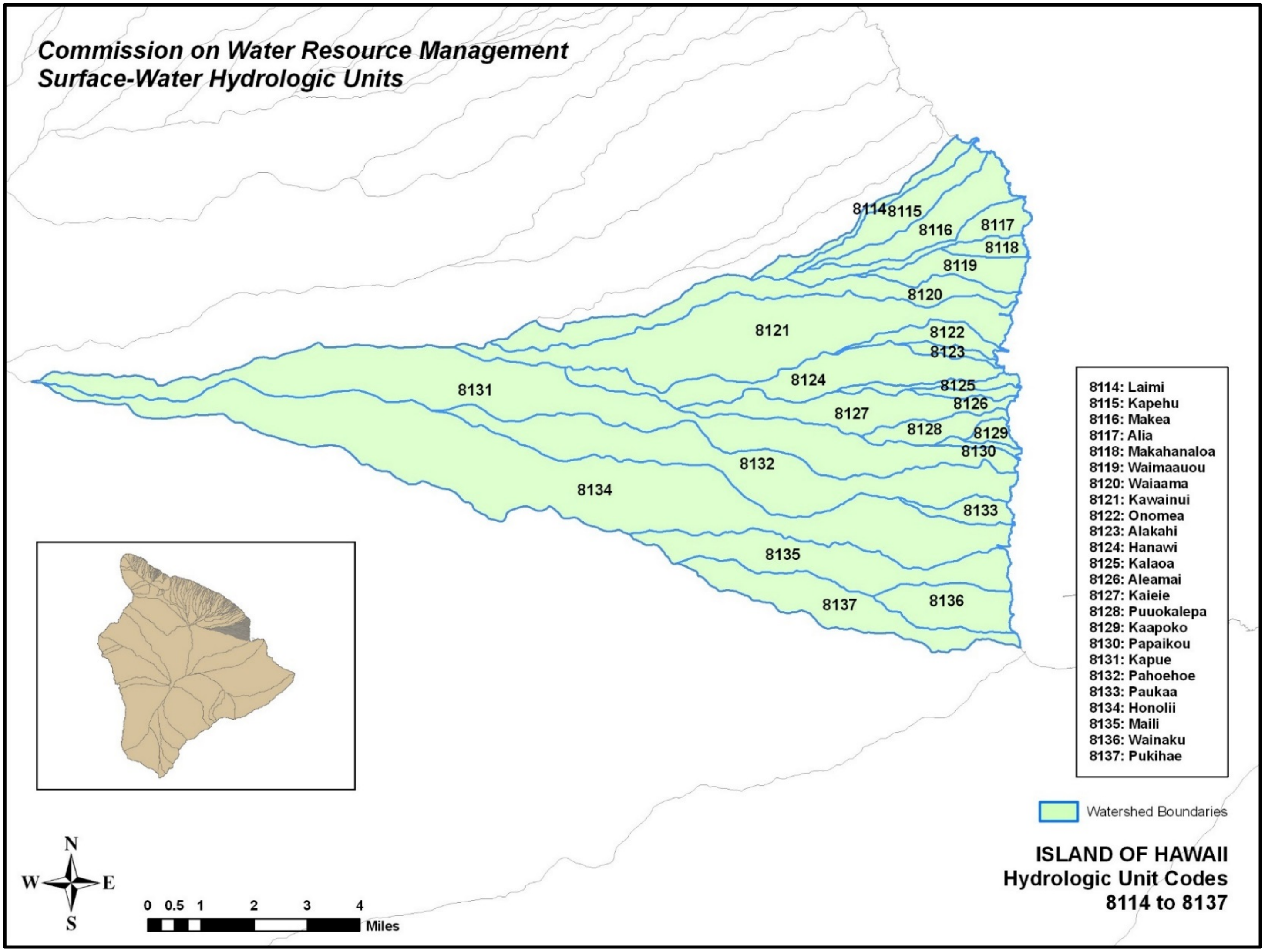


Figure F-30H Hawai‘i Surface Water Hydrologic Units, Unit Codes 8138 to 8147

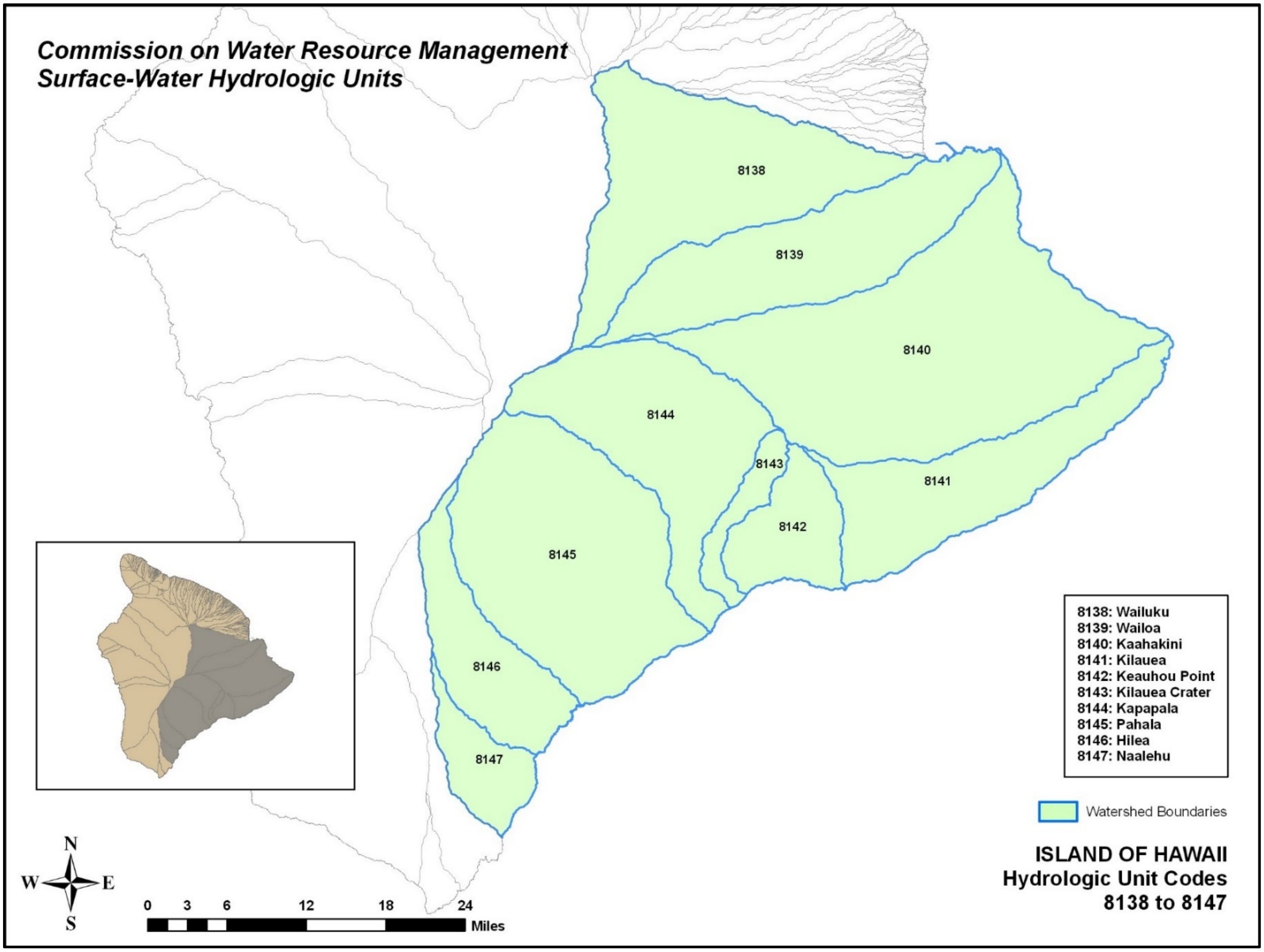


Figure F-30I Hawai‘i Surface Water Hydrologic Units, Unit Codes 8148 to 8157

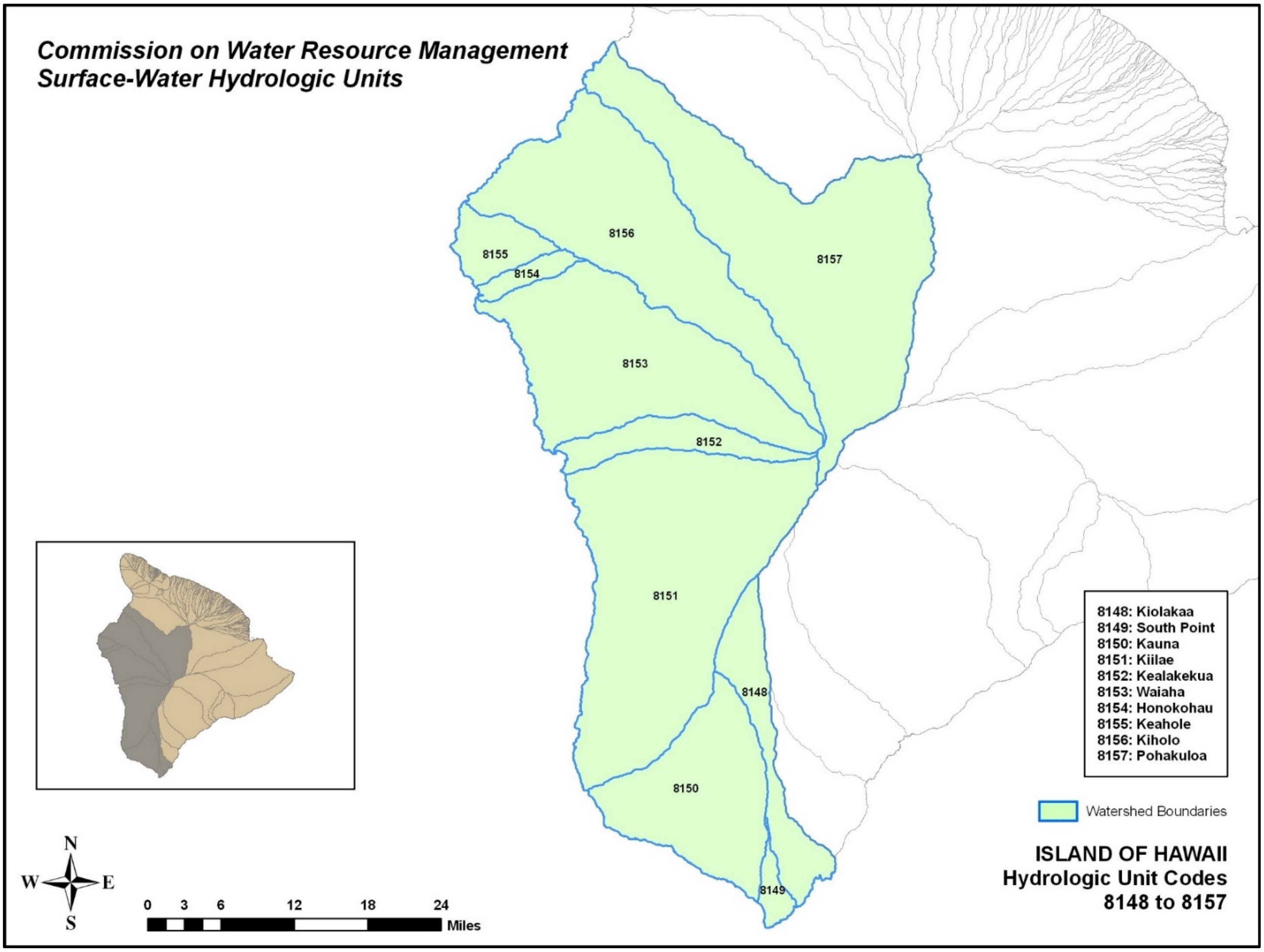
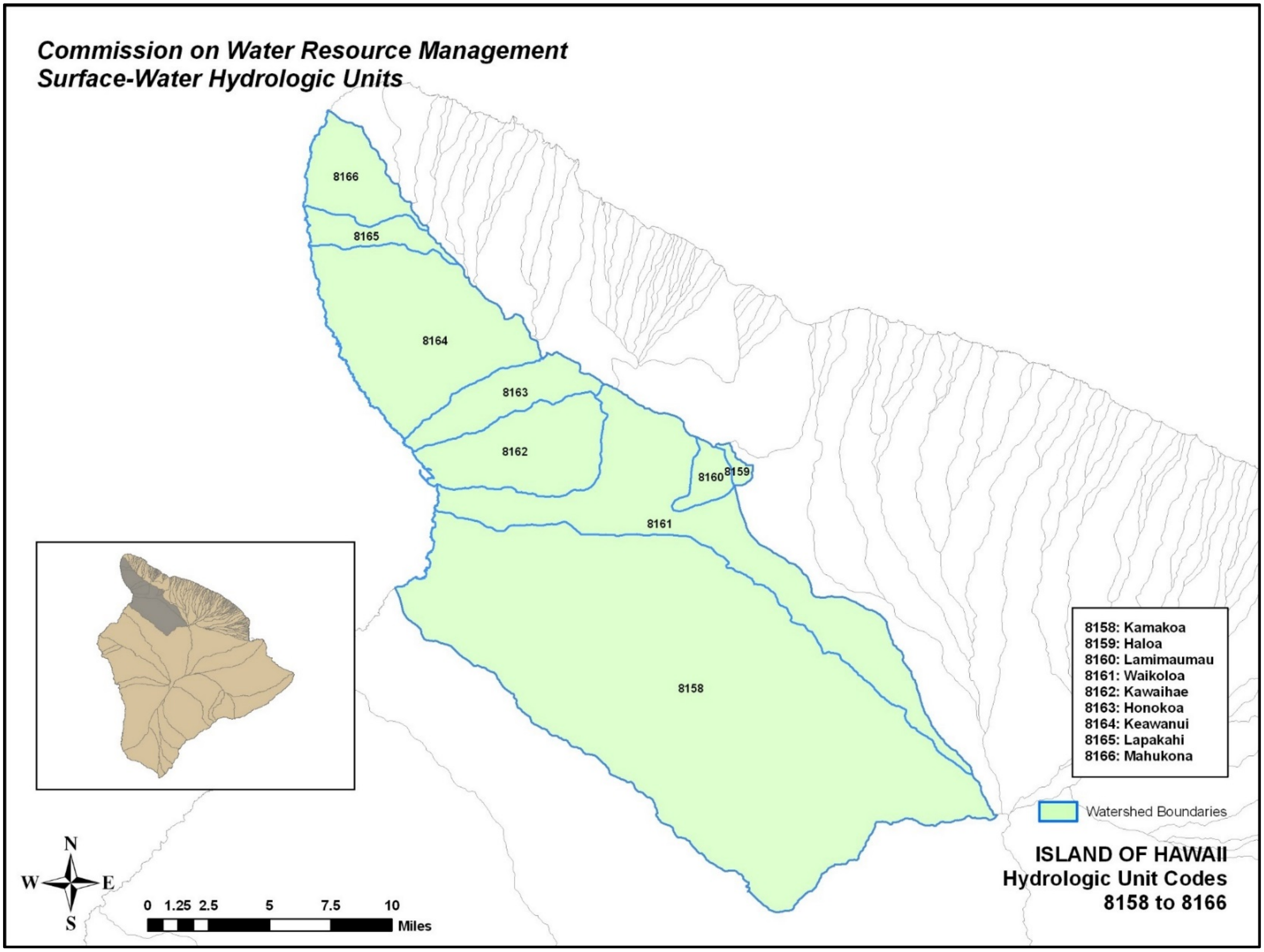


Figure F-30J Hawai‘i Surface Water Hydrologic Units, Unit Codes 8158 to 8166



F.5.3 Determining the Availability of Surface Water Resources: Assessing Instream Flow Standards

Unlike ground water resources that occur in subsurface aquifers, surface water resources are readily observed and measured. Scientists can rely on large amounts of field data and direct measurements, rather than assumptions based on interpolation and modeling tools. Field measurements can provide reliable information on streamflow and spring discharge, effectively indicating how much water is present in surface water settings. However, it is a different exercise to determine the amount of surface water available for human use and consumption. Determining the availability of surface water resources requires the evaluation of environmental, social, cultural, and economic considerations