Chapter 5

Hahai no ka ua i ka ulula'au

"The rain follows after the forest"

Climate and Water Resources

Wai (water) is the lifeblood of the Hawaiian people. Woven into their existence and etched into daily life, this precious resource enabled their ancient culture to thrive. Without fresh water life would simply not exist; it is essential to all living beings and becomes ever more critical on land completely surrounded by a salt-saturated sea.

Water's natural character and flow has historically been widely altered for our use. Beginning with the first Hawaiians and amplified 150 years ago by industrial agriculture, engineering projects diverted the natural flow of *wai* for irrigation projects. The greatest changes were made for the irrigation of sugarcane crops. These irrigation diversion projects lowered the water table, which in turn lowered the amount of water flowing through many streams. As a result, the estuaries where these streams flow into the ocean are shrunken slivers of their former selves, degrading the delivery of nutrients and the ecological health of estuaries for reef fish. These projects did, however, spread diverted water across porous fields, thus allowing at least some of it to return to the water table beneath the ground.

Today, a building and tourism boom has replaced the vast sugar plantations of yesterday with thousands of acres of impervious concrete surface that swiftly direct run-off into the ocean. This extraordinary population growth places increasing stress on our major water sources – which are located in the ground. Water located underground, or *groundwater,* is a vital source for all Hawai'i islands. On the island of Oahu for instance, groundwater provides more than 90 percent of the drinking water and about half of the water used for agricultural irrigation. Adding to the water stress are a long-term decrease in rainfall in the islands[1], and persistent pumping of groundwater at a rate that does not permit full, natural recharge. Water tables are falling around the state. Meanwhile, millions of gallons of, clear, fresh, no longer used irrigation water continue to flow into the sea through canals, chutes, and aqueducts even while the water table falls. Island-wide calls for restricted water use are broadcast, and we endure yet another multi-year drought. Hawaii does not have its water-house in order.

The need for more potable water increases yearly. In 1990, a resident population of 1,108,229 used nearly 136 million gallons per day (mgd) or 123 gallons per person per day. By 2010, population projections show an increase of the resident population to 1,367,000 people, and the Hawaii Department of Health anticipates that 168 mgd would be needed if the 1990 per person consumption does not change. Population growth with commensurate water demand continually challenges the ability of ground water to sustain Hawaii's needs. The Commission on Water Resource Management has stated that we are approaching the limits to developing our water resources in some parts of the state. For example, on Oahu, there is 415 mgd of groundwater available where water allocations total about 340 mgd. Within 25 years the unallocated amount of 75 mgd will be committed. Other problems facing the management of ground water supplies include inadequate data to estimate water availability, over estimation of water supplies, and inadequate planning to meet increasing water demands.

Although some former irrigation water is used in our homes and resorts, it is eventually returned to the ocean via sewage treatment plants, or injected into wells purposely located below (seaward of) potable groundwater supplies. Hence, it does not replenish our aquifers. Water tables around the state are dropping as a result and for no other reason than that no one has changed the diversion system now that sugarcane has left the islands.

The state of Hawaiʻi needs a management plan that comprehensively evolves us out of the days of sugar and other industrial crops, and into the days of sustainable development and climate change. It is reckless to allow millions of gallons of diverted freshwater to pour un-used into the ocean every day while West Molokaʻi, Kona, Honolulu, central Maui, windward Kauai and other locations suffer water shortages. In an environment among the wettest places on Earth, to suffer such shortages should act as a wake-up call for improving our riparian management skills.

Waiwai

In the Hawaiian language, *waiwai* signifies an abundance of fresh water and embodies the meaning of wealth. Though blessed with annual rainfalls much greater than many parts of the world, Hawaiʻi nonetheless experiences localized water shortage problems. These are partly the product of inadequate water resources in places we have chosen to populate and partly the product of inadequate water distribution and management.

With water, as with most limited essential commodities in contemporary life, we attach rights, rules and regulations to govern its fair distribution. The current management approach follows a fundamentally different design than the one established by early Hawaiians. Today's model is one of engineering strength, where natural boundaries are overridden when inconvenient and water is regarded as an abundant resource to be moved where we see fit. The consequences of this system are frequently felt not only by humans but also by a range of organisms from bacteria to gobies and the downstream plants and animals impacted by water withdrawal.

The single most important factor contributing to the success of the Polynesian settlers was an abundance of pure water and unfortunately, through our current negligence, we put at risk the very resource that enabled life on the Hawaiian Islands to flourish. By unfolding the native Hawaiians' relationship to water and the process through which they allocated this precious resource, we may discover lessons to better manage today's supply.

For ancient Polynesians who arrived on Hawaiian shores, water was freely available to everyone and was divided amongst the people in a spirit of mutual dependence, the single stipulation being that since everyone used the water, everyone must help build and maintain the islands' expansive irrigation systems. The word *kanawai*, literally "belonging to the waters," is the Hawaiian word for water rights. Water, like land, did not belong to any individual, and with its use came the responsibility of care and respect. The *ali'i nui* (high chief) administered *wai* along with the *konohiki* (headman of the ahupua'a).[2]

Ancient residents paid close attention to the shifting moods of the climate, developing an eloquent vocabulary to describe its countless nuances. Rain was generically termed *ua*, but poetic descriptions depict the intricacies of rainfall. *'Awa* falls as mountain mist, a continuous rain is *ua ho 'okina*, a downpour *ua lani-pili*, and *kualua*, falls as rain on the sea.[3] The Hawaiians studied the detailed movements of *ua*, selecting their dwellings and communities based on its presence or absence. Through their resourcefulness and deep connection to the land they managed to live in Hawai'i's more challenging climates including the desert regions.

Troughs made from the wood of the ohia, koa, and kukui trees were carved to collect water inside blackened lava tubes, and milk from coconuts was extracted to sustain life during periods of drought. This thoughtful attention to the behavior of water and the seasonal shifts that molded their daily activities led early Hawaiians to recognize two broad seasons: *Ka'u wela*, the high sun period corresponding to warmth and steady trade winds, and *ho'oilo*, the cooler period when trades are less frequent and rainy-stormy days may be more common. We now know that weather in Hawai'i follows a more complex pattern than originally contemplated.

