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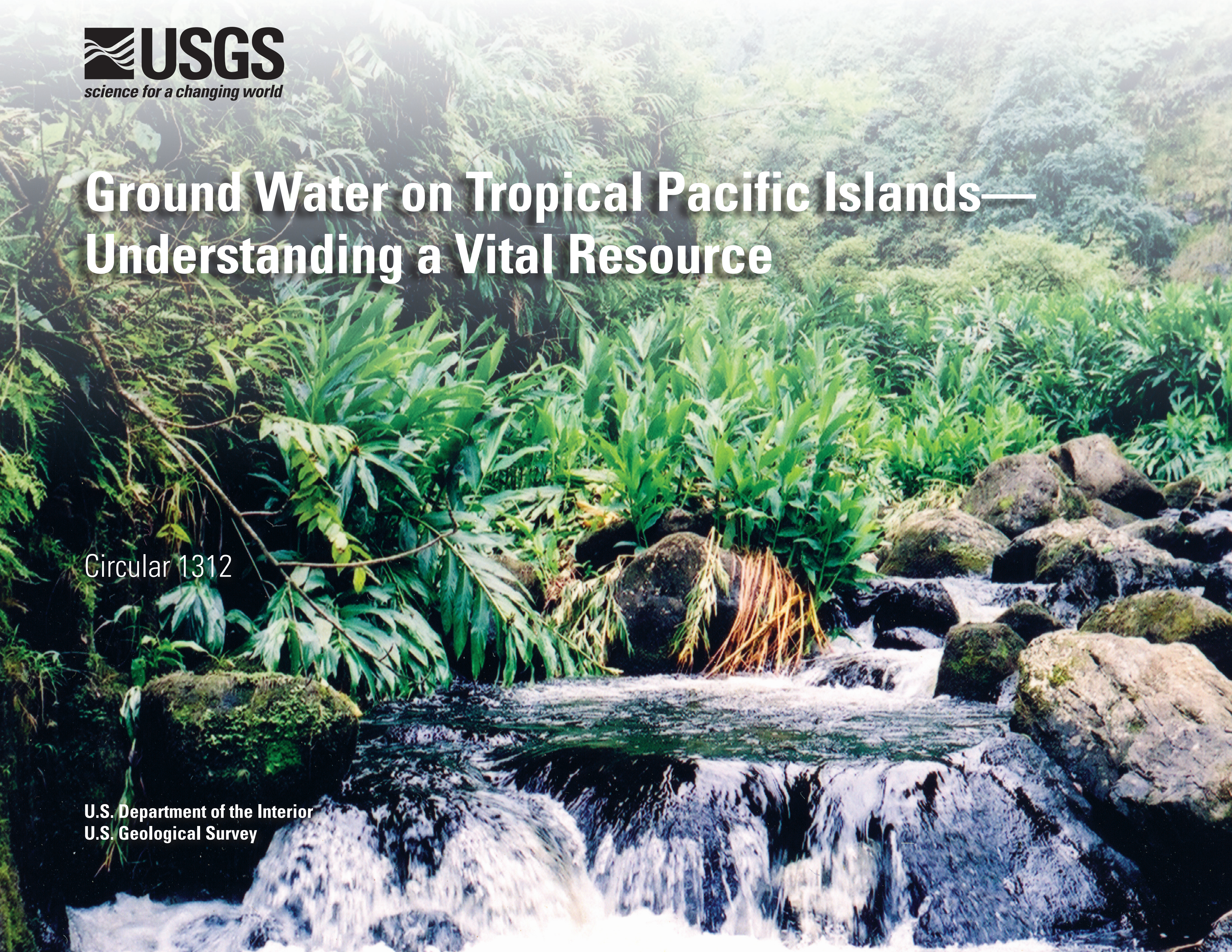
Ground Water on Tropical Pacific Islands—Understanding a Vital Resource



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Ground Water on Tropical Pacific Islands—Understanding a Vital Resource

By Gordon Tribble

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

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Suggested citation:
Tribble, Gordon, 2008, Ground Water on Tropical Pacific Islands—Understanding a Vital Resource: U.S. Geological Survey Circular 1312, 35 p.

Cataloging-in-Publication data are on file with the Library of Congress (URL http://www.loc.gov/).

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, April 19, 2007
Text edited by James W. Hendley II
Layout and design by Jeanne S. DiLeo and Susan Mayfield

Cover—Perennial flow in Ko‘iawe Stream, Waipi‘o Valley on the Island of Hawai‘i. The sustained flow of water in the stream results in the discharge of dike-impounded ground water from high elevations at the back of the valley. Streams that flow perennially because of ground-water discharge are important sources of water for traditional and modern agricultural practices, provide habitat for a unique group of stream animals, and contribute to the aesthetic value of the islands. (USGS photograph by Gordon Tribble.)

CONTENTS

Freshwater cascades from a spring on a cliff face into a pool next to the Pacific Ocean near Nāhiku on the Hawaiian island of Maui. The water comes from rain that fell at higher elevations on Haleakalā Volcano, seeped into the ground, and has traveled slowly toward the coast. (USGS photograph by Gordon Tribble.)

Foreword

To a casual observer, tropical Pacific islands seem idyllic. Closer scrutiny reveals that their generally small size makes them particularly vulnerable to economic and environmental stresses imposed by rapidly growing populations, increasing economic development, and global climate change. On these islands, freshwater is one of the most precious resources. Ground water is the main source of drinking water on many islands, and for quite a few islands, it is the only reliable source of water throughout the year. Faced with a growing demand for this valuable resource, and the potential negative effects on its availability and quality from changes in global climate, increasingly sophisticated management approaches will be needed to ensure a dependable supply of freshwater for the residents of these islands.