as indicated by the State Water Code. The following sections provide an overview of the factors that must be addressed in the establishment of instream flow standards and the data available for review. For a diagram of the regulatory process for setting instream flow standards, see **Appendix D CWRM Permit Process Diagrams**.

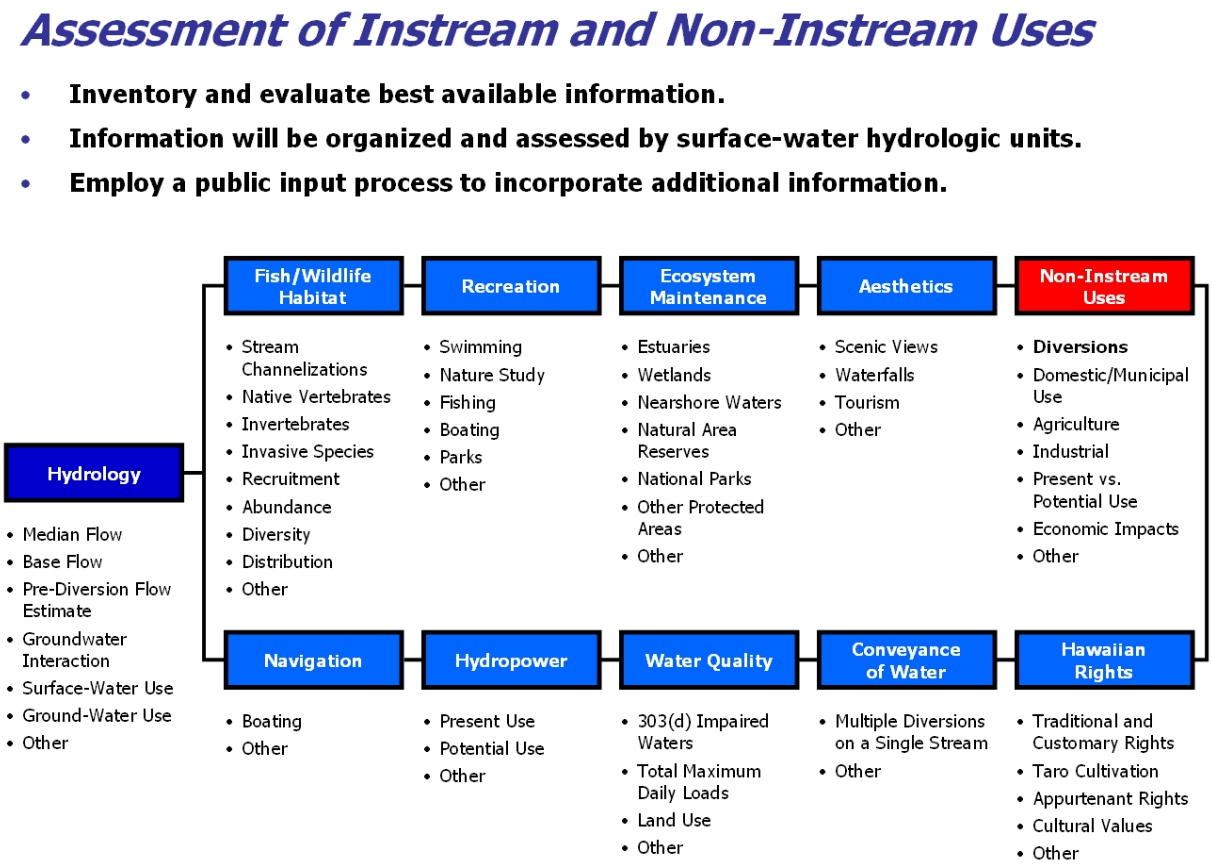
F.5.3.1 Assessing Instream Flow Standards

Instream flow standards are defined by the State Water Code as "*a quantity or flow of water or depth of water which is required to be present at a specific location in a stream system at certain specified times of the year to protect fishery, wildlife, recreational, aesthetic, scenic, and other beneficial instream uses*." However, the State Water Code also prescribes that "*in formulating the proposed standard, the commission shall weigh the importance of the present or potential uses of water from the stream for noninstream purposes, including the economic impact of restriction of such use*." CWRM has developed a methodology for establishing measurable instream flow standards based upon best available information, along with input from interested parties and agencies.