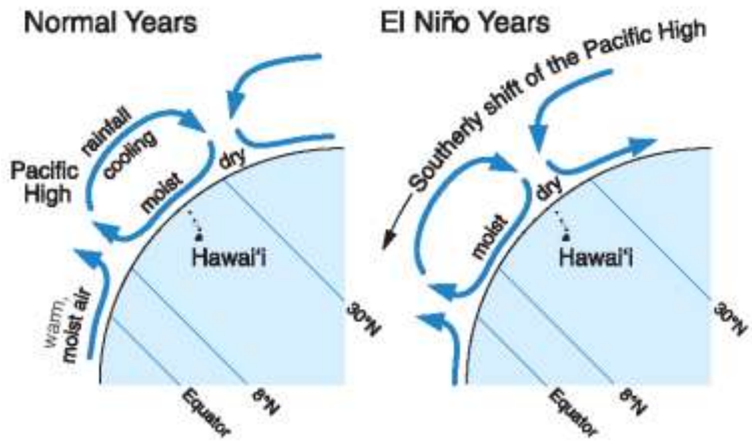
Climatology of Wai

In a study of trends in stream flow characteristics at long-term gauging stations in Hawai'i[4], the U.S. Geological Survey reports that year to year changes in stream flow are related to the *El Niño – Southern Oscillation* (ENSO) phenomenon as well as the *Pacific Decadal Oscillation* (PDO). Not surprisingly, trends in rainfall are also linked to these phenomena; Hawaii tends to be dry during most El Niño events, but low rainfall may also occur in the absence of El Niño[5]. Similarly, rainfall tends to be low during "warm" phases of the PDO; such as Hawaii experienced from mid-1970 to 2001. The state was previously characterized by high rainfall lasting for 28 yr in the preceding "cool" phase through the 1950's and 60's. ENSO and PDO are regional climate patterns that affect the distribution of rainfall in the Hawai'i Islands, and therefore exert important influence on the discharge of streams and the recharge of groundwater stores from one year to the next.

ENSO is a large-scale meteorological pattern characterized by two conditions: the so-called *La Niña* and the *El Niño*.[6] These govern temperature and rainfall trends in the Pacific Ocean as well as exert a global influence on weather patterns. ENSO is related to the atmospheric pressure difference between a body of dry air (a high pressure system) located in the southeast Pacific over Easter Island and a body of wet air (a low pressure system) located over Indonesia in the southwest Pacific. Under normal conditions (La Niña) air flows from the high pressure to the low pressure and creates the trade winds. These blow east to west across the surface of the equatorial Pacific and drive a warm surface current of water into the western Pacific. This water is replaced in the east by nutrient-rich cold ocean water that rises from the deep sea, a process called *upwelling*. The upwelling current is loaded with nutrients fueling an important fishing industry off the coast of South America.

On occasion, the pressure difference between the two centers decreases and the trade winds respond by weakening. This condition is known as El Niño. As a result, the warm water of the west Pacific surges to the east and heats up the ocean surface in the central and eastern Pacific. Precipitation in the east increases because the warmer water evaporates more readily. Upwelling temporarily stops. Torrential rains and damaging floods across the southern U.S. have resulted as well as faltering of the Peruvian fishing industry, wreaking economic hardship.

During an El Niño, the Hawaiian Islands usually experience a decrease in rainfall. In fact, the ten driest years on record are all associated with El Niño years. This happens because El Niño causes a southerly shift in the atmospheric circulation system of the north Pacific, a feature called the *Hadley Cell*.[7] The Hadley Cell is a large continuous belt of air that rises, moisture-laden, from the warm waters north of the equator at about 8° latitude (Hawaiʻi lies between 16° and 23°north latitude), and moves north across the Hawaiian Islands, raining as it goes. During its journey to the north the air cools, moisture condenses, and produces abundant rainfall. Eventually airflow descends back to the ocean surface as a column of dry, cool air and creates a pressure system known as the *Pacific High* to the north of the islands at around 30° to 35° north latitude.[8] Under normal conditions, the Hawaiian Islands experience a wet climate, while to the north and northeast, the Pacific High creates a dry climate. However, during El Niño the surface waters at the equator become significantly warmer and the rising motion of the Hadley Cell shifts to the south. This brings the Pacific High south as well, and the Hawaiian Islands experience a decrease in rainfall as we fall under the influence of the dry high pressure center.

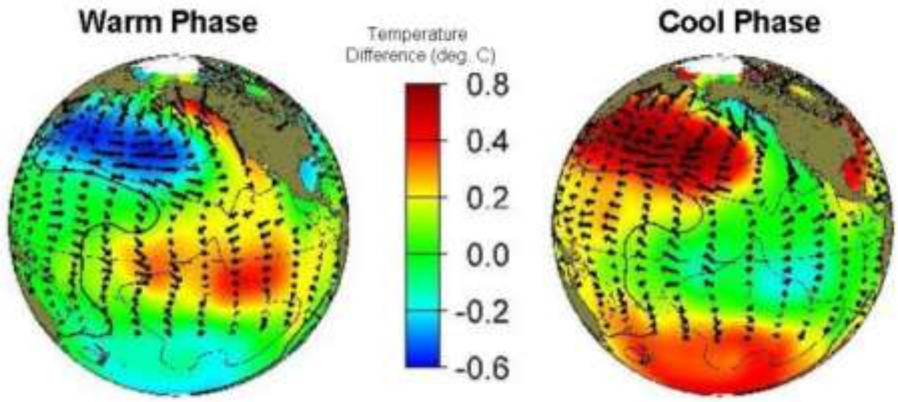


Location of the Hadley Cell during normal (left) and El Niño conditions (right).

The other important phenomenon that impacts rainfall in Hawai‘i is the PDO.[9] The PDO, like ENSO, is a pattern of climate variability in the Pacific caused by shifting surface waters. During a “warm” or “positive” phase of the PDO, the western Pacific above 20^{o} N latitude cools and part of the eastern Pacific warms; during a “cool” or “negative” phase, the reverse pattern occurs. The underlying cause of this oscillation has not yet been identified by scientists but it is recognized that shifts in phase occur approximately every twenty to thirty years.

Researchers have reconstructed that the PDO displayed a strong warm phase beginning in 1905, changed to a cool phase in 1946, and reverted back to a warm phase in 1977.[10] Beginning in 1998 the PDO showed several years of cool behavior but has not remained consistently in that pattern. A cool phase is characterized by a wedge of lower than normal sea-surface heights and cooler than normal ocean temperatures in the eastern equatorial Pacific and a warm horseshoe pattern of higher than normal sea-surface heights connecting the north, west and southern Pacific. Hawai’i tends to receive more rainfall in a cool phase. In the warm phase, which appears to have lasted from roughly 1977-2000, the west Pacific Ocean becomes cool and the wedge in the east warms. Hawai’i tends to receive less rainfall in a warm phase.

The PDO can modulate aspects of the ENSO pattern. When the PDO is in a cool phase, surface layer water temperatures are colder than normal over a large area of the Pacific and La Niña events predominate in Hawai‘i, usually leading to more rainfall in the islands. The reverse is true for the warm phase, i.e., El Niño events tend to predominate and drought may persist in the islands.



The Pacific Decadal Oscillation cool phase is characterized by a wedge of cool ocean temperatures in the eastern equatorial Pacific and a warm horseshoe pattern of ocean temperatures connecting the north, west and southern Pacific. In the warm phase the west Pacific Ocean becomes cool and the wedge in the east warms. Credit: JISAO, University of Washington (PDO web page) http://jisao.washington.edu/

The 2004 U.S. Geological Survey study of stream flow in the Hawaiian Islands found that during the months of January to March the average total stream discharge tends to be low under El Niño conditions and high under La Niña conditions.[11] This pattern is accentuated during positive or warm phases of the PDO. In Chapter 8, we review findings suggesting that global climate change is going to additionally impact water conditions in the islands later this century.