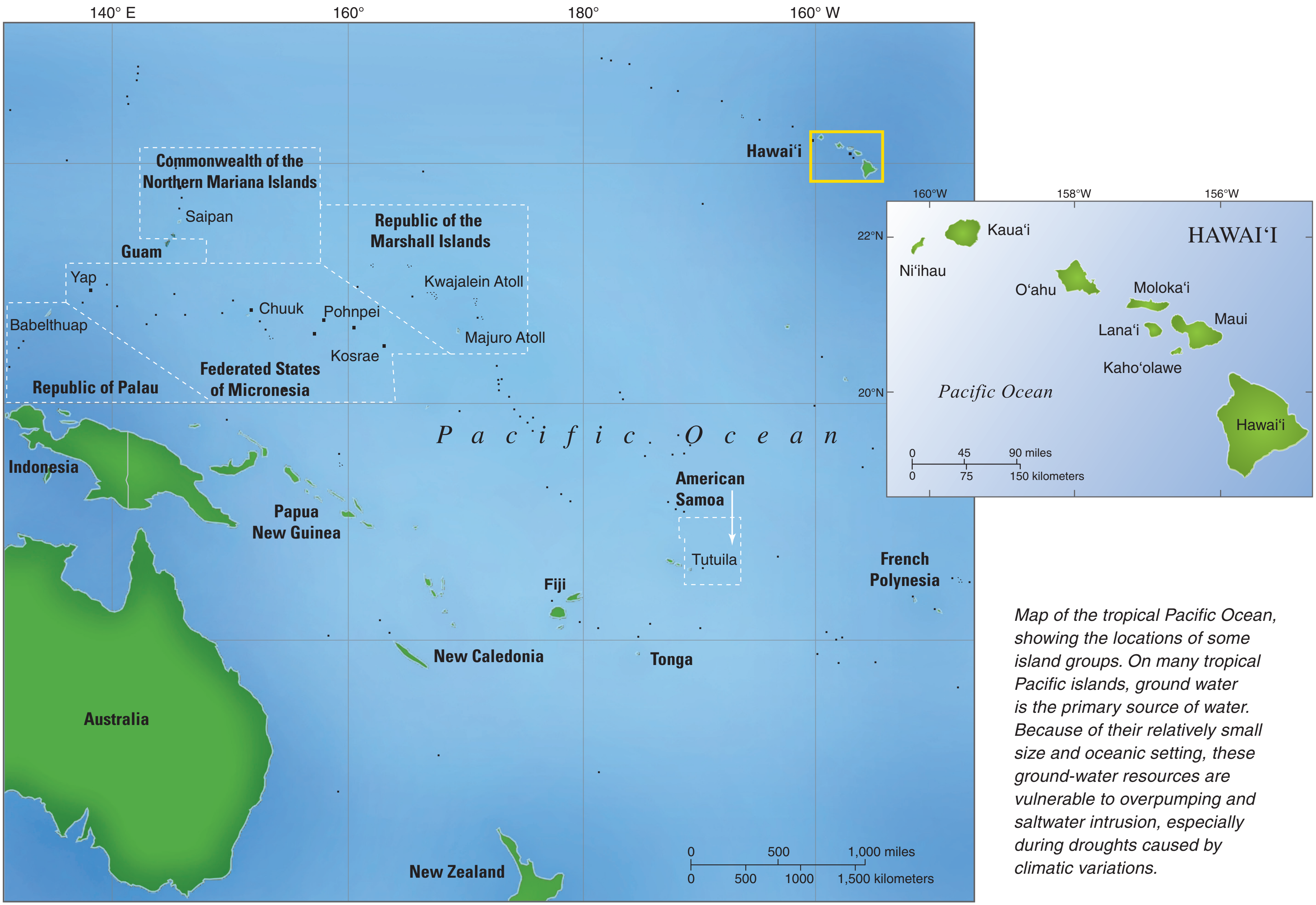
Much scientific information has been collected by the U.S. Geological Survey (USGS) and other organizations about the ground-water resources of tropical Pacific islands. The aim of this Circular is to give members of the public, policymakers, and other stakeholders knowledge that will help ensure that this information can be used to make informed decisions about the management of these life-giving resources.

As the demand for freshwater grows, new monitoring and research efforts will be needed to (1) characterize the extent and sustainability of ground-water resources on different tropical Pacific islands, (2) better understand linkages between ground-water discharge and freshwater and nearshore ecosystems, and (3) prepare for the effects of climate change, which will likely include the loss of habitable land and reduced areas for the accumulation of ground water as a result of rising sea levels.

The welfare of people living on tropical Pacific islands is of great interest to the United States. These islands not only include the State of Hawai‘i but also the U.S. territories of American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands, as well as the Freely Associated States of the Federated States of Micronesia, the Republic of the Marshall Islands, and the Republic of Palau. The Secretary of the U.S. Department of the Interior (DOI) has the administrative responsibility for coordinating Federal policy in the territories and for administering and overseeing Federal assistance provided to the Freely Associated States. The Office of Insular Affairs executes these responsibilities on behalf of the Secretary.

As the DOI’s science bureau, the USGS serves the Nation by providing reliable and impartial scientific information so that decisions can be made on an informed basis. We look forward to continued service to Pacific islanders by providing the science to help them manage their water resources to ensure a reliable supply of freshwater.

DIRK KEMPTHORNE
SECRETARY OF THE INTERIOR



Map of the tropical Pacific Ocean, showing the locations of some island groups. On many tropical Pacific islands, ground water is the primary source of water. Because of their relatively small size and oceanic setting, these ground-water resources are vulnerable to overpumping and saltwater intrusion, especially during droughts caused by climatic variations.

Ground Water on Tropical Pacific Islands—Understanding a Vital Resource

By Gordon Tribble

Introduction

Underground water or "ground water" is the primary source of water on many tropical Pacific islands. Contained in porous, regionally extensive geologic formations or "aquifers," fresh ground water on these islands floats on and is surrounded by more dense saltwater from the ocean. The potential for an aquifer to provide a reliable source of good-quality water depends on the amount of recharge that occurs from rainfall, the physical properties of the aquifer, and how the water is pumped or removed from the ground. Because of their relatively small size and oceanic setting, ground-water resources on tropical Pacific islands are vulnerable to overpumping and saltwater intrusion, especially during droughts caused by climatic variations such as El Niño events. Also, this vulnerability is made worse because the effects of ground-water pumping are initially difficult to perceive. This book describes some of the factors that influence the availability of ground water on tropical Pacific islands, such as recharge, aquifer properties, patterns of flow, salinity distribution, and the effects of pumping. Some examples of U.S. Geological Survey (USGS) studies in Hawai‘i and other Pacific islands are used to illustrate these concepts and their relevance to the management of ground-water resources.

Importance of Ground Water

Ground water is a vital source of water on many tropical Pacific islands. For example, on the Island of O‘ahu (Hawai‘i), ground water provides more than 90 percent of the drinking water and about half of the water used for agricultural irrigation. Ground water provides 80 percent of the drinking water on the Island of Guam and nearly all of the public water supply on the Islands of Saipan (Northern Mariana Islands) and Tutuila (American Samoa).