The sections below describe the types of information, based on the State Water Code's definition of instream use, to be evaluated in establishing instream flow standards. In addition, instream flow standards must address water for public trust purposes (see **Appendix C Legal Authorities and Guidance** for a discussion of the Public Trust Doctrine and public trust purposes). **Figure** F-31 provides a conceptual illustration of information categories that should inform instream flow standard assessments.

Maintenance of Fish and Wildlife Habitats: A stream's ability to provide for fish and wildlife habitat is largely dependent upon the condition of the stream bed and/or stream banks. A stream in its natural, unaltered condition tends to have a higher potential for ensuring the survival of native stream animals. Streams that are highly altered, with features such as embankments, hardened channels, realignments, and culverts, have a tendency to inhibit the recruitment and viability of native species. Channelizations and, conversely, the integrity of stream channels are major factors in defining faunal habitat.

Figure F-31 Conceptual illustration of information that should be considered in assessments of instream flow standards and in the evaluation of instream and non-instream uses.



Stream channelization projects are generally implemented to reduce flood risk, drain low-lying areas, mitigate erosion, and provide road crossings or other construction. The effect is an increase in developable land area. Channelization can result in the loss of habitat for marine, aquatic and riparian species. Other negative impacts may include reduced recreational opportunities, loss of view planes and aesthetic resources, and reduced ground water recharge.

Hawaiian streams support a relatively small number of native aquatic fauna, including freshwater fish, mollusks, crustaceans, and insects. A number of these native stream animals have a life cycle involving both the stream and the ocean. This type of life history, in which an animal lives its entire adult life in freshwater and its early larval period in the ocean, is called amphidromy.

Although the habitat requirements of native stream animals are not fully understood, it is widely accepted that some native species utilize the entire stream in their life history. Stream connectivity with nearshore waters is important for recruitment of amphidromous organisms. Another consideration is the prevalence of non-native species that compete for food and habitat any may prey upon native species. Habitat requirements of native stream animals generally include clear, well-oxygenated stream water that flows over cobble and gravel. Some native fishes are clearly adapted to life in turbulent streams with modified (fused) ventral fins that function as suction disks. These organisms can climb waterfalls and colonize stream reaches inaccessible to other fishes.

In addition to native stream fauna, waterbirds such as stilts, coots, and the native duck Koloa, rely upon stream systems for breeding, nesting, and feeding. Aquatic stream fauna provide a supply of food, while natural riparian areas present quality nesting and breeding habitats.

The HSA includes an assessment of biological and riparian resources for perennial streams statewide, including an inventory of channelizations statewide. Recent work by the DLNR Division of Aquatic Resources provides an updated and improved database of information on biological resources statewide. Other sources of habitat information include the DLNR Division of Forestry and Wildlife, the U.S. Fish and Wildlife Service, and other studies conducted for specific streams. CWRM is also developing a comprehensive statewide database of stream channel activities (i.e., stream channel alteration permits, requests for determination, complaints, etc.). Information from the database may provide additional insight as to stream habitat availability.

Outdoor Recreational Activities: Water-related recreation is a part of everyday life in Hawaiʻi, and though beaches clearly attract more users, many local residents grew up recreating in backyard streams. Certain recreational water activities, such as fishing, swimming, boating, and nature study, are relatively limited in Hawaiʻi due to the short, narrow, and shallow nature of typical Hawaiʻi streams in comparison to continental streams and rivers. Although not directly dependent upon streamflow, other land-based recreational activities, such as hiking, camping, and hunting, are enhanced by streams that provide added value to the experience.

A state Recreational Resources Committee was formed as part of the Hawaiʻi Stream Assessment to design a recreation inventory and assessment that identified various opportunities related to specific streams. Regional committees were established on each island. Committees were tasked with compiling an inventory for their respective island. The regional committees ranked each stream using a modified U.S. Forest Service Recreation Opportunity Spectrum, based on factors such as diversity of experiences, quality of experiences, specific unique characteristics, and unique combinations of attributes. This assessment provides an excellent starting point for assessing streamflow requirements for outdoor recreational activities.

Maintenance of Estuarine, Wetland, and Stream Ecosystems: The maintenance of estuarine, wetland, and stream vegetation are directly dependent upon streamflow. These areas provide important riparian habitats for many species, often serving as nursery areas. Although relatively few studies have been conducted on the function of estuaries within the larger ecosystem, it is widely believed that estuaries play a vital role in the recruitment of native stream macrofauna and the development of fish species in the nearshore waters. For example, one study indicates that increases in salinity resulting from a reduction of freshwater to the estuary could affect the juvenile development of two native fish species. [43] In general, estuaries are regarded as some of the most ecologically productive areas in the world, primarily attributed to two general phenomena; 1) the continual movement of water, and 2) the trapping of nutrients. Tidal influences, salinity gradients, freshwater discharge, runoff, and winds, all contribute to water movement, while nutrients are washed into the estuary from the entire watershed and metabolic wastes are removed. The movement of nutrients throughout the entire estuarine system is critical to sustain both plants and animals.

There are various types of wetland classifications, not all of which are directly related to streamflow. However, it is widely accepted that wetlands are valuable because they perform multiple ecosystem functions. Wetlands encourage ground water recharge, provide flood water storage, offer biological habitat, and promote the cycling, storage, and removal of nutrients. In Hawaiʻi, many wetlands have been drained and converted to agricultural or urban land uses. It is increasingly important to protect remaining wetland areas.

The HSA briefly addresses wetlands, however, there are few studies of estuaries, wetlands, and stream vegetation in relation to instream uses. In recent years, awareness of the importance of estuaries and wetlands to the greater ecosystem has been emphasized. The DLNR Division of Aquatic Resources plans to expand its biological assessments into estuaries and study the recruitment patterns of native stream fishes, the function of estuaries as fishery nurseries, and energy flows within estuaries.

Aesthetic Values such as Waterfalls and Scenic Waterways: The relationship between streamflow and aesthetic value cannot be determined in quantitative or absolute terms. Aesthetic value depends on the perception of multi-sensory experiences that vary between individuals. Despite the qualitative nature of aesthetics, the HSA attempts to address scenic views as part of its recreational resource assessment, considering view planes from roads, trails, and the ocean. Additional studies would need to be conducted and other resources should be examined to further assess the present and potential streamflow requirements to support aesthetic values.

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[43] Englund, R. 1998, Biological assessment and the effects of water withdrawls on Waikele Stream, Oahu, Aquatic biota, Report prepared for Belt-Collins Hawaii, 31 p.

Navigation: There are few navigable streams in Hawai‘i. Streams tend to be short, narrow, and shallow. Only a few areas have developed estuaries where recreational boating is possible. Even fewer streams are actually used for commercial boating operations. The HSA addresses boating as part of its recreational resource assessment but does not differentiate between recreational and commercial use. Additional studies should be conducted, and other resources should be examined to further assess the present and potential uses of streams for navigation and boating.

Instream Hydropower Generation: Hydroelectricity is typically generated by instream dams and power generators, but the nature of Hawai‘i streams requires a different hydropower plant design whereby surface water is usually diverted to an offstream power plant. Generally, water is diverted through ditches, pipes and penstocks to the power plant, then returned to the stream. Hydropower plants may take advantage of changes in elevation to generate power; energy is recovered from the change in head and diverted water is subsequently applied to irrigate agricultural fields at lower elevations. When the HSA was conducted, 18 hydroelectric power plants were identified (seven on Kauai, four on Maui, and seven on Hawai‘i). At the time, hydroelectricity accounted for roughly 1.5% of the state’s total electrical energy consumption.

In 1981, the State Department of Planning and Economic Development (now Department of Business, Economic Development and Tourism [DBEDT]), published *Hydrolectric Power in Hawaii: A Reconnaissance Survey*, in conjunction with the U.S. Department of Energy. The purpose of the survey was to assess potential sources of hydroelectric power, in consideration of various parameters such as storage, utilization of irrigation systems and reservoirs, upgrading of existing facilities, and construction of new power plants. Although the appeal of hydropower has since declined, renewed interest may be spurred by the desire to reduce Hawai‘i’s dependence on oil, provided environmental considerations can be satisfied.

Maintenance of Water Quality: Water quality is an essential part of any evaluation of water requirements for health, safety and habitat protection. Information on surface water quality has been collected in Hawai‘i since the 1960’s, however most agencies collect water quality data to meet specific short-term goals that are usually problem-oriented. The results of water quality monitoring are often used to assess mitigation actions and improve management practices. Though surface water monitoring at instream locations is ideal, testing of nearshore waters may also provide information about the quality of contributing surface water flows. Water quality parameters range widely, but can generally be grouped into the four categories listed below:

- **Physical characteristics** include temperature, specific conductance, turbidity, color, odor, pH, and suspended solids.

- **Biological characteristics** include bacteria (fecal coliform and fecal **streptococcus**), phytoplankton, zooplankton, periphyton, and macroinvertebrates.

- **Chemical characteristics** include total dissolved solids, major ions, hardness, silica, phosphorus species, nitrogen species, detergents, other minor elements, radiochemical species, organic species, pesticide species, biochemical oxygen demand, chemical oxygen demand, dissolved oxygen, and other dissolved gasses.

- **Sediment characteristics** include suspended sediment concentration, suspended sediment discharge, bed load, total concentration, and particle size and distribution.

The two primary sources of surface water quality information are the USGS and the DOH. The USGS has collected basic water quality information at stream gaging stations since 1967 as part of a nationwide program. More detailed water quality parameters are collected at certain sites for specific programs (e.g., National Stream Quality Accounting Network, National Water Quality Assessment) and projects. The DOH is responsible for monitoring the quality of water used for consumptive or recreational purposes and has varying standards for acceptable levels of contaminants, depending on the use. County water departments are another source of water quality information, as these agencies cooperate with DOH to monitor drinking water. Water quality data, both general and site-specific, may also be found in studies and reports that have been completed for particular projects.