Ahupuaʻa Revitalized

The concept of ahupuaʻa evokes a sacred image imbued with the principles of stewardship, cooperation, and respect. Unrecognized to many, it also evokes a system of management based on scientific principles grounded in observations of natural processes. Ahupuaʻa has now taken hold as the guiding principle of the Hawaiʻi Ocean Resource Management Plan, the official state effort to unify and coordinate coastal and ocean-related activities and missions among government agencies.

As described in Chapter Two, the basic definition of the ahupuaʻa is a land division that stretches from the mountain ridges to the ocean, tracking the movement of water within the confines of the topography. The term arose from the practice of marking the seaward boundary of each district with an altar (*ahu*) on which a sculptured woodenhead of a pig (*puaʻa*) was offered to the aliʻi as a ceremonial gift. Each ahupuaʻa was designed to take into account the ecological characteristics of its specific location, and boundaries were set to ensure subsistence shares in food, fishing rights, firewood, housing timbers, and water. People living in one ahupuaʻa were free to use whatever grew wild within their own borders, except for the revered portions high in the watershed. They were forbidden to take from a neighboring ahupuaʻa without permission but trade between ahupuaʻa was widespread.

Ahupuaʻa were also political subdivisions. Individuals were viewed as part of their unit and subject to taxation through tributes to the aliʻi in the form of kappa weaving mats, food, clothing, and other products. Health and orderly governance was assured through a rigid regulatory system that assigned duties, roles, and consequences for disobedience. For example, an unauthorized diversion of wai was punishable by death.[12] Political boundaries coincided with agricultural and natural resource boundaries, affording immense power to the chiefs. Still, no person claimed ownership of the land. Instead, the native Hawaiians embraced the notion of *territorial custody*.

During the reign of the ahupuaʻa management system, Hawaiian agriculture ranked among the most productive in Polynesia, mostly due to their meticulous observations of how the flora and fauna responded to various weather conditions. A carefully conceived zoning arrangement demonstrates the truly integrated Hawaiian system of beliefs. The *ʻilima*, the flower used for the lei of the aliʻi, grew in a narrow band of soil just below the *wao,* the upland zones. From the edge of the rarely used rain forest to the sea spanned the *kula*, the dry plains. Within the kula, there were three sections. Furthest inland from the ocean lay the dry forest uplands, *kula uka,* cultured with drought-tolerant sweet potato and yam, carefully nurtured by moisture-rich recycled mulches. The middle plain, *kula waena,* spanned in between the *kula kai*, or sea plain, and kula uka. Here fields of taro absorbed the diverted fresh cool waters through irrigation ditches. The *kahakai* (seashore), although inappropriate for cultivation, became the ideal region for Hawaiian's to build villages. All of the major Hawaiian settlements developed along the coast. Within every ahupuaʻa, the aliʻi discouraged residents from using certain areas to ensure a constant, untainted source of water.

Success as a civilization rested in large part on understanding water flow dynamics, complex hydrological processes, and the ways to apply this knowledge to land management. This understanding enabled Hawaiians to complete feats that still intrigue researchers today, including the construction of waterways to channel fresh water and their layered agricultural terraces carved out of the mountain slopes. In many ways, the early Hawaiians merged with nature by accepting the limits imposed by the physical and ecological properties of their ahupuaʻa.

Early Environmental Impact

Although the Polynesians transported strict conservation ethics to the islands, their arrival and subsequent behavior would shape the future quantity and quality of water and the ecosystem where it collected. After traveling thousands of miles in their sea-faring canoes, the Polynesians introduced many hardy plants such as *kukui* (candlenut), *ʻulu* (breadfruit), *kalo* (taro), *kō* (sugar), *maiʻa* (banana), *ʻuala* (sweet potato) and others. These food sources, all important staples to this day, had a demanding thirst and when introduced into the delicately balanced Hawaiian ecosystem precipitated unforeseen changes in the movement and natural storage of wai.

Lush forests covering the mountain slopes acted as cloud nets before the land was settled, catching the updraft of air currents and capturing their moisture over the trees. But as villages blossomed across the landscape and the inhabitants cleared windward talus slopes with intentional fires, these steady rain cycles were disrupted. When the land was cleared for cultivation by Hawaiian and later western settlers, rains caused the barren volcanic soil to wash down the now craggy hillsides turning streams brown.

The destruction of forests accelerated in the 19^{th} century and triggered a progressive desiccating cycle. Lacking the protective upper canopy dominated by *ohia* and a secondary canopy formed by *hapuu* tree ferns, the amount of solar radiation reaching the soil increased, robbing moisture from the earthen surface. Less water resulted in less vegetation and a degrading cycle ensued resulting in the loss of the "A" soil horizon, the primary nutrient-providing layer for forest growth. Water ran off the land surface rather than seeping into the subsurface and refreshing the water table. Increased runoff caused gully erosion, washing topsoil and nutrients off the slopes. With no protective ground cover, wind velocities blew unchecked, whisking even more soil from the slopes. Throughout this accelerated cycle the sun continued to beam strongly on the barren soil, enhancing the cycle of increased evaporation and land degradation.

In many areas of Hawaiʻi today this pattern of accelerated erosion is perpetuated by poor soil management, fallow ranch lands, sugar, and pineapple fields lacking vegetative cover, tilled earth exposed to heavy rains, and open soil exposed to erosion during housing construction.

Planting the Land

Early Hawaiians replaced cleared forest with fields of nourishing crops. Subsistence agriculture demanded less environmental disruption than modern industrial farming and, being a resourceful society, they added manure and blue green algae to fertilize the crops. Many crops such as dry land taro, sweet potato, yam, and breadfruit thrived on the arid lava-coated slopes, relying solely on the rain for hydration. In these rocky areas, fields were allowed to lay fallow for periods in order to replenish soil nutrients. These simple yet wise methods yielded prolific crops. Even today, calls for untilled agriculture, mulching, cover crops, and crop rotation reverberate throughout industrialized nations, which Hawaiians have implemented from the beginning.

Nowhere in Polynesia was the cultivation of plants brought to a higher state of refinement than in Hawaiʻi, and of all that was grown *kalo* (taro) became the most revered. Kalo is the spiritual and nutritional centerpiece of Hawaiian culture, with its success depending heavily on steady flows of cool, fresh water. Elaborate ditch systems were built, diverting mountain streams to kalo fields to sustain wetland cultivation. These diversions stole a portion of the natural *base flow* of streams (water from the water table that feeds a stream), but not in the totality that the later western plantations achieved. Three hundred varieties of kalo are named in the Hawaiian language, eighty-five of which are still known today.[13] In addition to being the source of the staple Hawaiian food *poi*, kalo was also used for fishing bait and as a dye. The slopes and valleys of old Hawaiʻi waved green with vast fields of kalo and the number of kalo planters exceeded any other occupation. But things change, and so it was with the hydrology of Hawaiʻi.