On many tropical Pacific islands, ground water is the preferred source of drinking water because its treatment to meet water-quality standards is generally easier and cheaper than that of surface water. Also, ground water is less affected by variations in rainfall than surface water and water collected by rain-catchment systems, making it more reliable during droughts. Overall, the use of surface water is limited because many islands lack the available land to construct reservoirs large enough to store enough water to meet their needs. Additionally, the diversion of surface water from streams can adversely affect the plants and animals living in them, the scenic beauty of the landscape, and the availability of surface water for other purposes, such as recreational use. Because of all of these factors, ground water has been and will continue to be desirable as a reliable, economical, and safe source of freshwater on many tropical Pacific islands.

Measuring the water "budget" is key to understanding the extent of ground-water resources. This picture shows a station in a remote part of West Maui that records information so that the total amount of precipitation, evaporation, and transpiration can be calculated. The specific instruments at the top of the pole measure (from left to right) rainfall, humidity, total solar energy, net solar energy, and wind speed. A solar panel on the pole provides electricity for the instruments and data recorders. The tripod on the right holds a collector that accumulates cloud moisture, also known as "fog drip." By collecting this information in different settings, hydrologists can determine the relation between precipitation, vegetation, and ground-water recharge. (USGS photograph by Toby Vana.)

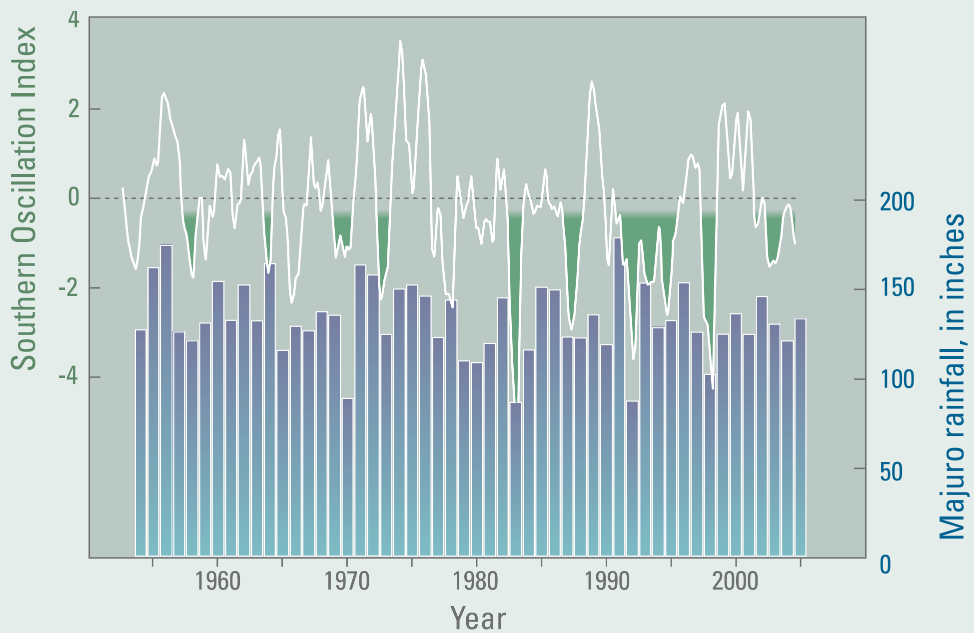
Precipitation and Ground-Water Recharge

Precipitation, mainly rainfall, is the source of the freshwater that recharges aquifers. On islands with high mountains, rainfall is commonly heavier on the windward side (the side exposed to the prevailing wind) and over mountainous areas, and rainfall is lighter on the leeward side (the side protected from the prevailing wind by the mountains). In the Hawaiian Islands, the amount of annual rainfall can range from several hundred inches on windward mountains to less than 10 inches on leeward areas only a few miles away. At high elevations, moisture in clouds can directly condense on the ground and vegetation; known as fog drip, this precipitation is not recorded by conventional rain gages. The amount of fog drip is substantial in some areas, and measuring it and its contribution to recharging aquifers remains a significant challenge.

Most tropical Pacific islands have distinct wet and dry seasons, and rainfall can also vary considerably over time. One of the major causes of this variation is the El Niño phenomenon, which results from large-scale, anomalous warming of sea-surface temperatures in the tropical eastern Pacific Ocean. The fully developed interaction between the atmosphere and ocean is called the El Niño-Southern Oscillation (ENSO). Large variations in rainfall between different years are commonly associated with the ENSO

As moisture-laden air moves over the high mountains found on some tropical Pacific islands it cools, forming rain clouds. The side of the mountains exposed to the prevailing wind (windward side) typically has more rainfall than the more protected side (leeward side), and this rain recharges nearby aquifers. This photograph shows a rainbow and clouds on Mount Wai'ale'ale on the Island of Kaua'i, Hawai'i. Wai'ale'ale typically receives more than 430 inches of rainfall annually, making it one of the wettest places on Earth. Real-time rain data from this area and others in Hawai'i can be found at http://hi.water.usgs.gov/. (Copyrighted photograph courtesy of Arjun Roychowdhury.)

El Niño Events Can Cause Water Shortages



During years when the El Niño atmospheric phenomenon is active, many tropical Pacific islands experience decreased rainfall and droughts. During droughts, people must rely more heavily on ground water because surface-water sources and water collected in rain-catchment systems are depleted more rapidly. This diagram shows annual rainfall (in inches) on Majuro Atoll, Republic of the Marshall Islands, during the past 50 years, compared to the El Niño-Southern Oscillation (ENSO) index. Negative ENSO values indicate that the phenomenon is active. Periods when El Niño has been active are shaded green, and in general the island has received less rainfall during these years. The photograph shows many Marshall islanders waiting at a water distribution site in 1998 after local water resources on their island were depleted during a severe drought caused by an El Niño. The water used in the relief effort was pumped from a larger and carefully managed aquifer on a nearby island. (FEMA photograph by Angel Santiago.)