The Conveyance of Irrigation and Domestic Water Supplies to Downstream Points of Diversion: To ensure the availability of steam water for irrigation and domestic use in downstream areas, upstream diversions must allow the bypass of sufficient water supplies and the stream channel must be protected to allow for unimpeded flow downstream. The State Water Code provides for the regulation stream diversions and alterations through a permitting system. In addition, CWRM has jurisdiction statewide to hear and render decisions on any dispute regarding water resource protection, water permits, constitutionally protected water interests, or insufficient water supply to meet competing needs.

CWRM is in the process of developing a comprehensive database to manage surface water resources statewide, which will include all registered and permitted surface water diversions, permitted stream channel alterations, complaints, and requests for determination of permitting requirements. A project to verify and characterize all registered surface water diversions is also being executed by CWRM to provide updated information on diversion structures, water uses, and basic stream conditions. Additional information related to stream channel conditions can be obtained through the various regulatory agencies that have jurisdiction related to stream channel alteration. Example of such agencies include the U.S. Army Corps of Engineers, the DOH's Environmental Management Division, DBEDT's Coastal Zone Management Program, and county planning and/or permitting departments.

The Protection of Traditional and Customary Hawaiian Rights: With regard to surface water resources, the State Water Code provides for the protection of traditional and customary rights including, but not limited to, the cultivation or propagation of taro and the gathering of hihiwai, opae, and oopu for subsistence, cultural, and religious purposes. This State Water Code also protects appurtenant water rights (see **Appendix C Legal Authorities and Guidance** for a discussion of water rights and uses in Hawaiʻi).

The process for claiming and proving an appurtenant water right is the responsibility of the landowner and can be arduous, however, the State Water Code also assures that appurtenant rights shall not be diminished or extinguished by a failure to apply for, or claim, such right. With the exception of Na Wai Eha on the Island of Maui, very few claims for appurtenant rights have been made. Therefore, at this time, it is difficult to quantify the amount of water required to satisfy all appurtenant rights for a given area or hydrologic unit. Regardless, if an appurtenant right is established, it is CWRM's responsibility to assure that an appropriate volume of water is afforded to the claimant.

One method for assessing the protection of traditional and customary Hawaiian rights is to evaluate incidental sources of information, such as taro cultivation and various other cultural resources and studies. The HSA provides an initial assessment of cultural resources in relation to the stream valley, considering the extent of archaeological survey coverage, the ability to predict what historic sites might be in unsurveyed areas, the actual number of known historic sites, the overall significance of the valley, the density and significance of historic sites, and the overall sensitivity of the valley.

The HSA Cultural Resources Committee identified a number of factors important to current Hawaiian cultural practices: current taro cultivation, the potential for taro cultivation, appurtenant rights, subsistence gathering areas, and stream-related hydrology. Though the committee felt that these items should be included in the assessment, information was limited at the time such that only current taro cultivation could be assessed. Various other cultural studies and surveys are available for specific regions and may provide additional information with respect to present and potential surface water requirements.

F.5.3.2 Recommendations for Assessing Instream Flow Standards

Considerably more research and study should be completed to accumulate the data and perspective necessary to conduct a thorough and meaningful assessment of instream flow standards. While some of the information categories described above are partially addressed through existing federal, State, and county programs, other categories remain virtually unexplored. In many respects, CWRM's ability to assess instream flow standards are dependent upon policy and program direction, funding availability, and staffing requirements. However, CWRM recognizes that the information in the HSA should be updated, expanded, and interpreted in light of developing case law. Notwithstanding the requirements of CWRM's process for adopting interim instream flow standards, the following actions are recommended.

- Develop, fund, and conduct cultural resource studies or surveys in priority areas;
- Fund and complete an inventory of stream channel alterations; and
- Continue to coordinate with the USGS to fund and execute stream studies and share surface water information.

F.5.4 Inventory of Surface Water Resources and Interim IFS

Table F-21 lists the surface water hydrologic units by island according to hydrologic unit code. Key characteristics of each hydrologic unit are listed, including the total area (in square miles), the number of registered and/or permitted stream diversions, and the number of historic and currently active continuous USGS and CWRM gages within the unit. The final column indicates the current interim IFS. In most cases, the current interim IFS were established pursuant to amendments to HAR §13-169, as noted here.

- Interim Instream Flow Standard for East Maui, HAR §13-169-44
Date of Adoption: 6/15/1988
Effective Date: 10/8/1988
- Interim Instream Flow Standard for Kauaʻi, HAR §13-169-45
Date of Adoption: 6/15/1988
Effective Date: 10/8/1988
- Interim Instream Flow Standard for Hawaiʻi, HAR §13-169-46
Date of Adoption: 6/15/1988
Effective Date: 10/8/1988
- Interim Instream Flow Standard for Molokaʻi, HAR §13-169-47
Date of Adoption: 6/15/1988
Effective Date: 10/8/1988
- Interim Instream Flow Standard for West Maui, HAR §13-169-48
Date of Adoption: 10/19/1988
Effective Date: 12/10/1988
- Interim Instream Flow Standard for Leeward Oʻahu, HAR §13-169-49
Date of Adoption: 10/19/1988
Effective Date: 12/10/1988

- Interim Instream Flow Standard for Windward Oʻahu, HAR §13-169-49.1
  Date of Adoption: 4/19/1989
  Effective Date: 5/4/1992

Generally, the interim IFS for all streams in a given region were adopted by CWRM and defined as the "amount of water flowing in each stream on the effective date of this standard, and as that flow may naturally vary throughout the year and from year to year without further amounts of water being diverted offstream through new or expanded diversions." The interim IFS of individual streams have subsequently been amended as a direct result of petitions to amend the instream flow standards, contested case hearings, or other regulatory actions. References to specific actions amending the interim instream flow standard of specific streams are also provided in the last column of **Table F-21 Inventory of Surface Water Resources**. For further clarification, refer to HAR §13-169. For a discussion of the regulatory process for setting IFS, see **Appendix I CWRM Regulatory Programs**.

Table F-21 Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi^2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
KAUAI						
2001	Awaʻawapuhi	1.29	0	0	0/0	HAR §13-169-45
2002	Honopū	1.74	0	0	0/0	HAR §13-169-45
2003	Nakeikionaiwi	0.49	0	0	0/0	HAR §13-169-45
2004	Kalalau	4.23	0	1	0/0	HAR §13-169-45
2005	Pōhakuao	0.58	0	0	0/0	HAR §13-169-45
2006	Waiolaa	0.36	0	0	0/0	HAR §13-169-45
2007	Hanakoa	2.01	0	1	0/0	HAR §13-169-45
2008	Waiahuakua	0.66	0	0	0/0	HAR §13-169-45
2009	Hoʻolulu	0.38	0	0	0/0	HAR §13-169-45
2010	Hanakāpīʻai	3.76	0	1	0/0	HAR §13-169-45
2011	Maunapuluo	0.45	0	0	0/0	HAR §13-169-45
2012	Limahuli	1.92	7	1	0/0	HAR §13-169-45. Amended to include SCAP KA-155 on Limahuli Stream for diversion of 0.115 MGD for landscape irrigation (07/19/1995).
2013	Mānoa	1.04	1	0	0/0	HAR §13-169-45
2014	Wainiha	23.71	29	3	1/0	HAR §13-169-45
2015	Lumahaʻi	14.44	0	1	0/0	HAR §13-169-45. Amended to include SDWP.3936.2 for diversion of 0.54 MGD
2016	Waikoko	0.69	0	0	0/0	HAR §13-169-45

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi^2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
KAUAI (continued)						
2017	Waipā	2.52	2	0	0/0	HAR §13-169-45
2018	Waiʻoli	5.48	1	1	0/0	HAR §13-169-45
2019	Hanalei	23.96	10	3	1/0	HAR §13-169-45
2020	Waileia	0.82	0	0	0/0	HAR §13-169-45
2021	ʻAnini	3.20	4	0	0/0	HAR §13-169-45
2022	Kalihikai West	0.30	0	0	0/0	HAR §13-169-45
2023	Kalihikai Center	0.24	0	0	0/0	HAR §13-169-45
2024	Kalihikai East	0.49	0	0	0/0	HAR §13-169-45
2025	Kalihiwai	11.36	6	2	0/0	HAR §13-169-45. Amended to include SCAP KA-060 on Pake Stream for diversion of 0.028 MGD for aquaculture (10/18/1989).
2026	Puʻukumu	1.28	3		0/0	HAR §13-169-45
2027	Kauapea	1.05	0	0	0/0	HAR §13-169-45
2028	Kīlauea	12.87	9	3	1/0	HAR §13-169-45
2029	Kulihaili	1.10	0	0	0/0	HAR §13-169-45
2030	Pilaʻa	2.58	4	0	0/0	HAR §13-169-45
2031	Waipake	2.46	1	0	0/0	HAR §13-169-45
2032	Moloaa	3.67	7	0	0/0	HAR §13-169-45
2033	Pāpaʻa	4.41	5	0	0/0	HAR §13-169-45
2034	Aliomanu	1.64	0	0	0/0	HAR §13-169-45
2035	Anahola	13.86	6	3	0/0	HAR §13-169-45
2036	Kumukumu	1.21	0	0	0/0	HAR §13-169-45
2037	Kapaʻa	16.74	13	2	0/0	HAR §13-169-45
2038	Moikeha	2.26	1	0	0/0	HAR §13-169-45
2039	Waikaea	7.13	2	5	0/0	HAR §13-169-45. Amended to include SCAP KA-396 on Waikaea and Konohiki Streams for streams are impacted by a pumped well (07/12/2006).
2040	Wailua	53.34	30	7	3/1	HAR §13-169-45