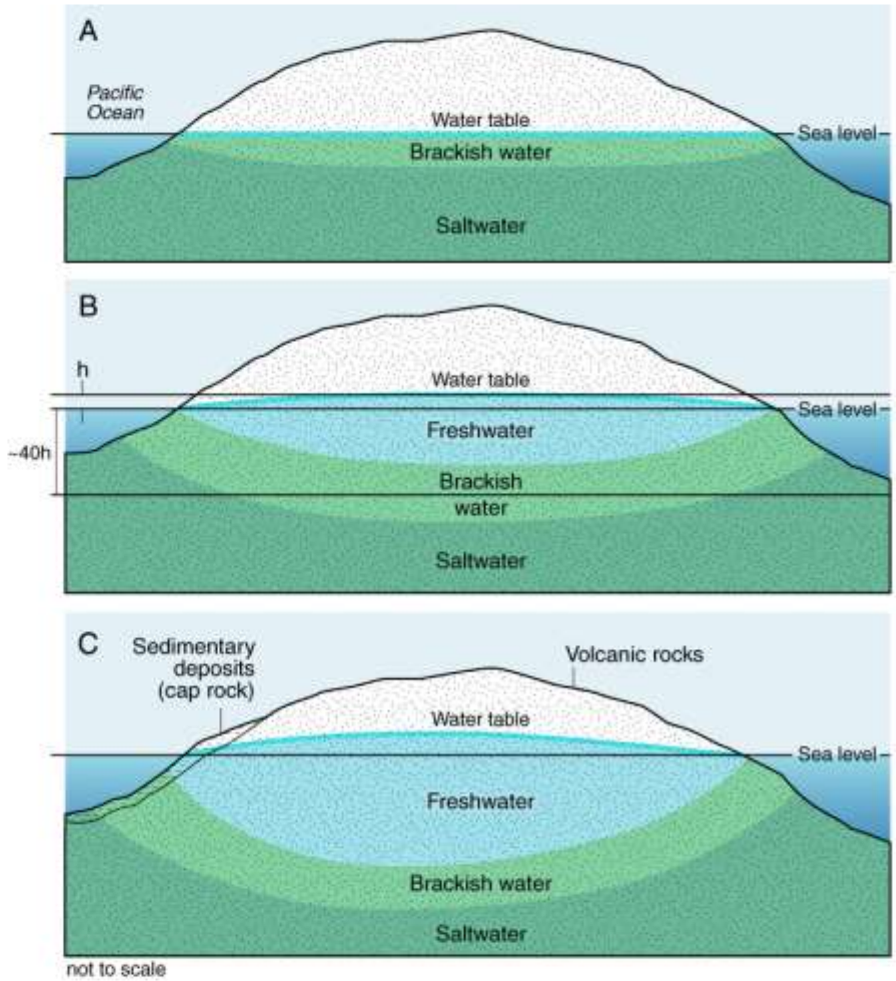
As European ships unloaded their cargo in the late 1700's, goats, pigs, sheep, and cattle were part of the inventory. These grazers and grubbers roamed and reproduced in the native forests and lowland hills of Hawaiʻi and further upset the flow of water across the landscape. Their hoofs dug into the soft earth creating new pathways for water and opening up the now muddy slopes to erosion. Physical damage to the landscape is only part of the story with ungulates. The bigger problem, at least with goats, deer, sheep, and cattle, is the unchecked grazing that denudes the landscape. Ungulates also spread invasive plants and diseases that decimate native bird populations.

Captain Cook left behind the first three goats on the island of Niʻihau. They proliferated and by the mid-1800s occupied all of the Hawaiian Islands. A few years later, Captain Vancouver delivered several cattle to Kamehameha I, who imposed a kapu to protect them from being hunted. Like the rats, pigs, and goats before them, the cattle population swelled beyond any natural balance. Adding insult to injury, the European boar, brought in by Captain Cook, was crossed with the smaller Polynesian pig, and the resulting new species has wreaked havoc on Hawaiian vegetation ever since. In these animals' wake remains a roto-tilled landscape, bearing little resemblance to the original forest. Many species of native Hawaiian orchid and other plants are being devoured to extinction by these pigs.[14]

Blessed with Wai

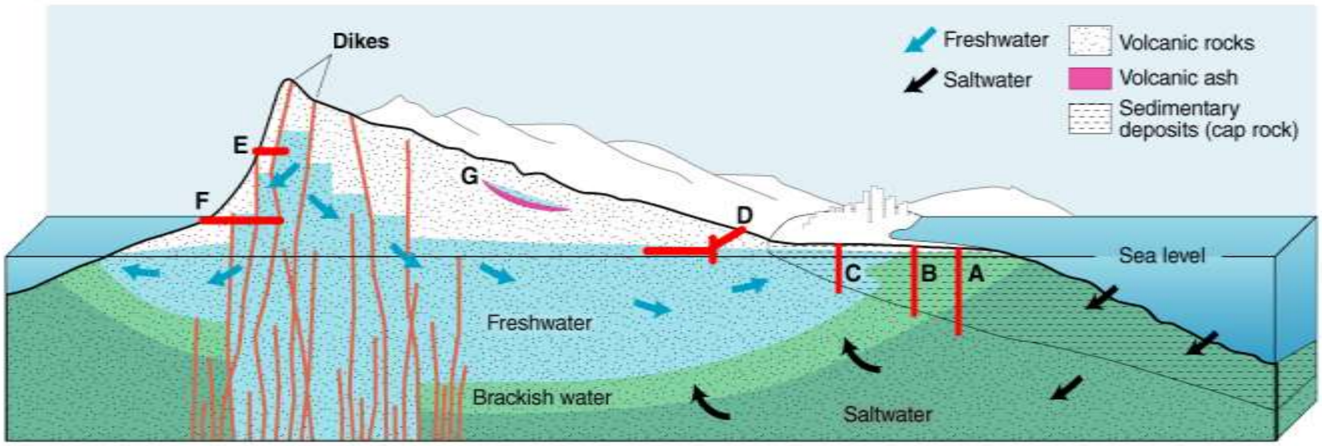
Hawai'i's rugged topography is the critical factor in its hydrologic cycle[15]. The islands' towering peaks and cliffs form a barrier to the moisture-laden trade winds, and as this air rises against the island, the falling temperature allows condensation to outpace evaporation forming familiar rain clouds. Meteorologists call this the *orographic effect*. When rain bursts forth and gushes down the volcanic slopes, porous, permeable lava and cinder layers store the waters that seep underground. Solar energy and gravity constantly move the moisture from the ocean to the atmosphere and back to Earth again. This great cycle converts salt water to fresh, perpetually recycling the treasured liquid through a natural cleansing process. Within the ground is concealed rain from past decades while today's sky is the source of our tap water many years into the future.

To reach these underground coffers, a raindrop must undertake a long and slow journey. Condensing as mist caught by high forests, water drips off the canopy, seeps into the moist vegetative mat on the forest floor, and gains dissolved nutrients from the decomposing mat. Soon, it percolates into the porous soil. From soil to permeable bedrock, through pores, cracks, and vesicles, gravity pulls the trickle into and through the basaltic rock of the shield volcano. Deep within the roots of our volcanic home, rainfall accumulates as a lens of fresh water that we draw upon for our daily needs. The fresh water floats on an underlying layer of seawater that seeps into the core of the island through submerged fractures and other permeable routes from the surrounding ocean. Fresh upon salt, this hydrologic stratigraphy is the result of density – seawater is denser than fresh water by virtue of its dissolved salt and other compounds. The position of the boundary between the seawater and fresh water lens is controlled by a combination of forces: the level of the sea around the island, the mass of fresh water pushing downward on the saltwater, the rate of fresh water flowing through the lens, and the amount of ground water pumped for human consumption.