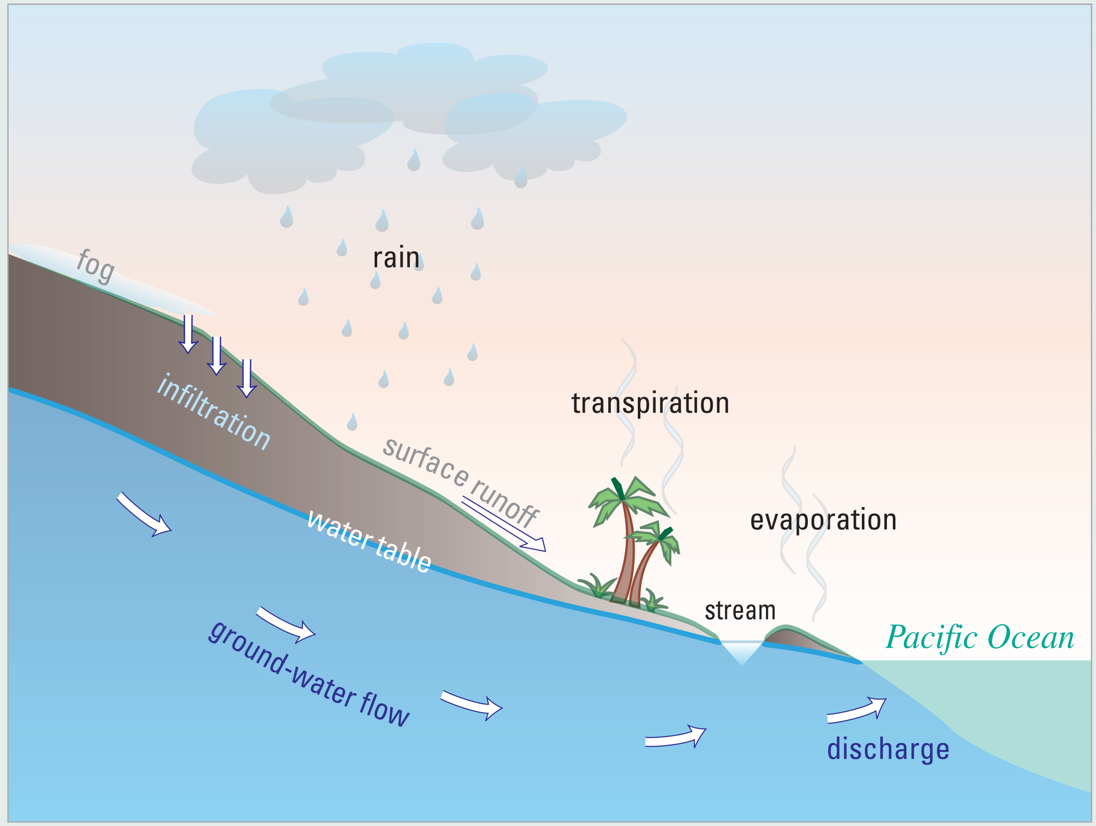
cycle. El Niño events generally correspond to decreased rainfall and droughts on many islands. During droughts, people must rely more heavily on ground water because surface-water sources and water collected in rain-catchment systems are depleted more rapidly.

On reaching the ground, precipitation can evaporate to the atmosphere, run off to the ocean, or drain into the soil. Water in soil is subject to further evaporation and transpiration (the evaporation of water from the leaves and stems of plants). Water not removed by these processes becomes ground-water recharge. Estimating the amount of recharge an aquifer receives is complex and commonly limited by lack of data. The amount of recharge is typically calculated by estimating the amount of total precipitation and then subtracting the estimated amounts of evapotranspiration (evaporation and transpiration) and direct runoff. Although such calculations are limited by knowledge of the actual amounts of total precipitation, direct runoff, and evapotranspiration, the use of a computer geographic information system (GIS) allows for more accurate estimates of these processes by including their geographic variation in the calculation of recharge. Estimates of recharge on tropical Pacific islands typically range from 10 to 50 percent of total precipitation. Accurate estimates of recharge are extremely important in determining the availability and sustainability of ground-water resources.

Freshwater-Lens Systems

As freshwater recharges an island aquifer, saltwater is displaced, and the freshwater forms a "lens" that floats on underlying, denser saltwater. Under natural conditions, water in the lens flows toward the ocean, such that the amount of recharge is balanced by discharge to nearshore springs or as widespread seepage into the ocean. Frictional resistance to water flow within the aquifer elevates the "water table" relative to sea level. In general, the water table is the surface where water pressure is equal to atmospheric pressure, but more simply, the water table is the top of the underground body of water. The elevation or level of the water table generally increases with distance from the coast. Near the coast, water levels may undergo daily changes driven by ocean tides. Water levels in a freshwater-lens system are also influenced by seasonal and annual variations in sea level.

The Hydrologic Cycle



This diagram shows the major components of the ground water or "hydrologic" cycle on most tropical Pacific islands. Arrows show the movement of the rainfall and other precipitation that recharges aquifers and the generalized direction of ground-water flow toward the ocean. Water vapor is also shown returning to the atmosphere, where it again becomes precipitation.

Ground water on tropical Pacific islands is pumped from a wide variety of wells. At top left, an inexpensive hand pump is being used to draw small volumes of water from a simple well in a shallow aquifer on an atoll island (Majuro Atoll, Marshall Islands) (USGS photograph by Stephen Anthony). However, to draw large volumes of water from wells in deeper aquifers, such as those found on the Island of Hawai‘i, complex high-voltage pumps may be needed (see USGS photograph at left by Gordon Tribble). Regardless of how water is pumped from an aquifer, certain principles apply that determine the quality and quantity of water that can be withdrawn on a sustainable basis.

Most wells on tropical Pacific islands pump water from aquifers that have a freshwater-lens system. To provide a reliable source of freshwater, these aquifers need to be carefully managed so that overpumping does not draw up the salty or “brackish” water that is beneath the freshwater lens. Within an aquifer, mixing of seaward-flowing water with underlying saltwater forms a brackish zone of transitional salinity. The thickness of this “transition zone” depends on the physical properties of the aquifer, the amount of ground-water flow, and the extent to which water mixes within the aquifer.