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
KAUAI (continued)						
2041	Kawailoa	3.94	0	0	0/0	HAR §13-169-45
2042	Hanamāʻulu	11.65	4	1	0/0	HAR §13-169-45
2043	Līhuʻe Airport	1.83	0	0	0/0	HAR §13-169-45
2044	Nāwiliwili	6.40	3	0	0/0	HAR §13-169-45
2045	Puali	2.05	6	0	0/0	HAR §13-169-45
2046	Huleia	28.32	26	5	0/0	HAR §13-169-45
2047	Kipu Kai	3.04	1	0	0/0	HAR §13-169-45
2048	Mahaulepu	13.43	6	0	0/0	HAR §13-169-45
2049	Waikomo	9.12	11	0	0/0	HAR §13-169-45
2050	Aepo	2.58	5	0	0/0	HAR §13-169-45
2051	Lāwaʻi	9.73	11	2	0/0	HAR §13-169-45
2052	Kalāheo	6.56	9	0	0/0	HAR §13-169-45
2053	Wahiawa	7.34	1	0	0/0	HAR §13-169-45
2054	Hanapēpē	27.09	9	4	1/0	HAR §13-169-45
2055	Kukamahu	3.21	0	0	0/0	HAR §13-169-45
2056	Kaumakani	3.09	0	0	0/0	HAR §13-169-45
2057	Mahinauli	8.78	1	0	0/0	HAR §13-169-45
2058	Aʻakukui	5.27	3	0	0/0	HAR §13-169-45
2059	Waipao	9.26	1	0	0/0	HAR §13-169-45
2060	Waimea	86.50	46	15	3/0	Natural flow on Kokee Stream; 0.7 MGD on Kauaikinana Stream below Kokee Ditch; 4.9 MGD on Kawaikoi Stream below Kokee Ditch; 1.4 MGD on Waiakoali Stream below Kokee Ditch; 2.0 MGD on Koaie Stream below Kekaha Ditch; 8.0 MGD on Waimea River below Kekaha Ditch (Waiahulu diversion); 25 MGD at USGS gaging station 16031000 on Waimea River with a minimum flow of 6.0 MGD in the Kekaha Ditch (04/18/2017).
2061	Kapilimao	6.44	1	0	0/0	HAR §13-169-45
2062	Paua	5.10	0	0	0/0	HAR §13-169-45
2063	Hōʻea	16.64	1	0	0/0	HAR §13-169-45
2064	Niu	2.82	0	0	0/0	HAR §13-169-45
2065	Kaʻawaloa	7.50	0	0	0/0	HAR §13-169-45

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi^2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
KAUAI (continued)						
2066	Nahomalu	17.63	1	1	0/0	HAR §13-169-45
2067	Ka‘ula‘ula	2.55	0	0	0/0	HAR §13-169-45
2068	Hā‘ele‘ele	2.45	0	0	0/0	HAR §13-169-45
2069	Hikimoe	2.20	0	0	0/0	HAR §13-169-45
2070	Kā‘aweiki	2.15	0	0	0/0	HAR §13-169-45
2071	Kauhao	3.98	1	0	0/0	HAR §13-169-45
2072	Mākaha	2.80	0	0	0/0	HAR §13-169-45
2073	Miloli‘i	4.34	1	0	0/0	HAR §13-169-45
2074	Nu‘alolo	2.83	0	0	0/0	HAR §13-169-45
O‘AHU						
3001	Kālunawaika‘ala	2.30	1	0	0/0	HAR §13-169-49.1
3002	Pākūlena	0.90	0	0	0/0	HAR §13-169-49.1
3003	Paumalū	7.79	1	0	0/0	HAR §13-169-49.1
3004	Kawela	2.07	1	0	0/0	HAR §13-169-49.1
3005	‘Ō‘io	10.74	3	0	0/0	HAR §13-169-49.1
3006	Mālaekahana	7.03	0	3	0/0	HAR §13-169-49.1
3007	Kahawainui	5.49	1	1	0/0	HAR §13-169-49.1
3008	Wailele	2.28	0	1	0/0	HAR §13-169-49.1
3009	Koloa	2.41	1	1	0/0	HAR §13-169-49.1
3010	Kaipapa‘u	3.00	0	1	0/0	HAR §13-169-49.1
3011	Ma‘akua	1.55	1	0	0/0	HAR §13-169-49.1
3012	Waipuhi	1.10	2	0	0/0	HAR §13-169-49.1
3013	Kaluanui	2.37	0	2	1/0	HAR §13-169-49.1
3014	Pāpa‘akoko	0.29	0	0	0/0	HAR §13-169-49.1
3015	Halehaa	0.25	0	0	0/0	HAR §13-169-49.1
3016	Punalu‘u	6.79	9	4	1/0	HAR §13-169-49.1
3017	Kahana	8.42	2	4	1/0	13.3 MGD (07/13/2006).
3018	Makaua	0.83	0	0	0/0	HAR §13-169-49.1
3019	Ka‘a‘awa	2.76	5	0	0/0	HAR §13-169-49.1
3020	Kualoa	0.87	0	0	0/0	HAR §13-169-49.1
3021	Hakipu‘u	2.09	7	1	0/0	HAR §13-169-49.1
3022	Waikāne	2.69	3	2	1/0	3.5 MGD (07/13/2006).
3023	Waianu	1.07	0	0	0/0	HAR §13-169-49.1
3024	Waiāhole	3.99	9	7	1/0	8.7 MGD on Waiahole Stream; 3.5 MGD on Waianu Stream (07/13/2006).
3025	Ka‘alaea	1.78	9	0	0/0	HAR §13-169-49.1
3026	Haiamoa	0.64	9	0	0/0	HAR §13-169-49.1
3027	Kahalu‘u	6.74	23	9	2/0	HAR §13-169-49.1

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi²)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
O‘AHU (continued)						
3028	He‘eia	4.47	1	3	1/0	HAR §13-169-49.1
3029	Kea‘ahala	1.17	1	0	0/0	HAR §13-169-49.1
3030	Kāne‘ohe	5.73	2	11	1/0	HAR §13-169-49.1
3031	Kawa	2.11	1	1	1/0	HAR §13-169-49.1
3032	Pu‘u Hawai‘iloa	3.68	0	0	0/0	HAR §13-169-49.1
3033	Kawainui	15.05	15	10	2/0	HAR §13-169-49.1
3034	Ka‘elepulu	5.27	0	0	0/0	HAR §13-169-49.1
3035	Waimānalo	5.95	9	1	1/0	HAR §13-169-49.1
3036	Kahawai	4.68	0	0	0/0	HAR §13-169-49.1
3037	Makapu‘u	0.51	0	0	0/0	HAR §13-169-49.1
3038	Koko Crater	3.66	0	0	0/0	HAR §13-169-49
3039	Hanauma	0.39	0	0	0/0	HAR §13-169-49
3040	Portlock	0.74	0	0	0/0	HAR §13-169-49
3041	Kamiloiki	2.39	0	0	0/0	HAR §13-169-49
3042	Kamilonui	2.02	0	0	0/0	HAR §13-169-49
3043	Haha‘ione	2.18	0	0	0/0	HAR §13-169-49
3044	Kuli‘ou‘ou	1.82	0	1	0/0	HAR §13-169-49
3045	Niu	2.70	0	0	0/0	HAR §13-169-49
3046	Wailupe	5.12	0	1	0/0	HAR §13-169-49
3047	Wai‘alaenui	6.03	0	0	0/0	HAR §13-169-49. Amended to include SCAP OA-309 on Kapakahi Stream for restoration of wetland habitat at Pouhala Marsh (06/21/2000).
3048	Diamond Head	0.39	0	0	0/0	HAR §13-169-49
3049	Ala Wai	19.02	16	11	6/1	HAR §13-169-49
3050	Nu‘uanu	9.54	9	3	0/0	HAR §13-169-49
3051	Kapālama	3.38	3	0	0/0	HAR §13-169-49
3052	Kalihi	6.27	1	3	1/0	HAR §13-169-49
3053	Moanalua	10.70	0	3	1/0	HAR §13-169-49
3054	Ke‘ehi	2.49	0	0	0/0	HAR §13-169-49
3055	Manuwai	6.65	0	0	0/0	HAR §13-169-49
3056	Salt Lake	0.62	0	0	0/0	HAR §13-169-49
3057	Hālawa	14.21	1	6	2/0	HAR §13-169-49
3058	‘Aiea	2.06	0	0	0/0	HAR §13-169-49
3059	Kalauao	3.34	0	2	0/0	HAR §13-169-49
3060	Waimalu	12.30	1	2	0/0	HAR §13-169-49

Table F-21: (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
O‘AHU (continued)						
3061	Waiawa	27.47	5	1	0/0	HAR §13-169-49. Amended to include SCAP OA-221 on Panakauahi Stream to address instream uses impacted by an arched culvert (10/22/1997).
3062	Waipi‘o	2.81	0	0	0/0	HAR §13-169-49
3063	Kapakahi	3.45	3	0	0/0	HAR §13-169-49
3064	Waikele	48.92	13	4	1/0	HAR §13-169-49. Amended to include SCAP OA-046 on Waikele Stream for diversion of 2.95 MGD for irrigation of three golf courses (07/15/1992)
3065	Honouliuli	19.93	0	2	2/0	HAR §13-169-49
3066	Kalo‘i	26.53	0	0	0/0	HAR §13-169-49
3067	Makaīwa	12.03	0	0	0/0	HAR §13-169-49
3068	Nānākuli	5.45	0	0	0/0	HAR §13-169-49
3069	Ulehawa	4.62	0	0	0/0	HAR §13-169-49
3070	Mā‘ili‘ili	19.85	0	1	0/0	HAR §13-169-49
3071	Kaupuni	9.41	6	2	0/1	HAR §13-169-49
3072	Kamaile‘unu	1.97	0	0	0/0	HAR §13-169-49
3073	Mākaha	7.37	0	1	1/0	HAR §13-169-49
3074	Kea‘au	4.24	0	0	0/0	HAR §13-169-49
3075	Mākua	6.62	0	0	0/0	HAR §13-169-49
3076	Kaluakauila	2.14	0	0	0/0	HAR §13-169-49
3077	Manini	3.03	1	0	0/0	HAR §13-169-49
3078	Kawaihāpai	7.01	0	0	0/0	HAR §13-169-49
3079	Pahole	2.45	0	0	0/0	HAR §13-169-49
3080	Makaleha	6.85	1	1	0/0	HAR §13-169-49
3081	Waialua	4.70	0	0	0/0	HAR §13-169-49
3082	Kiikii	59.03	4	11	4/0	HAR §13-169-49
3083	Paukauila	22.11	9	3	2/0	HAR §13-169-49
3084	Anahulu	16.48	4	0	0/0	HAR §13-169-49
3085	Loko Ea	2.17	4	0	0/0	HAR §13-169-49
3086	Keamanea	7.77	0	0	0/0	HAR §13-169-49
3087	Waimea	13.89	1	3	2/0	HAR §13-169-49