Within islands, a fresh water lens floats on saltwater. The transition zone between the two water bodies extends about forty feet below sea level for each foot the water table stands above sea level.[16]

Over millennia a fresh water lens accumulates within an island. Fresh water displaces the underlying salt water, but only in proportion to the difference in density. A ratio of 40:1 defines the midpoint of this water body; half fresh water and half salt water. That may seem like a great deal of water, but consequently, for every foot the groundwater table is lowered by pumping for our use, the contact between fresh water and saltwater rises forty feet – bringing the salty interface within reach of our drinking wells. The result is that if we carelessly over-pump the aquifer, as has been done with the Iao Aquifer of Maui, and the Pearl Harbor Aquifer in Honolulu, we run the risk of saltwater intrusion into the wells that supply human needs, destroying that essential resource as a water source. If pumping is stopped or sufficiently decreased, it will recover. But that can take a while, and in the meantime, considering that most island populations are served from a single aquifer, where will you turn for your water needs?



On O'ahu, freshwater occurs as an underground lens or as a confined water body behind impermeable dikes of volcanic rock. Wells A, B, and C produce water from a volcanic rock aquifer that is confined under sedimentary cap rock (mostly limestone, clay, and sand). Well A produces salt water. Well B produces brackish water. Well C produces freshwater. Shaft D produces large amounts of freshwater by skimming groundwater just below the top of the water table. Shafts E and F produce freshwater from aquifers confined behind volcanic dikes; and shaft F probably gets more water because it penetrates through more dikes. At site G a layer of impermeable volcanic ash creates a "perched aquifer." Arrows indicate the generalized pattern of flow in these water bodies.[17]

Island water occurs underground in another form. If a saturated zone develops where solid layers of rock or ash retard percolating groundwater from moving toward the fresh water lens in the core of the island, a *perched aquifer* is formed. This water is less common but can constitute an important resource for our use. Secured upon low permeability ash beds, dense lava flows, or buried clays, perched aquifer systems can be substantial and they are known to feed many streams. Islands lacking the fresh water lens-type of aquifer are forced to rely more on these high elevation secluded water bodies as well as surface streams to provide for agriculture and industry. Perched aquifers may be detected by the presence of springs; however springs can also come from dike-confined aquifers and a vertically-extensive lens in the core of the island. An island lens may also discharge at low elevation through coastal springs.

Groundwater is important for more than just drinking. Most Hawaiian streams are fed by groundwater that seeps into their channels and thereby sustains a host of native aquatic ecosystems. This water is called *base flow*; it is the portion of stream discharge that is not attributable to direct runoff from precipitation. Unfortunately, according to the U.S. Geological Survey base flow to our streams is decreasing, as is the long-term annual trend in rainfall.[18] As a result, our streams are slowly drying.

From 1913 to 2002, base flows generally decreased in streams for which there is data.[19] This trend is consistent with a long-term downward trend in annual rainfall over much of the state over the same period. During the early part of this period, 1913 to the 1940's, monthly mean base flow to streams was generally above the long-term average. However, following the early 1940's, monthly base flow decreased to below the average. The primary factor responsible for this decrease is likely to be the decreased recharge to groundwater stores resulting from decreased rainfall (and potentially other sources). Additionally, where pumping for human use has historically been important, base flow to streams may suffer from reduced groundwater storage because of human consumption.

Search for Wai

Though blessed with prolific rainfall, the search for water nevertheless intensified during the 1800's and continues to escalate today. The "communal" or "feudal" system of land ownership enjoyed by Kamehameha III held lands in trust by a high chief, *aliʻi ʻai moku*, who then distributed his land to subchiefs, *konohiki*.[20] They, in turn, allotted lands to the commoners, who grew food for the masses. Before the *Mahele*, the peaceful yet revolutionary episode of partition and distribution of lands in 1848 that substantially altered the ahupuaʻa system, disputes concerning water were rare. But the Mahele sparked a hunger for private property rights; the outcome of which was the acquisition of large acreages of land for the full development of commercial agriculture.

By the late 1800's, the face of Hawaiian agriculture was undergoing a dramatic shift. As Hawaiʻi developed into a significant trade route, many prosperous entrepreneurs discovered Hawaiʻi's agriculture-friendly climate. The only complication facing these savvy business moguls was access to enough fresh water to transform gigantic plots of arid land into flourishing plantations.

Enter James Campbell, a California agricultural tycoon who time and again watched the dark waterlogged clouds hanging over Oʻahu's eastside while his 41,000 acres of parched leeward soils remained deprived of the elusive rain. The frustrated businessman eventually turned his sights downward and hired well-borer James Ashley to accomplish his vision. In 1879, equipped with only a hand-operated tool, Ashley struck subterraneous water on the Ewa Plain at Honouliuli. Overflowing the top of the pipe, a seemingly endless supply of buried water treasure was released from its geologic grasp.[21] Once these underground reservoirs were identified, misguided users began expunging the water faster than nature could replace it.

By the turn of the 20th century, industrial agriculture companies learned the secrets of tapping into the groundwater reserves of the Hawaiian Islands. Sugar cane, pineapple, and cattle farming began a century-long consumption of fresh water that was essentially unregulated. Drilled wells, *infiltration galleries*, and *drainage tunnels* probed the volcanic canyons and valleys for water and found abundant quantities of the elusive liquid stored within. More than one thousand substantial wells have been drilled on Oʻahu alone with most production wells 250-750 feet deep.[22] The 4,000 foot deep Waikiʻi Well located on the slopes of Mauna Kea is one of the deepest water wells in the world.[23]

Infiltration galleries are dug slightly below sea level with one or more tunnels extending outward to skim fresh water from the surface of an aquifer. Oʻahu's most famous infiltration gallery, Halawa Shaft, draws enough water each day for the needs of more than 100,000 people.[24] Horizontal shafts drilled into mountain areas to tap high-level perched or dike-confined water have only been successful on a couple of islands, though they have been attempted on all. The largest operation statewide is the controversial Waiahole system traversing a three-mile tunnel punched through the Koʻolau Mountain range.[25] However, the longest transmission tunnel in the state brings water across five miles of arid scrubland in western Molokaʻi.[26]

By the time of annexation in 1893, Hawai‘i’s plantation economy was owned and controlled largely by five corporations: Castle & Cook, Theo H. Davies, C. Brewer, American Factors, and Alexander & Baldwin.[27] Sugar interests expropriated the irrigable lowlands and rain drenched prime upland, and pineapple interests seized most of the remaining land suitable for cultivation. Plantations soon dominated the landscape and used the islands’ fresh water supply for the production of export crops, directly contradicting the self-sustaining model of the ahupua‘a system. The sugar industry demanded a copious and secure supply of water, the right to own the waters that originated on lands they owned, and the right to transport water out of its original watershed, even if transport greatly depleted the stream flow to the detriment of the people downstream. These demands, and the fact that they were met by a willing government, changed the fundamental principles of water management throughout the Hawaiian Islands.