Porosity, Permeability, and Hydraulic Conductivity

The porosity and permeability of an aquifer affect the shape of the freshwater lens and how water flows through the aquifer. “Porosity” is the percentage of a geologic formation (sediment or rock) that consists of small pores or spaces that can contain water, and “permeability” is a measure of the ease with which water can flow through a geologic formation. Effective porosity reflects the volume of an aquifer that consists of interconnected spaces through which water can flow. All

The Ghyben-Herzberg Principle and the Transition Zone

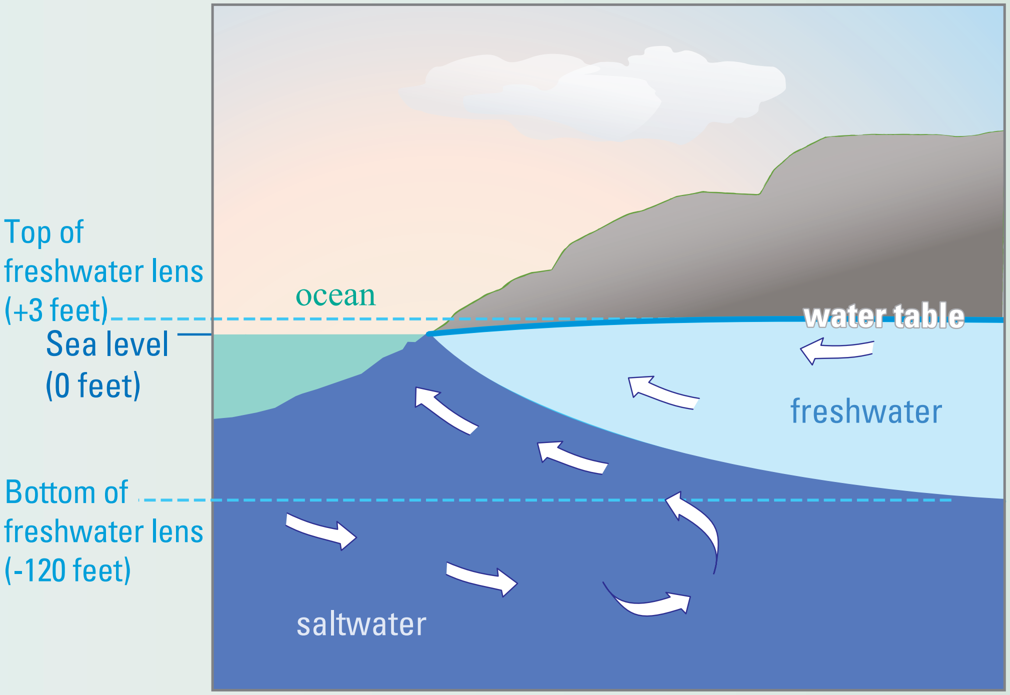
Willem Badon Ghijben (circa 1900). (Photograph provided by Royal Netherlands Academy of Arts and Sciences.)

The principle commonly used to estimate the thickness of freshwater in a freshwater-lens system is called the Ghyben-Herzberg principle. This principle was independently formalized by Captain Willem Badon Ghijben (Dutch Army) in 1889 and A. Herzberg (German) in 1901, but it was originally described in 1818 by Joseph Du Commun, an instructor at the United States Military Academy at West Point.

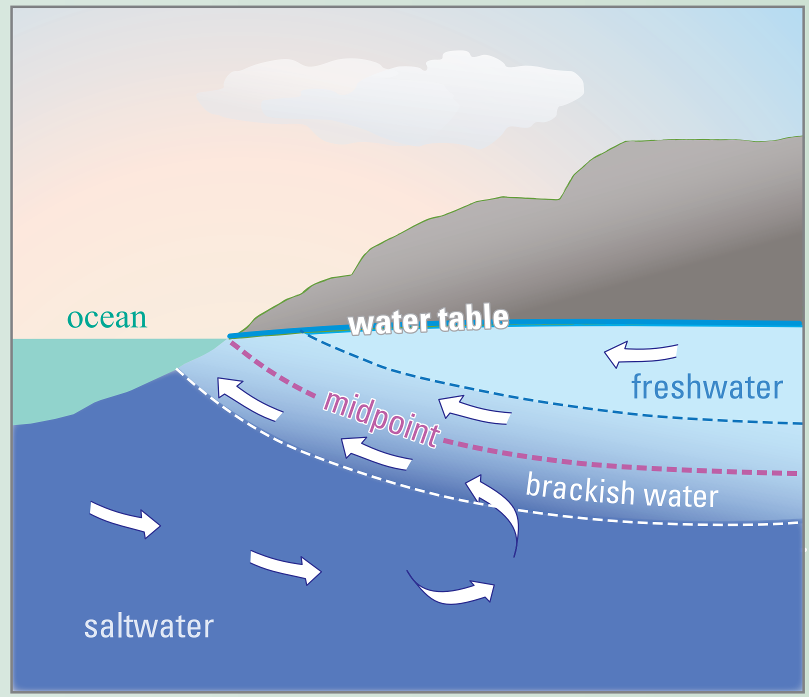
Because seawater is about 2.5 percent denser than freshwater, the fresh ground water in a freshwater-lens system "floats" on the underlying saltwater. However, the weight of the freshwater depresses the surface or top of the saltwater downward 40 feet for every foot the water table is above sea level. Therefore, the estimated thickness of a freshwater lens is about 40 times the elevation of the water table above sea level. For example, a freshwater lens that is elevated 3 feet above sea level will extend to a depth of 120 (3×40) feet below sea level (left image on page 7). In reality, a broad "transition zone" of brackish water commonly exists between freshwater and saltwater. In this situation, the Ghyben-Herzberg principle estimates the depth in the transition zone where the brackish water has a salinity about 50 percent of that of seawater (known as the "midpoint," right image on page 7).

Although a useful approximation, the Ghyben-Herzberg principle assumes no mixing between freshwater and saltwater and does not calculate the actual thickness of the drinkable or "potable" part of the lens, which is typically much less than the total thickness of the lens to the midpoint of the transition zone. The Ghyben-Herzberg principle also assumes that freshwater flow is predominantly horizontal. Thus, the principle does not apply in settings with complex geology or where vertical ground-water flow is significant.

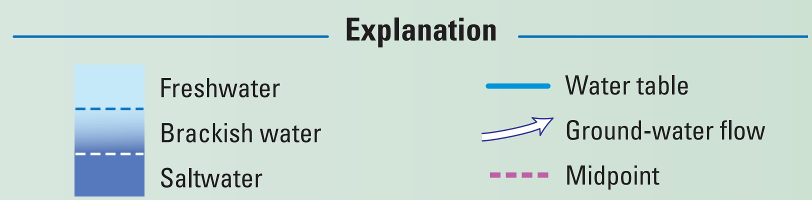
The thickness of the transition zone is determined by several factors, such as the physical properties of the aquifer, flow rates, and the distribution of wells pumping ground water from the aquifer. Predicting the thickness and dynamic movement of the transition zone in response to pumping and changes in recharge is a considerable challenge. In general, a high-permeability aquifer will have a thicker transition zone than a low-permeability aquifer. In addition, ocean tides and ground-water pumping can cause vertical mixing of water, also resulting in a thicker transition zone.