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MOLOKAI						
4001	Waihānau	7.73	1	1	0/0	HAR §13-169-47
4002	Waiʻaleʻia	4.36	0	0	0/0	HAR §13-169-47
4003	Waikolu	4.63	6	3	0/1	HAR §13-169-47. Amended to include SCAP MO-169 onWaikolu Stream for the installation of a fish ladder (03/14/1995).
4004	Wainēnē	0.54	0	0	0/0	HAR §13-169-47
4005	Anapuhi	0.44	0	0	0/0	HAR §13-169-47
4006	Waiohookalo	1.40	0	0	0/0	HAR §13-169-47
4007	Keawanui	0.21	1	0	0/0	HAR §13-169-47
4008	Kaʻiliʻili	0.50	0	0	0/0	HAR §13-169-47
4009	Pelekunu	7.11	2	5	0/0	HAR §13-169-47
4010	Waipū	0.54	0	0	0/0	HAR §13-169-47
4011	Hāloku	0.15	0	0	0/0	HAR §13-169-47
4012	Oloupena	0.37	0	0	0/0	HAR §13-169-47
4013	Puʻukaʻōkū	0.31	0	0	0/0	HAR §13-169-47
4014	Wailele	0.42	1	0	0/0	HAR §13-169-47
4015	Wailau	11.94	4	2	0/0	HAR §13-169-47
4016	Kalaemilo	0.19	0	0	0/0	HAR §13-169-47
4017	Waiahookalo	0.25	0	0	0/0	HAR §13-169-47
4018	Kahiwa	0.20	0	0	0/0	HAR §13-169-47
4019	Kawainui	3.74	0	1	0/0	HAR §13-169-47
4020	Pīpīwai	1.21	0	0	0/0	HAR §13-169-47
4021	Hālawa	7.64	3	1	1/0	HAR §13-169-47
4022	Pāpio	1.90	1	1	0/0	HAR §13-169-47
4023	Honowewe	2.45	0	0	0/0	HAR §13-169-47
4024	Pōhakupili	1.61	0	0	0/0	HAR §13-169-47
4025	Honoulimaloʻo	1.62	2	0	0/0	HAR §13-169-47
4026	Honouliwai	2.65	8	0	0/0	HAR §13-169-47. Amended to include SCAP MO-139 on Honouliwai Stream for diversion of 1.008 MGD for taro and aquaculture (04/14/1994).
4027	Waialua	3.41	4	0	0/0	HAR §13-169-47
4028	Kainalu	1.41	0	0	0/0	HAR §13-169-47
4029	Honomuni	1.59	1	0	0/0	HAR §13-169-47
4030	ʻAhaʻino	2.14	1	0	0/0	HAR §13-169-47
4031	Mapulehu	4.22	1	1	0/0	HAR §13-169-47
4032	Kaluaʻaha	2.05	1	0	0/0	HAR §13-169-47

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MOLOKAI (continued)						
4033	Kahananui	1.78	0	0	0/0	HAR §13-169-47
4034	ʻŌhiʻa	3.77	2	0	0/0	HAR §13-169-47
4035	Wāwāʻia	2.67	1	0	0/0	HAR §13-169-47
4036	Kamalō	13.74	1	0	0/0	HAR §13-169-47
4037	Kawela	5.44	5	2	1/1	HAR §13-169-47
4038	Kamiloloa	12.54	0	0	0/0	HAR §13-169-47
4039	Kaunakakai	9.23	0	2	1/0	HAR §13-169-47
4040	Kalamaʻula	9.65	0	0	0/0	HAR §13-169-47
4041	Manawainui	13.82	1	2	0/0	HAR §13-169-47
4042	Kāluapeʻelua	14.70	0	0	0/0	HAR §13-169-47
4043	Waiahewahewa	5.64	0	0	0/0	HAR §13-169-47
4044	Kolo	19.02	0	0	0/0	HAR §13-169-47
4045	Hakina	5.32	0	0	0/0	HAR §13-169-47
4046	Kaunalā	13.27	0	0	0/0	HAR §13-169-47
4047	Pāpōhaku	25.42	0	1	0/0	HAR §13-169-47
4048	Kaʻa	3.19	0	0	0/0	HAR §13-169-47
4049	Moʻomomi	11.45	0	0	0/0	HAR §13-169-47
4050	Maneʻopapa	13.79	0	0	0/0	HAR §13-169-47
MAUI						
6001	Waikapū	16.40	12	1	0/1	2.9 MGD below the South Waikapū Ditch diversion (04/17/2014).
6002	Pōhākea	8.31	0	0	0/0	HAR §13-169-48
6003	Pāpalaua	4.88	0	0	0/0	HAR §13-169-48
6004	Ukumehame	8.28	2	1	0/2	2.9 MGD below the lower dam (03/20/2018)
6005	Olowalu	8.40	2	1	0/1	2.33 MGD at abandoned USGS gaging station 16646200 (03/20/2018)
6006	Launiupoko	6.60	1	1	0/0	0.0 MGD (03/20/2018)
6007	Kauaʻula	8.44	1	3	0/1	3.36 MGD below the main diversion near 1540-ft. elevation and 4.1 MGD below kuleana users near 270-ft. elevation (03/20/2018)
6008	Kahoma	8.50	7	6	0/1	3.49 MGD below diversion 951 near 1850-ft. elevation; 0.8 MGD below diversion 954; By November 2023 IIFS becomes 1.55 MGD (11/20/2018)
6009	Wahikuli	9.79	0	0	0/1	HAR §13-169-48

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MAUI (continued)						
6010	Honokōwai	8.86	2	3	0/2	HAR §13-169-48. Amended to include SCAP MA-117 on Honokōwai Stream for the installation of a flow-through desilting basin (08/17/1994).
6011	Kāhana	9.07	1	0	0/0	HAR §13-169-48
6012	Honokahua	5.35	0	0	0/0	HAR §13-169-48
6013	Honolua	4.79	4	2	0/1	HAR §13-169-48
6014	Honokōhau	11.58	8	1	1/0	HAR §13-169-48
6015	Anakaluahine	2.73	0	0	0/0	HAR §13-169-48
6016	Poʻelua	2.02	0	0	0/0	HAR §13-169-48
6017	Honanana	4.66	2	0	0/0	HAR §13-169-48
6018	Kahakuloa	4.24	10	3	1/0	HAR §13-169-48. Amended to include SCAP MA-133 on Kahakuloa Stream for reconstruction of an existing stream diversion (06/02/1994).
6019	Waipili	2.65	2	0	0/0	HAR §13-169-48
6020	Waiolai	0.97	1	0	0/0	HAR §13-169-48
6021	Makamakaʻole	2.28	4	1	0/0	HAR §13-169-48
6022	Waiheʻe	7.11	5	1	1/1	10.0 MGD below Spreckels Ditch (04/17/2014).
6023	Waiehu	10.14	12	3	0/2	1.0 MGD below the Waiheʻe Ditch on North Waiehu Stream; Remaining instream flow allowing for 0.25 MGD to kuleana users on South Waiehu Stream (04/17/2014).
6024	ʻĪao	22.55	10	3	1/0	10.0 MGD below ʻĪao - Waikapu and ʻĪao -Maniania Ditch Diversion with stipulations for low-flows; 5.0 MGD at or near the stream mouth (04/17/2014).
6025	Kalialinui	30.28	0	0	0/0	HAR §13-169-44
6026	Kailua Gulch	29.76	0	0	0/0	HAR §13-169-44
6027	Māliko	27.38	10	0	0/0	HAR §13-169-44
6028	Kuiaha	8.38	30	0	0/0	HAR §13-169-44
6029	Kaupakulua	3.84	15	1	0/0	HAR §13-169-44

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MAUI (continued)						
6030	Manawaiiao	2.37	3	0	0/0	HAR §13-169-44
6031	Uaoa	2.39	6	0	0/0	HAR §13-169-44
6032	Keali‘i	0.53	4	0	0/0	HAR §13-169-44
6033	Kakipi	9.53	21	4	0/0	HAR §13-169-44
6034	Honopou	2.73	23*	4	1/1	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6035	Ho‘olawa	4.86	37	2	0/0	HAR §13-169-44
6036	Waipi‘o	1.03	15	0	0/0	HAR §13-169-44
6037	Hanehoi	1.43	12*	0	0/1	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6038	Hoalua	1.24	4	0	0/0	HAR §13-169-44
6039	Hanawana	0.65	5	0	0/0	HAR §13-169-44
6040	Kailua	5.25	6	5	0/0	HAR §13-169-44
6041	Nailiilihaele	3.57	12	2	0/0	HAR §13-169-44
6042	Puehu	0.36	1	0	0/0	HAR §13-169-44
6043	Oopuola	1.24	15	2	0/0	HAR §13-169-44
6044	Kaaiea	1.15	3	1	0/0	HAR §13-169-44
6045	Punalu‘u	0.22	1	0	0/0	HAR §13-169-44
6046	Kolea	0.71	8	0	0/0	HAR §13-169-44
6047	Waikamoi	5.30	11	7	1/1	3.8 CFS (2.46 MGD) above Hana Hwy. per CCH-MA13-01 (06/20/2018).
6048	Puohokamoa	3.18	8	6	0/0	1.1 CFS (0.71 MGD) below Hana Hwy. per CCH-MA13-01 (06/20/2018).
6049	Haipua‘ena	1.59	5	5	0/0	1.36 CFS (0.88 MGD) below Hana Hwy. per CCH-MA13-01 (06/20/2018).
6050	Punalau	1.16	3	0	0/0	2.9 CFS (1.88 MGD) above Hana Hwy. per CCH-MA13-01 (06/20/2018).
6051	Honomanū	5.60	8	4	0/1	4.2 CFS (2.72 MGD) above Hana Hwy. per CCH-MA13-01 (06/20/2018).