Community Wai

In a report dated 1926, the Honolulu Sewer and Water Commission stated:

> *“The City is supplied with water through antiquated equipment which is by no means a system, but an unplanned patchwork of unrelated units. There are frequent water shortages in many parts of the City. There is an ever-present fire menace, growth is hampered, and, in general, the water system has lagged far behind the needs of the City.”*[28]

In response, the *Honolulu Board of Water Supply* was formed with the intention of modernizing the system of water needed to run the growing city of Honolulu.[29] Under the leadership of its first manager, Fred Ohrt, the new Board capped wasteful artesian wells, put casings inside leaky wells, and installed water meters for consumers and billed them at fixed rates.[30] The water table stabilized and watersheds critical to maintaining the natural flow that recharged the aquifer were placed under protected status.

By the end of WWII, land use shifts were imminent. Labor unions gained a major role in the Democratic Party and profits by large plantation companies began to decline. In the 1950s, unionization increased fair wages and benefits, driving up the costs of labor, while competition from other tropical producers (Brazil, Puerto Rico, and the Philippines) magnified. Water use across Hawai‘i became a focus of concern among multiple users: cattle ranchers, taro farmers, aquatic biologists, industrial agriculture, environmentalists, and others. Water conflicts catapulted to the forefront of political battles in the State.

In 1987, the landmark State Water Code established the Commission on Water Resource Management and its authorities and responsibilities.[31] This law asserts that, “the waters of the State are held for the benefit of the citizens of the State.”[32] Thus the State highlighted sovereign water rights and the concept of *public trust*. However, the Water Commission has not quite lived up to the promise of solving the problems associated with wai. A 1996 state auditor report criticized the commission for not moving fast enough to produce a plan for water use by Native Hawaiians, a plan to protect Hawai‘i’s streams, or a comprehensive water plan for the state.[33] Partially in response to these problems, the state administration in 2005 moved to transfer water management responsibilities to the counties and dismantle the commission.[34] Environmentalists objected to this plan and labeled it “an unraveling” of controls and a step backward in water resource management.[35]

Fears that local control of water management would be inadequate stem from numerous problems that persist in county water administration. In his 2004 annual "State of the County" address, Maui Mayor Alan Arakawa said that for years the county has performed "a delicate dance around the truth: that the ʻIao Aquifer — Central and South Maui's main domestic water source — was being tapped out."[36] The situation was so bad that in July the previous year the state water commission moved to take over control of the aquifer because of perceived problems in management by the county.[37] Further, Arakawa declared there was a "dire" need for alternative water sources, and proposed the construction of a desalinization plant.[38] Contributing to the problem is that fifty million gallons of surface flow each day remain under the control of private companies, a practice left over from the days of big sugar. Pledging to continue negotiations with water owners, the mayor declared, 'Ultimately, one way or another, Maui County will soon have this major water source under public control."[39] Four years later this has yet to happen.

Is there a problem with water? It would seem the answer is an unqualified "yes". When county authorities declare a dire water problem, are faced with take-over by the state, propose the need for expensive desalinization while tens of millions of gallons of fresh water flow unused into the sea, and must negotiate with commercial concerns to secure the lifeblood of their booming economy, something is clearly amiss with the management of *wai*.

Quench Our Thirst for Wai

The state of Hawaiʻi today has shifted away from the days of industrial sugar farming and into a mosaic of tourism and population-centered development activity. In this setting, water shortages promise to become even more pressing. Hawaiʻi's urban growth has been concentrated on Oʻahu where the population has doubled since 1950 and is projected to reach 930,000 people by 2010.[40] Population centers across the islands tend to spotlight sunny, dry coastlines where fresh water is scarce, amplifying the uncertainty of their water supply. This point is worth emphasizing, most growth and increase in water demand has been in leeward areas. This requires a more expensive and elaborate infrastructure to move water farther, plus more is needed because in the arid environment per capita water use is higher in leeward areas.

According to the U.S. Geological Survey, the total fresh water used in Hawaiʻi in 1995 averaged a little more than 981 million gallons a day (mgd). By 2000, the last year for which there is data, this had decreased to about 628 mgd, a decrease resulting from the demise of sugar cane as a major producer in the state.[41] In 2000:

1. Kauaʻi with a population of 58,460 withdrew 45.2 mgd (down from 239 mgd in 1995),
2. Oʻahu with a population of 876,160 withdrew 216.91 mgd (down from 264.23 mgd in 1995),
3. Maui County with a population of 128,090 withdrew 312.82 mgd (down from 368.83 mgd in 1995),
4. Hawaiʻi County with a population of 148,680 withdrew 53.41 mgd (down from 108.52 mgd in 1995).

On Kauaʻi, shifts in water usage have been dramatic. In 1995, more than 223 mgd of Kauaʻi's water went to agriculture (93% of total fresh water use). By 2000, irrigation use had dwindled to only about thirty mgd. On O‘ahu, 1995 agriculture use was almost ninety mgd but by 2000, had decreased so that irrigation use was only about forty mgd. Groundwater use on O‘ahu went from 227.85 mgd and surface water use of 36.38 mgd in 1995, to 208.84 groundwater and 8.07 surface water use by 2000. In Maui County, 1995 surface water use was about 240 mgd and by 2000 had fallen to 164.13 mgd. Groundwater use in Maui County rose over the same period from about 128 mgd in 1995 to 148.69 mgd.[42]

The comparison between each island’s supply of water and the amount of consumption suggests that there’s generally an adequate amount of water to meet present needs. But when projected population growth and encroaching urbanization are added to the equation, they threaten to deplete existing supplies. A combination of location, population density, urbanization and agricultural withdrawal set the stage for water shortages across the state, despite the apparent abundance of natural recharge.

A general shift to decreased surface water use related to the demise of the sugar industry and increased focus on groundwater sources related to growth in population characterizes the past decade of water use. Overall, the numbers showing water use island by island do not indicate a widespread problem as Hawai‘i continues to be blessed with wai and the end of sugar has decreased the demand for water.

But a problem exists in local form: shifts away from stream-borne water to groundwater as a major domestic supplier despite poor understanding of this resource; private corporate control of major stream resources and lack of public scrutiny over their use; salinization of Maui’s Iao Aquifer; declines in O‘ahu’s Pearl Harbor Aquifer; community disputes over water on Moloka‘i; and others. The Kona coast of Hawai‘i, the west portion of Maui, O‘ahu’s dry leeward coast, and even parts of Kaua‘i and Moloka‘i are rapidly developing or may be in the near future under sustained growth of tourism, which promises to propel water rights to the forefront of Hawaiian political debates in the 21st Century.

Hawai‘i does not have a water shortage problem; we have a *water distribution problem*. And despite the best intentions of managers, the Commission on Water Resource Management has yet to provide a comprehensive plan for the husbandry of our water resources.