Idealized freshwater-lens system, showing a sharp boundary between freshwater and saltwater



Typical freshwater-lens system, showing a "transition zone" of brackish water



other factors being equal, a zone of high effective porosity results in higher rates of ground-water flow than does a zone of low effective porosity. The permeability of an aquifer is typically described in terms of its “hydraulic conductivity” (*K*), which accounts for both the permeability of a geologic formation and the fluid properties of the water flowing through it. Typical *K* values range from less than 0.1 ft/d (feet per day) for low-permeability volcanic-dike rocks to more than 10,000 ft/d for some types of highly permeable limestone. All other factors being equal, high-permeability aquifers have higher rates of ground-water flow and lower water-table levels, and low-permeability aquifers have lower rates of ground-water flow and higher water-table levels.

Hydraulic Conductivity on Tropical Pacific Islands

The permeability of an aquifer is typically described in terms of its hydraulic conductivity, which accounts for both the permeability of a geologic formation and the fluid properties of the water flowing through it. This table shows examples of hydraulic-conductivity values for some common aquifer materials found on tropical Pacific islands.

Aquifer material	Location	Hydraulic conductivity in feet per day (ft/d)
• Volcanic-dike complexes	Hawaiian Islands	0.01 – 0.1
• Basin-filling volcanic rock	Līhu‘e Basin, Island of Kaua‘i	0.3
• Volcanic-ash formations	Hawaiian Islands	1–500
• Atoll-island Holocene-age sedimentary deposits (sand- to boulder-sized coral-reef debris)	Marshall Islands	20–200
• Atoll-island Pleistocene-age marine limestone	Marshall Islands	2,000–3,000
• Layered volcanic rock (mostly basalt)	Island of Hawai‘i	1,000–10,000
• Uplifted marine limestone	Mariana Islands	100–19,000

High-Level Ground Water

In addition to freshwater-lens systems, ground water may occur at elevations high above sea level on some tropical Pacific islands. High-level ground-water bodies can form where low-permeability geologic features or structures block or slow the movement of ground water, either vertically downward or horizontally toward the shoreline. High-level ground-water bodies are not typically subject to contamination by saltwater and in some areas are important sources of freshwater. Some high-level ground-water systems and the geologic features that can lead to their formation are described below:

Perched systems—Ground water may occur at high elevations where low-permeability rocks block or slow the downward movement of water, so that a perched water body develops. The low-permeability material may be a thickbedded lava flow, a weathered-soil or volcanic-ash layer, or a sedimentary deposit. Perched ground-water bodies that occur in many areas of Hawai'i have been an important source of water supply to rural communities. Although most of these perched water bodies appear to be small and localized, some regionally extensive perched aquifers have been identified by examining well-drilling records and the locations of springs.

Dike-impounded systems—Volcanic "dikes" are tabular sheets of volcanic rock that form when magma (molten rock) is injected or "intruded" into cracks or faults in the Earth's crust. Dikes typically are concentrated along elongate systems of vertically oriented fractures, called "rift zones," created when movement related to volcanic activity has caused the ground to spread apart. Much like a dam, dikes can block or slow the flow of water so that an elevated water table develops inland of the dikes. The hydraulic conductivity in areas with many dikes can be low (less than 0.1 ft/d), and if the dikes are oriented nearly perpendicular to the direction of ground-water flow, water levels inland of dikes can be many hundreds to several thousands of feet above sea level. For example, dikes impound water to great heights, as much as 3,300 feet above sea level on the islands of Maui and Hawai'i and as much as 1,600 feet above sea level on O'ahu. Much of the water collected from the windward side of the Island of O'ahu is through tunnels that penetrate dikes and harvest the impounded water.

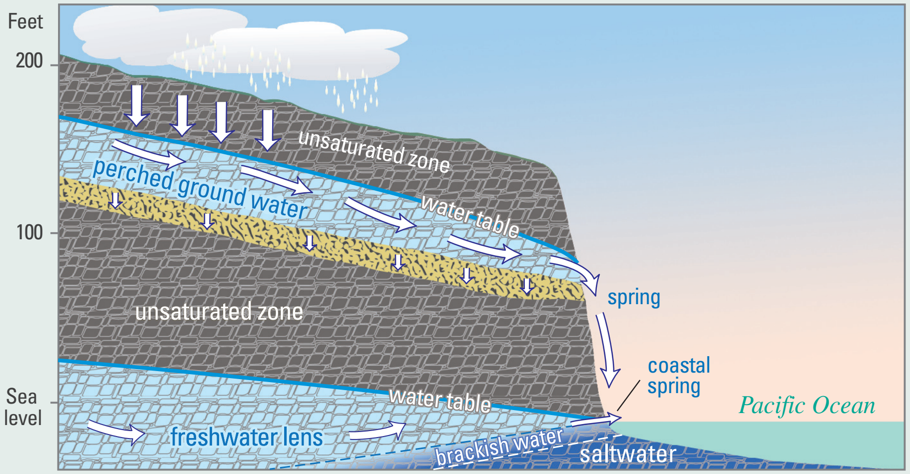
Vertically extensive freshwater-lens systems—Areas of low regional permeability may have a vertically extensive freshwater-lens system with a water table high above sea level. The low regional permeability may result from a high degree of weathering or be an inherent characteristic of the aquifer material, such as a sequence of thick lava flows that cooled slowly. The low permeability of such aquifers generally limits the water output of individual wells and reduces their usefulness as water-supply sources.

Frictional resistance associated with the low-permeability material blocks or slows the flow of water in the aquifer enough that a thick freshwater body develops. This is much like what happens when you steadily add water to a potted plant. If the soil in the pot is very fine grained (silt or clay; low permeability), the water level in the soil will remain higher as the water is draining through the soil than if the soil is coarse

Volcanic "dikes" are vertical sheets of volcanic rock that form when magma (molten rock) is "intruded" into cracks in the Earth's crust. These dikes can slow the flow of ground water and cause water-table levels to rise behind them. This trapped or "impounded" water can be an important source of freshwater on some tropical Pacific islands. This photograph shows people collecting water dripping from the roof of a tunnel used to reach and transport water impounded behind dikes on the windward side of the Island of O'ahu, Hawai'i. (Photograph courtesy of the Honolulu Board of Water Supply.)