** Stream Diversion Works Abandonment pending.*

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MAUI (continued)						
6052	Nuaʻailua	1.56	2	0	0/0	2.2 CFS (1.42 MGD) per CCH-MA13-01 (06/20/2018).
6053	Piʻinaʻau	21.95	14*	0	0/0	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6054	ʻŌhiʻa	0.28	1	0	0/0	HAR §13-169-44
6055	Waiokamilo	2.47	18*	1	0/0	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6056	Wailuanui	6.05	8*	3	1/1	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6057	W. Wailuaiki	4.18	1*	1	1/1	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6058	E. Wailuaiki	3.52	1	1	0/1	3.7 CFS (2.39 MGD) at Hana Hwy. per CCH-MA13-01 (06/20/2018).
6059	Kopiliula	5.20	2	1	0/1	Kopiliula: 3.2 CFS (2.07 MGD) below Hana Hwy. per CCH-MA13-01 (06/20/2018). Puaʻakaʻa: 0.2 CFS (0.13 MGD) above Hana Hwy. per CCH-MA13-01 (06/20/2018).
6060	Waiohue	0.82	3*	1	0/1	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).

** Stream Diversion Works Abandonment pending.*

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MAUI (continued)						
6061	Pa‘akea	1.05	2	1	0/0	0.77 CFS (0.12 MGD) at Hana Hwy. per CCH-MA13-01 (06/20/2018).
6062	Waiaaka	0.19	1	1	0/0	0.77 CFS (0.5 MGD) above Hana Hwy. per CCH-MA13-01 (06/20/2018).
6063	Kapā‘ula	0.84	2	2	0/0	0.56 CFS (0.36 MGD) on diversion at Ko‘olau Ditch per CCH-MA13-01 (06/20/2018).
6064	Hanawī	5.60	6	2	1/0	0.92 CFS (0.6 MGD) below Hana Hwy. per CCH-MA13-01 (06/20/2018).
6065	Makapipi	3.32	3*	1	0/2	Full restoration of streamflow at East Maui Irrigation Co. diversions per CCH-MA13-01 (06/20/2018).
6066	Kūhiwa	3.41	0	0	0/0	HAR §13-169-44
6067	Waihole	0.88	2	0	0/0	HAR §13-169-44
6068	Manawaikeae	0.52	0	0	0/0	HAR §13-169-44
6069	Kahawaihapapa	3.73	0	0	0/0	HAR §13-169-44
6070	Keaaiki	1.03	2	0	0/0	HAR §13-169-44
6071	Waioni	0.63	2	0	0/0	HAR §13-169-44
6072	Lanikele	0.70	1	0	0/0	HAR §13-169-44
6073	Helele‘ike‘ōhā	3.48	14	0	0/0	HAR §13-169-44
6074	Kawakoe	4.04	15	0	0/0	HAR §13-169-44
6075	Honomā‘ele	7.94	4	0	0/0	HAR §13-169-44
6076	Kawaipapa	10.78	0	0	0/0	HAR §13-169-44
6077	Moomoonui	2.95	0	0	0/0	HAR §13-169-44
6078	Haneo‘o	2.13	0	0	0/0	HAR §13-169-44
6079	Kapia	4.71	3	0	0/0	HAR §13-169-44
6080	Waiohonu	7.15	0	0	0/0	HAR §13-169-44
6081	Papahawahawa	1.96	0	0	0/0	HAR §13-169-44
6082	Alaalaula	0.48	2	0	0/0	HAR §13-169-44
6083	Wailua	1.26	4	0	0/0	HAR §13-169-44
6084	Honolewa	0.63	1	0	0/0	HAR §13-169-44
6085	Wai‘eli	0.96	0	0	0/0	HAR §13-169-44
6086	Kakiweka	0.34	1	0	0/0	HAR §13-169-44
6087	Hāhālawe	0.74	1	1	0/0	HAR §13-169-44

** Stream Diversion Works Abandonment pending.*

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
MAUI (continued)						
6088	Puaʻaluʻu	0.53	4	0	0/0	HAR §13-169-44
6089	ʻOheʻo	9.70	0	2	1/0	HAR §13-169-44
6090	Kalena	0.71	1	0	0/0	HAR §13-169-44
6091	Koukouai	4.56	2	0	0/0	HAR §13-169-44
6092	Opelu	0.53	2	0	0/0	HAR §13-169-44
6093	Kukuiʻula	0.74	1	1	0/0	HAR §13-169-44
6094	Kaʻāpahu	0.50	0	0	0/0	HAR §13-169-44
6095	Lelekea	0.78	0	0	0/0	HAR §13-169-44
6096	Alelele	1.20	0	0	0/0	HAR §13-169-44
6097	Kālepa	0.97	2	0	0/0	HAR §13-169-44
6098	Nuanuaaloa	4.24	3	0	0/0	HAR §13-169-44
6099	Manawainui	5.17	3	0	0/0	HAR §13-169-44
6100	Kaupō	22.50	1	0	0/0	HAR §13-169-44
6101	Nuʻu	10.48	0	0	0/0	HAR §13-169-44
6102	Pāhihi	7.85	0	0	0/0	HAR §13-169-44
6103	Waiopai	5.38	0	0	0/0	HAR §13-169-44
6104	Poʻopoʻo	1.92	0	0	0/0	HAR §13-169-44
6105	Manawainui Gulch	6.07	0	0	0/0	HAR §13-169-44
6106	Kīpapa	28.42	0	1	0/0	HAR §13-169-44
6107	Kanaio	34.11	0	0	0/0	HAR §13-169-44
6108	ʻĀhihi Kinau	3.68	0	0	0/0	HAR §13-169-44
6109	Moʻoloa	1.90	0	0	0/0	HAR §13-169-44
6110	Wailea	35.76	4	0	0/0	HAR §13-169-44
6111	Hāpapa	40.89	0	1	0/0	HAR §13-169-44
6112	Waiakoa	55.76	0	0	0/0	HAR §13-169-44
HAWAIʻI						
8001	Kealahewa	5.08	0	0	0/0	HAR §13-169-46
8002	Hualua	5.53	0	0	0/0	HAR §13-169-46
8003	Kumakua	3.48	0	0	0/0	HAR §13-169-46
8004	Kapua	0.65	0	0	0/0	HAR §13-169-46
8005	Ohanaula	1.26	0	0	0/0	HAR §13-169-46
8006	Hanaʻula	3.55	0	0	0/0	HAR §13-169-46
8007	Hapahapai	3.33	1	0	0/0	HAR §13-169-46
8008	Pali Akamoa	1.36	0	0	0/0	HAR §13-169-46
8009	Wainaia	4.30	5	0	0/0	HAR §13-169-46
8010	Halelua	2.28	0	0	0/0	HAR §13-169-46
8011	Hālawa	1.75	2	0	0/0	HAR §13-169-46
8012	Aamakao	10.56	7	0	0/0	HAR §13-169-46
8013	Niuliʻi	3.27	9	0	0/0	HAR §13-169-46
8014	Waikama	3.39	7	0	0/0	HAR §13-169-46

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
HAWAIʻI (continued)						
8015	Pololū	6.31	6	0	0/0	HAR §13-169-46
8016	Honokāne Nui	10.51	6	5	0/0	HAR §13-169-46
8017	Honokāne Iki	2.62	0	0	0/0	HAR §13-169-46
8018	Kalele	0.17	0	0	0/0	HAR §13-169-46
8019	Waipahi	1.00	0	0	0/0	HAR §13-169-46
8020	Honokeʻā	2.38	0	0	0/0	HAR §13-169-46
8021	Kāʻilikaula	0.79	0	0	0/0	HAR §13-169-46
8022	Honopue	2.65	0	0	0/0	HAR §13-169-46
8023	Kōlealiʻiliʻi	0.86	0	0	0/0	HAR §13-169-46
8024	Ohiahuea	1.96	0	0	0/0	HAR §13-169-46
8025	Nakooko	0.76	0	0	0/0	HAR §13-169-46
8026	Waiʻāpuka	0.73	0	0	0/0	HAR §13-169-46
8027	Waikaloa	1.62	0	0	0/0	HAR §13-169-46
8028	Waimaile	0.48	0	0	0/0	HAR §13-169-46
8029	Kukui	0.67	0	1	0/0	HAR §13-169-46
8030	Paopao	0.54	0	1	0/0	HAR §13-169-46
8031	Waiaalala	0.34	0	1	0/0	HAR §13-169-46
8032	Punalulu	1.25	0	1	0/0	HAR §13-169-46
8033	Kaimu	1.70	0	1	0/0	HAR §13-169-46
8034	Pae	0.65	0	0	0/0	HAR §13-169-46
8035	Waimanu	8.79	0	2	0/0	HAR §13-169-46
8036	Pūkoʻa	0.21	0	0	0/0	HAR §13-169-46
8037	Manuwaikaalio	0.50	0	0	0/0	HAR §13-169-46
8038	Naluea	0.88	0	0	0/0	HAR §13-169-46
8039	Kahoʻopuʻu	0.86	0	0	0/0	HAR §13-169-46
8040	Waipāhoehoe	1.34	0	0	0/0	HAR §13-169-46
8041	Wailoa/Waipiʻo	25.84	37	18	2/0	HAR §13-169-46
8042	Kaluahine Falls	0.22	0	0	0/0	HAR §13-169-46
8043	Waiulili	28.93	1	1	0/0	HAR §13-169-46
8044	Waikoekoe	1.61	0	0	0/0	HAR §13-169-46
8045	Waipunahoe	16.51	0	0	0/0	HAR §13-169-46
8046	Waiʻaleʻale	0.79	0	0	0/0	HAR §13-169-46
8047	Waikoloa	16.95	0	0	0/0	HAR §13-169-46
8048	Kapulena	3.08	0	0	0/0	HAR §13-169-46
8049	Kawaikalia	1.84	0	0	0/0	HAR §13-169-46
8050	Malanahae	2.24	0	0	0/0	HAR §13-169-46
8051	Honokaia	16.09	0	0	0/0	HAR §13-169-46
8052	Kawela	1.31	0	0	0/0	HAR §13-169-46
8053	Keaakaukau	0.87	0	0	0/0	HAR §13-169-46
8054	Kainapahoa	9.08	1	0	0/0	HAR §13-169-46
8055	Nienie	4.95	2	0	0/0	HAR §13-169-46