Moving Water

Hawai‘i is facing mounting problems resulting from the extraction of too much groundwater, decreased groundwater recharge, decreased rainfall (and therefore decreasing flow in streams), and potentially negative climate impacts to water availability and extreme events. These trends threaten the organisms that dwell in aquatic ecosystems, and impact the nearshore estuaries and bays where brackish water is important. By rerouting water where we need it, Hawai‘i has evolved into a massive experiment in the effects of moving water. But as water becomes scarce in aquatic systems, the stakes are getting higher.

We don’t even know how much water is in transit at any given moment, though it exceeds 200 billion gallons a year.[43] On O‘ahu more than eighteen tunnels transport large quantities of fresh water from high rainfall areas to dry agricultural and residential communities. Each island is riddled with miles of tunnels flowing with fresh water.

When water is diverted, it is channeled from the windward side of an island to the leeward side where most of the population resides. This diversion can have numerous effects on the ecological and cultural functions of the windward community: streambeds go dry and estuaries and reefs lose critical ecology. Basically these tunnels are diverting Hawaiʻi's waters from their original ecological functions into tourism and residential growth. As the windward side of the island experiences the stress of an interrupted water system, on the leeward side new neighborhoods, golf courses, hotels, and tourist adventures soak up the "extra" water. But in most instances this new use does not return the water to the water table. It sends it into the ocean or into salty groundwater in the coastal plain after treatment.

Are We Running Out?

The answer to this question depends on your point of view. On West Maui the population has increased (and along with it the withdrawal of groundwater), aquifer recharge rates have declined, chlorinity (saltiness) of well water is up, and sustained drought has hit the region – all this despite decreased agricultural use of groundwater over the past decade.

Since the combination of Hawaiʻi's geology and topography make its surface water difficult to exploit and most efforts to divert stream flow have been intended for irrigating sugar, water used by the burgeoning population for drinking and manufacturing comes from the easily extractable stores underground. For over a hundred years we have been siphoning from the water table, resulting in an estimated 40% decrease of the original volume according to the U.S. Geological Survey.[44] The last decade of the 20th Century and the first decade of the 21st Century have witnessed the most intense water shortages as the extraction rate grew by millions of gallons in the midst of a prolonged drought and sustained expansion in population and housing. In some places, the water table has plummeted by more than thirteen feet, allowing salt water to contaminate coastal wells as it replaced the retreating fresh water. In Kona and portions of Maui, drinking water has become less enticing as salt water finds its way into the lowered water table.

While some areas around the islands have an abundant supply and have even been referred to as possessing "extra water", other areas have extremely limited surface and groundwater supplies. The inequality of water resource distribution has serious implications. For example, water supply in Lihue, Kauaʻi (mere miles from Mt. Waialeale, among the wettest spots on Earth) is constrained by a lack of new groundwater sources and the county is paying to use a new desalinization plant. The problem with groundwater near Lihue is that the aquifer has a low permeability. When a well is pumped, water levels drop a lot, so only a limited amount of water can be pumped out of each well. When they ran the numbers, Kauai authorities decided it was cheaper to just treat salt water than put in a whole lot of small capacity wells. As a major population center on the island and an area slated for new residential development, the water shortage in the Lihue area is becoming a major problem. This not only limits future development around Puhi and Hanama'ulu but also restricts current residential plans. Elsewhere on the island pristine freshwater gushes into the sea through out-of-date irrigation ditches used by the tourism industry for kayak rides.

What quickly becomes evident when examining the Hawaiian Islands' water supply is that the Lihue situation is not atypical. In fact, several populous areas (Honolulu, central and west Maui) across the islands are withdrawing amounts of water dangerously close to the estimated availability level. And these estimates are just that - estimates - with margins of error existing that may be cloaking the fact that many towns are already flirting with disaster.

Though very difficult to estimate, planners use the concept of *maximum sustainable yield* (MSY) to determine how much groundwater is extractable. This important planning guide 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 Water Commission."[45] Considerable disagreement exists over how to derive valid estimates for maximum sustainable yield since the outcome dictates the future fresh water supply for the entire state.

The Commission for Water Resources Management presently divides each island into "aquifer sections" and estimates the MSY for each. Withdrawal rates for municipal and agricultural demand are established in accordance with these MSY targets. For decades the state has used methods that tend to overestimate the MSY, and while they still use these liberal estimates, they have begun a process to incorporate more modern computer modeling approaches when such information becomes available. Critics claim there are serious flaws in this approach since over-pumping in one aquifer can pull water from an adjacent watershed. For instance, water shortages in portions of the Pearl Harbor Aquifer may be due to over-pumping from other sectors of the same aquifer. New models are being proposed by federal agencies that take into account water transport between aquifer sections.

As areas approach the sustainable yield estimates and water tables begin to fluctuate, refinements of MSY estimates are mandatory. On O‘ahu, the MSY has been reduced several times over the past few years. Prior to 1991, MSY was set at 495 mgd, and then was reduced to 465 in 1992 due to overstated estimates for the central aquifer.[46] Discrepancies between guidelines such as MSY and the ability of natural recharge to replace these withdrawals can spell problems on a local scale. Because of population growth, and the shift from agriculture to residential and tourism uses, rates of water usage are on a path of convergence with rates of sustainable yield. Given the high degree of uncertainty in our models of the groundwater resource, actual usage and MSY may be already overlapping in places, or soon will – a very undesirable situation.

Following the path blazed by central Maui, Lihue, and Kona, some hydrologists feel that O‘ahu will soon face a water crisis. Two factors will determine to a large extent how much water reaches the aquifer: groundwater recharge (remember, this is ultimately governed by climate), and decisions about future land use. In light of this, two questions should be present on all residents' minds: Are we willing to risk contaminating groundwater aquifers by withdrawing too much fresh water? What does climate change hold in store for our water resources?

This heated debate on water management has barely touched on the overarching concept of *sustainability*. Does a commitment exist to preserve the integrity of the hydrologic system into the middle of this century, or is the concern only with the short-term? If the word sustainable is interpreted to mean "without impairing the utility or quality of the water source," then we have already violated this standard in several places and now have a lot of back-peddling to do.

Water Recycling

Water recycling was implicit within the valley-type ahupua‘a management system, with boundaries between adjacent land units following ridgelines to separate the drainage basin of one ahupua‘a from the next. Today, water recycling and reuse have been successful elsewhere but until the 1970's Hawai'i largely ignored this important opportunity. But as water shortages become a reality, Hawai'i is scrambling for solutions to the water crisis.

The largest potential users of recycled water in the state are large tourism complexes, large scale farms and ranches, residential and commercial landscaping, and golf courses; all currently consuming most of the potable water in use. Not only is treated wastewater a reliable source of water since it flows evenly throughout the year, but it can be treated to a safe level of use and save millions of gallons of fresh water each year. At the same time, it allows natural aquifers to be replenished when recycled water is spread on the land. Of the more than 157 million gallons a day of wastewater generated in the state, at least half of it is reusable, which is enough to water more than 100 golf courses each day. In 2004, only twenty-four mgd out of 150 mgd (approximately 16%) of treated wastewater was put to reuse.[47]

While we dispose of more than 144 million gallons a day of potentially reusable "waste" water, parts of Hawai'i face the prospect of fresh water shortages. Yet, a solution based on water reuse remains in the shadows of acceptance. Notably[48], Los Angeles County, home to 10 million people, treats its waste water to a tertiary level, pumps it to natural recharge areas, and allows it to infiltrate back into the potable groundwater system in a massive (and successful) display of efficient water reuse.