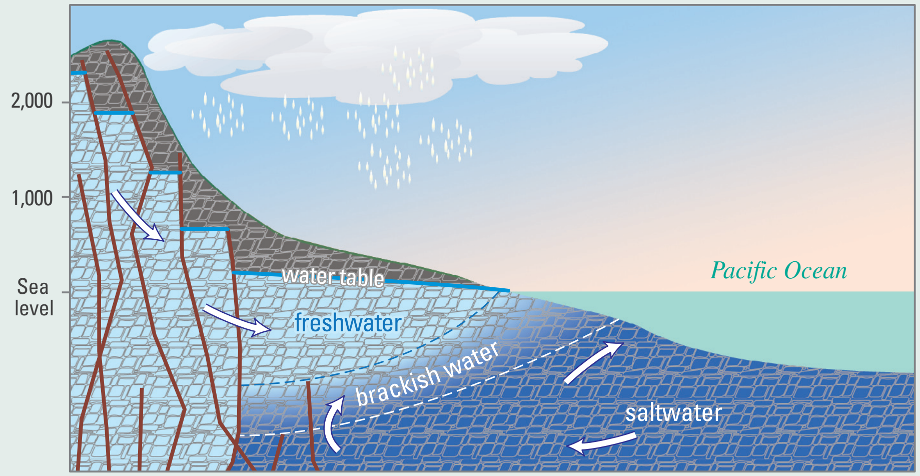
High-Level Ground-Water Systems

Perched system



A low-permeability, horizontal layer results in a perched aquifer.

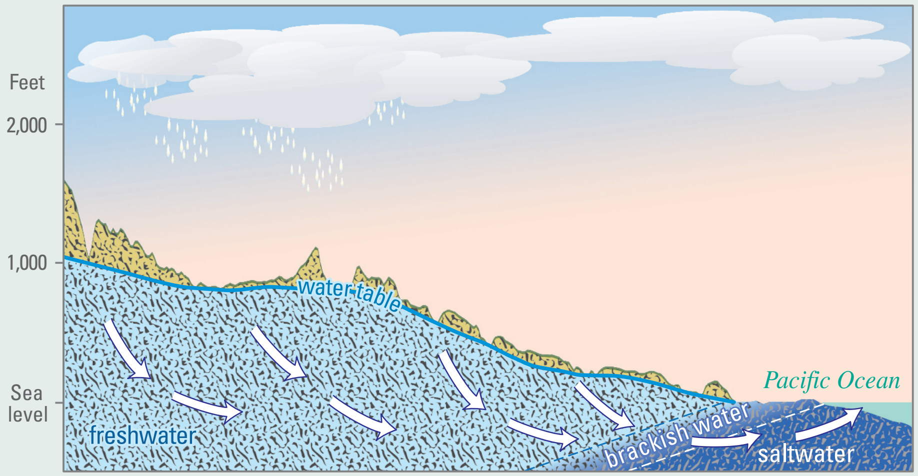
Dike-impounded system



Volcanic dikes compartmentalize ground-water bodies.

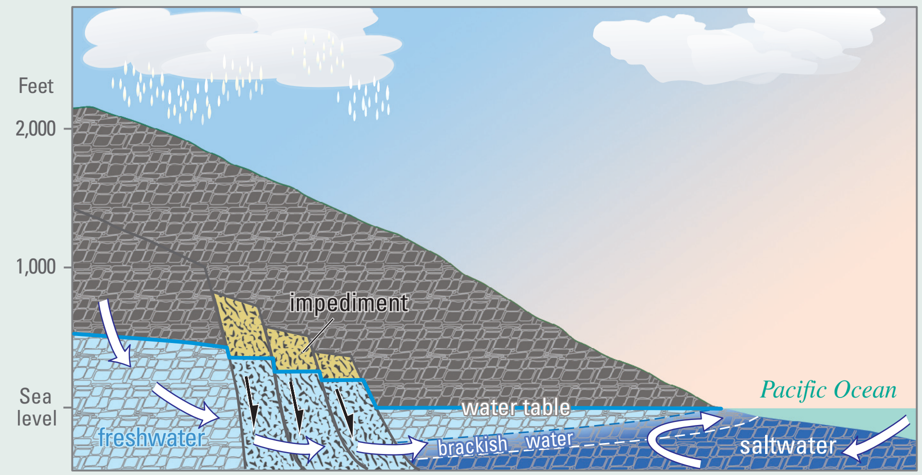
Ground water may occur at elevations high above sea level on some tropical Pacific islands. High-level ground-water bodies can form where low-permeability geologic features or structures block or slow the movement of ground water, either vertically downward or horizontally toward the shoreline.

Vertically extensive freshwater-lens system



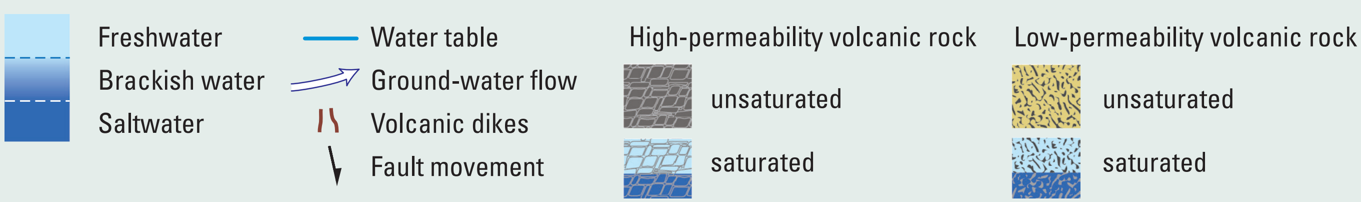
A regional low-permeability geologic formation results in a vertically extensive freshwater lens.

System created by low-permeability geologic structure



A low-permeability geologic sructure of unknown origin forms an impediment that slows the seaward flow of ground water.