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
HAWAIʻI (continued)						
8056	Papuaa	4.73	0	0	0/0	HAR §13-169-46
8057	Ouhi	0.45	0	0	0/0	HAR §13-169-46
8058	Kahaupu	11.27	0	0	0/0	HAR §13-169-46
8059	Kahawailiʻilʻi	15.56	0	0	0/0	HAR §13-169-46
8060	Keahua	1.70	0	0	0/0	HAR §13-169-46
8061	Kalōpā	30.94	0	0	0/0	HAR §13-169-46
8062	Waikaalulu	3.06	0	0	0/0	HAR §13-169-46
8063	Kukuilamalamahii	2.28	0	0	0/0	HAR §13-169-46
8064	Alilipali	1.60	0	0	0/0	HAR §13-169-46
8065	Kaumōʻali	9.39	0	0	0/0	HAR §13-169-46
8066	Pohakuhaku	2.45	0	0	0/0	HAR §13-169-46
8067	Waipunahina	15.86	0	0	0/0	HAR §13-169-46
8068	Waipunalau	3.84	0	0	0/0	HAR §13-169-46
8069	Paʻauilo	1.57	1	0	0/0	HAR §13-169-46
8070	ʻĀʻāmanu	0.64	0	0	0/0	HAR §13-169-46
8071	Koholālele	14.40	0	0	0/0	HAR §13-169-46
8072	Kalapahapuu	6.43	0	0	0/0	HAR §13-169-46
8073	Kūkaʻiau	2.40	0	0	0/0	HAR §13-169-46
8074	Puʻumaile	9.13	0	0	0/0	HAR §13-169-46
8075	Kekualele	2.18	0	0	0/0	HAR §13-169-46
8076	Kaʻala	6.62	0	0	0/0	HAR §13-169-46
8077	Kealakaha	3.49	0	0	0/0	HAR §13-169-46
8078	Keehia	1.72	0	0	0/0	HAR §13-169-46
8079	Kupapaulua	2.54	0	0	0/0	HAR §13-169-46
8080	Kaiwiki	2.24	0	0	0/0	HAR §13-169-46
8081	Kaʻula	14.35	0	0	0/0	HAR §13-169-46
8082	Kaohaoha	1.49	0	0	0/0	HAR §13-169-46
8083	Kaawalii	13.93	0	0	0/0	HAR §13-169-46
8084	Waipunalei	2.07	0	0	0/0	HAR §13-169-46
8085	Laupāhoehoe	4.71	0	0	0/0	HAR §13-169-46
8086	Kilau	2.43	1	0	0/0	HAR §13-169-46
8087	Manowaiʻōpae	1.74	2	1	0/0	HAR §13-169-46. Amended to include SCAP HA-195 on Manowaiopae Stream for a permitted diversion (05/03/1996).
8088	Kuwaikahi	0.72	1	0	0/0	HAR §13-169-46
8089	Kihalani	0.70	1	0	0/0	HAR §13-169-46

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
HAWAIʻI (continued)						
8090	Kaiwilahilahi	6.69	1	0	0/0	HAR §13-169-46
8091	Haʻakoa	6.26	0	0	0/0	HAR §13-169-46
8092	Pāhale	3.92	0	0	0/0	HAR §13-169-46
8093	Kapehu Camp	1.74	2	0	0/0	HAR §13-169-46
8094	Paeohe	0.85	0	0	0/0	HAR §13-169-46
8095	Maulua	5.30	0	0	0/0	HAR §13-169-46
8096	Pōhakupuka	3.63	1	1	0/0	HAR §13-169-46
8097	Kulanakiʻi	0.71	0	0	0/0	HAR §13-169-46
8098	Ahole	0.67	0	0	0/0	HAR §13-169-46
8099	Poupou	0.62	0	0	0/0	HAR §13-169-46
8100	Manoloa	1.32	0	0	0/0	HAR §13-169-46
8101	Nīnole	1.67	2	0	0/0	HAR §13-169-46
8102	Kaaheiki	0.27	1	0	0/0	HAR §13-169-46
8103	Waikolu	0.63	4	0	0/0	HAR §13-169-46
8104	Waikaumalo	16.10	0	0	0/0	HAR §13-169-46
8105	Waiehu	0.61	1	0	0/0	HAR §13-169-46
8106	Nanue	5.53	1	0	0/0	HAR §13-169-46
8107	Opea	2.31	0	0	0/0	HAR §13-169-46
8108	Peleau	1.12	3	0	0/0	HAR §13-169-46. Amended to include SCAP HA-314 on Peleau Stream for diversion of 8.0 MGD for agricultural use (08/23/2000).
8109	Umauma	33.83	1	0	0/0	HAR §13-169-46
8110	Hakalau	10.26	0	0	0/0	HAR §13-169-46
8111	Kolekole	20.82	8	0	0/0	HAR §13-169-46
8112	Pāheʻeheʻe	2.87	0	0	0/0	HAR §13-169-46
8113	Honomū	3.12	2	0	0/0	HAR §13-169-46. Amended to include SCAP HA-317 on Malamalamaiki Stream for 2.0-in. pipe diversion for washing farm equipment (02/28/2001).
8114	Laʻimi	0.89	1	0	0/0	HAR §13-169-46
8115	Kapehu	1.60	2	0	0/0	HAR §13-169-46
8116	Makea	2.08	4	0	0/0	HAR §13-169-46
8117	Alia	1.31	2	1	0/0	HAR §13-169-46. Amended to include SCAP HA-387 on Alia Stream for diversion of 0.058 MGD for agricultural use (05/24/2006).
8118	Makahanaloa	0.48	0	0	0/0	HAR §13-169-46

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
HAWAIʻI (continued)						
8119	Waimaauou	1.33	1	0	0/0	HAR §13-169-46
8120	Waiaama	3.53	2	0	0/0	1.0 MGD below diversion at 890-ft elevation (01/15/19)
8121	Kawainui	8.52	1	1	0/0	HAR §13-169-46
8122	Onomea	0.85	5	0	0/0	HAR §13-169-46. Amended to include SCAP HA-214 on Onomea Stream for relocation of a pipe diversion to mitigate concerns over an existing diversion dam (03/19/1997).
8123	Alakahi	0.30	1	0	0/0	HAR §13-169-46
8124	Hanawī	3.96	0	0	0/0	HAR §13-169-46
8125	Kalaoa	0.51	3	0	0/0	HAR §13-169-46
8126	ʻAleamai	0.32	0	0	0/0	HAR §13-169-46
8127	Kaʻieʻie	2.75	0	0	0/0	HAR §13-169-46
8128	Puuokalepa	0.93	2	0	0/0	HAR §13-169-46
8129	Kaʻāpoko	0.32	0	0	0/0	HAR §13-169-46
8130	Pāpaʻikou	0.19	0	0	0/0	HAR §13-169-46
8131	Kapue	11.86	0	0	0/0	HAR §13-169-46
8132	Pāhoehoe	6.96	1	0	0/0	HAR §13-169-46
8133	Paukaa	0.65	0	0	0/0	HAR §13-169-46
8134	Honoliʻi	16.59	0	2	1/0	HAR §13-169-46
8135	Maili	4.09	1	0	0/0	HAR §13-169-46
8136	Wainaku	1.86	0	0	0/0	HAR §13-169-46
8137	Pukihae	3.23	0	0	0/0	HAR §13-169-46
8138	Wailuku	225.56	11	7	1/0	HAR §13-169-46. Amended to include SCAP HA-219 on Waiau Stream for a diversion dam constructed to generate electricity for a farm operation (10/22/1997). Amended to include SCAP HA-047 on Hookelekele Stream for three diversions structures constructed as part of a hydroelectric project (10/18/1989).
8139	Wailoa	180.18	1	5	0/0	HAR §13-169-46

Table F-21 (continued)
Inventory of Surface Water Resources

Unit Code	Unit Name	Area (mi^2)	No. of Diversions	No. of Gages	Active Gages	Interim IFS
HAWAIʻI (continued)						
8140	Kaahakini	388.99	3	0	0/0	HAR §13-169-46
8141	Kīlauea	152.29	0	0	0/0	HAR §13-169-46
8142	Keauhou Point	66.58	0	0	0/0	HAR §13-169-46
8143	Kīlauea Crater	27.10	0	0	0/0	HAR §13-169-46
8144	Kapāpala	183.57	0	0	0/0	HAR §13-169-46
8145	Pahala	271.38	1	1	1/0	HAR §13-169-46
8146	Hīlea	94.44	6	3	0/0	HAR §13-169-46
8147	Nā'ālehu	46.45	1	0	0/0	HAR §13-169-46
8148	Kiolakaʻa	66.21	0	0	0/0	HAR §13-169-46
8149	South Point	11.75	1	0	0/0	HAR §13-169-46
8150	Kauna	140.63	0	0	0/0	HAR §13-169-46
8151	Kiʻilae	340.31	4	1	0/0	HAR §13-169-46
8152	Kealakekua	45.29	0	0	0/0	HAR §13-169-46
8153	Waiʻaha	224.39	8	4	1/0	HAR §13-169-46
8154	Honokōhau	14.20	0	0	0/0	HAR §13-169-46
8155	Keahole	32.73	0	0	0/0	HAR §13-169-46
8156	Kīholo	236.29	0	0	0/0	HAR §13-169-46
8157	Pōhakuloa	348.76	4	0	0/0	HAR §13-169-46
8158	Kamakoa	192.20	0	0	0/0	HAR §13-169-46
8159	Hāloa	1.07	0	0	0/0	HAR §13-169-46
8160	Lamimaumau	3.88	0	1	0/0	HAR §13-169-46
8161	Waikoloa	51.96	11	6	0/0	HAR §13-169-46
8162	Kawaihae	22.03	0	0	0/0	HAR §13-169-46
8163	Honokoa	12.61	10	0	0/0	HAR §13-169-46
8164	Keawanui	43.90	2	0	0/0	HAR §13-169-46
8165	Lapakahi	6.27	0	0	0/0	HAR §13-169-46
8166	Māhukona	12.61	0	0	0/0	HAR §13-169-46