The Hawai'i State Department of Health released the Guidelines for the Treatment of Use of Reclaimed Water on May 15, 2002.[49] These guidelines provide specifics for evaluating reuse projects to safeguard public health and preclude environmental degradation of aquifers and surface waters while seeking to maximize the potential of the relatively new resource. While water reuse is on the upswing among consumers such as golf courses and other forms of water use not directly tied to human consumption, as a state we remain behind the times in terms of water recycling. For instance, no large-scale groundwater recharge effort exists which would utilize recycled water. Global warming, and the drought that may accompany it, may force us to have a higher appreciation for the value of water reuse.

The three main stumbling blocks to recycling water are demand (public acceptance), money, and governmental organization. Demand for reused water is quite insignificant, in part because many potential users already enjoy low-cost, high-quality water. The initial start-up expenses for water recycling are considerable. Understandably, customers are hesitant to assume the added financial cost of water reuse. The state of Hawai'i's water management structure must change in order to attract users and make it economically and politically desirable to incur the initial hassle and cost of switching over to reused water.

Using the threat of fines as an incentive, the federal government goads state and county agencies into promoting reclamation efforts. At issue is who should pay, and whose responsibility is it? This lingering obstacle of responsibility pits those who create potentially recyclable wastewater against those who reuse it. Managing the environmental risks is costly and potentially hazardous because improperly treated wastewater can contain fouling nutrients, toxins, and disease-causing organisms. Unfortunately, the lines of liability are unclear leaving considerable opportunity for wanton neglect and inaction.

To date, the recycling strategy of Hawai'i has embodied myopic rights and responsibilities rather than creating a vision for the entire state. Consequently, sewage facilities aren't accountable for how much fresh water they use in treatment, no single agency has a clear mandate or authority for managing water, and the supply agencies are not forced to worry about how treated effluent gets to potential recycling users from treatment plants.

However, shifting sentiments are beginning to redefine the way Hawai‘i manages water and a suite of solutions are being discussed.

- New sewage treatment plants can be located close to agricultural production to reduce distribution costs.
- For many of the mega-hotel complexes the reuse and treatment facilities could be integrated from the beginning.
- Wastewater treatment plants can be designed with re-use as part of a single system, supplying all the needed water to irrigate their golf courses, lawns, and open space.
- Merging water supply offices with waste water managers under one roof may also be a step in the right direction to promote more urgent examination of the long-range costs that effluent re-use can avoid.

On the Horizon: Changing Climate and Shifting Land Use

Climate change has the potential to move the discussion of water use from its present footing of concern to a new footing of crisis. The orographic effect that supplies much of our rainfall is the primary source of recharge to the aquifers we use. However, scientists are unsure exactly how our local system of water production will respond to global warming. One hypothesis proposes that increased drought will result as surface heating in coming decades drives the cloud base higher. Another posits that higher sea surface temperatures will enhance evaporation and offset this trend. Cloud base elevation today is approximately 2,000 feet. As it rises, former groundwater recharge areas will receive less rainfall, aridity in leeward regions will increase, and the overall amount of rainfall falling on mountainous lands will decrease. Only monitoring of our environment will reveal the emerging pattern among these critically important processes.

The Intergovernmental Panel on Climate Change hypothesizes that global surface temperatures will rise between 2.5^0F and 10.4^0F by 2100 relative to 1990.[50] How high this heating will raise cloud base, or sea surface temperature, and what their offsetting roles may be in Hawai’i is the subject of ongoing research.

Above the clouds lies the upper elevation *inversion*. This is a region of dry, still air that limits the top of orographic clouds. Those who have visited the summits of Mauna Loa or Mauna Kea have experienced the inversion firsthand as they looked down on the tops of Hawai‘i’s clouds. Climate researchers are uncertain if warming will raise the inversion, or if it will hold its present elevation and constrict the zone of orographic rainfall between a rising base and an immoveable ceiling. It is even conceivable that the inversion could descend – further squeezing our water source in the sky.

One pattern of future rainfall in Hawai’i that should be of particular concern is the possibility of increased extreme rainfall. Climate models suggest that extreme rainfall events, such as the type that caused over $80 million in damage to the University of Hawaii library in 2004[51], will become more frequent in a warmer climate.[52] Researchers used a combination of direct meteorological patterns and advanced computer models to reveal a distinct link between rainfall extremes and temperature with heavy rain events increasing during warm periods and decreasing during cold periods. Notably, they found that rainfall extremes were larger than the events predicted by global circulation models, implying that predictions of extreme rain events in response to future global warming may be underestimated. With Hawaii's high topography, heavily developed and cemented watersheds, and natural proclivity for flash floods and heavy rainfall, weather patterns with more extreme behavior pose a dangerous future for both steep housing tracts and low lying coastal plains where floods fan out and stagnate.

Though water supply has certainly been a major issue for the state over the course of history, new dilemmas heighten concern. The closure of large-scale agricultural operations is leaving future use of the land uncertain. The fate of our water supply may well be linked to the fate of fallow fields. Many hydrologists agree that converting agricultural land into impervious residential sprawl will cause groundwater supplies to be depleted more rapidly, especially if residential withdrawal rates continue at their present pace. At Maui, Kona, and Honolulu at least, this pattern is well underway and threatens to hasten the already declining water levels in those communities.

Combine these shifts in land-use, with potential decreases of our main source of water due to climate change, and add to this the fact that no one is integrating these disparate issues and sources of information into an overarching water management plan – and you have the basis for continued, potentially accelerated, water shortages. Here again is another reason why Hawai‘i needs a state science agency rather than a disparate collection of federal, state, and local offices that operate without integration and lacking the proper mandate.

Water's Role in the Future of our Society

There are no easy answers to the questions concerning growth management, reduced cloud production, and water rights in Hawai‘i. The state of Hawai‘i needs to address land use changes and the privatization of water. We also need to devote resources toward improving our understanding of the potential impacts of climate change on local water availability. With a resource as finite and essential as water, solutions to these issues are emerging as the foundation for Hawai‘i's future. The time has arrived for the people of Hawai‘i to decide, as the Polynesians did upon arrival, water's role in the future of our society. The Hawaiians agreed that water was a right, a resource entitled to all living things, and a life force that needed to be protected and worshiped, for existence depended on it.

Let us remember the lessons of the ahupua‘a and the basic tenants that underlie this management system: stewardship, cooperation, and respect. All of these concepts must be incorporated within our land management system if Hawai‘i is to choose a sustainable future. Only by recognizing water as a public commodity can the State of Hawai‘i begin to equitably allocate water resources in a manner that respects the present and future integrity of water supplies.

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