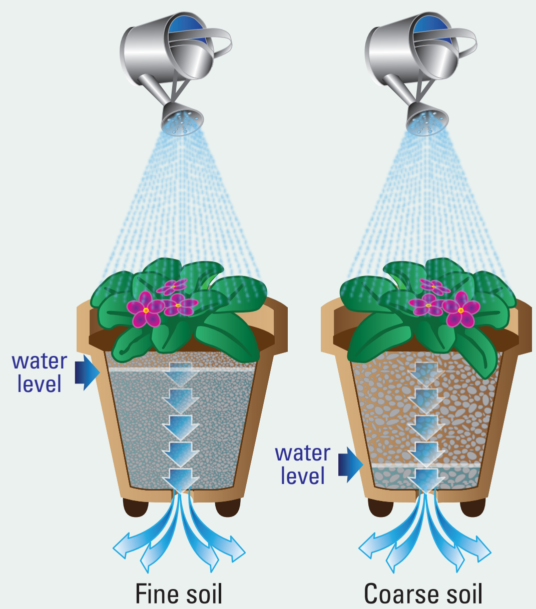
Explanation



grained (sand or gravel; high permeability). In both cases, the water will eventually drain out the holes at the bottom of the pot at the same rate as you are adding water at the top.

Well-water levels throughout a vertically extensive freshwater-lens system are much higher than those that would occur in an ordinary freshwater-lens system. In recharge areas, the elevation or level of the top of the water in a well that penetrates deeply into a vertically extensive freshwater-lens system is significantly lower than that in a well that penetrates only the upper part of such an aquifer. This decline in well-water level with depth occurs because of the predominately downward flow of water in such aquifers. As the water flows downward through a low-permeability geologic formation, it loses energy because of friction and therefore water levels in deeper wells are lower. In areas where the ground water is discharging, such as near the coast, the situation is reversed. In this case, the upward movement of water results in water levels in deeper wells being higher in elevation than water levels in shallower wells.

Other high-level ground-water systems— In some areas, a low-permeability geologic structure of unknown origin separates a high-permeability aquifer with water levels high above sea level from a freshwater-lens system, slowing the flow of water between them. One example is on the west side of the Island of Hawai‘i, which has an aquifer of relatively unweathered flows of layered basalt with hydraulic conductivities higher than 1,000 ft/d. A buried low-permeability impediment oriented nearly parallel to the coast appears to slow the movement of ground water toward the ocean, so that the elevation of the water table is less than 10 feet on the ocean side and several hundred feet on the inland side of the impediment. Other examples of areas with high ground-water levels resulting from a structure of uncertain origin are the central plateau of O‘ahu and the Waimea area on the northern part of the Island of Hawai‘i.



Frictional resistance associated with low-permeability geologic material can block or slow the flow of water in an aquifer enough that a thick freshwater body develops. This is much like what happens when you steadily add water to a potted plant. If the soil in the pot is very fine grained (silt or clay; low permeability), the water level in the soil will remain higher as the water is draining through the soil than if the soil is coarse grained (sand or gravel; high permeability). In both cases, the water will eventually drain out the holes at the bottom of the pot at the same rate as you are adding water at the top.

Interactions Between Ground Water and Surface Water

Water beneath the ground surface occurs in two principal zones—the “unsaturated zone” and the “saturated zone.” In the unsaturated zone, the pore spaces in rocks contain both air and water, whereas in the saturated zone pore spaces are only filled with water. The upper surface of the saturated zone is the water table. Where the water table of an aquifer intersects the land surface, ground water discharges to a spring or stream even during periods of no rain. Streamflow sustained by such discharge is known as “base flow.”

In areas where the water table is lower than a stream channel, water infiltrates downward from the stream to the aquifer, and streamflow is reduced as the aquifer is recharged. Perennial streamflow (flowing continuously throughout the year) at high elevations indicates the presence of a high-level ground-water body with a water table above the stream channel. Overall, the base-flow characteristics of streams are controlled by the distribution of ground water, which, in turn, is controlled by the local geologic setting and climatic conditions.

Dike-impounded and perched ground-water bodies are typical sources of perennial discharge that sustain streamflow at higher elevations. Erosion has exposed volcanic dikes in many of the deeply incised valleys on the windward sides of the Hawaiian Islands, and discharge of the dike-impounded water is the source of base flow to many streams.

Perched ground-water bodies may discharge to isolated springs, or to more regionally extensive features that provide base flow to several streams. For example, an area on the north flank of Haleakalā Volcano (Ha‘ikū, Island of Maui) appears to be an extensive perched aquifer. Ground water in this area occurs in both an upper perched aquifer and a lower freshwater-lens system; the two aquifers are separated by an unsaturated zone several hundred feet thick. The water table in the perched aquifer typically is within a few hundred feet of the land surface, intersecting the surface in deep valleys. About 10 percent of the total ground-water recharge from precipitation in the area subsequently discharges from the upper aquifer and provides base flow to streams. The remaining 90 percent of the recharge infiltrates past the low-permeability layer (beneath the perched ground-water body) and recharges the lower freshwater-lens system.

An extreme example of ground-water discharge to streams is the Līhu‘e Basin on the southeast side of the Island of Kaua‘i. The regional hydraulic conductivity for the entire Līhu‘e Basin has been estimated to be a few tenths of a foot per day, although localized exceptions exist. The low permeability of the area, in combination with high recharge, results in an aquifer that is saturated many hundred feet above sea level, with a water table at or near the land surface. This water table intersects stream channels into which water discharges from the aquifer. As a result, the base flow of streams in the basin increases in the downstream direction. Discharge to streams accounts for 60 to 70 percent of the total ground-water recharge in the basin, with the rest either discharged directly into the ocean or withdrawn by wells.

Freshwater-lens systems generally contribute to streamflow only at low elevations near the coast because the water table is close to sea level. Thus, if no high-level water bodies discharge ground water, streams will be ephemeral (flowing only as a result of nearby and recent precipitation), except where they intersect the freshwater-lens system at low elevations. Streams that intersect a freshwater-lens system typically start perennial flow near the shoreline, and much of the ground-water discharge is within the estuarine parts of these streams, where freshwater comes into seawater and tidal effects occur.

Ground-Water Quality

On most tropical Pacific islands, the availability of ground water from freshwater-lens systems that is suitable for drinking is limited primarily by salinity. The salt in the ground water comes from the seawater that surrounds and underlies the islands, and natural processes and pumping mix this saltwater with freshwater. Seawater contains many dissolved salts, and the concentration of dissolved chloride (Cl^-) is typically used to indicate the presence of salt from seawater, which has a dissolved chloride concentration of about 19,500 milligrams per liter (mg/L). The U.S. Environmental Protection Agency’s recommended or "secondary" standard for dissolved chloride in drinking water is 250 mg/L, or about 1.3 percent of the chloride concentration of seawater. What this standard means is that freshwater mixed with only a small amount of seawater will be of poor quality for drinking.

Island aquifers are susceptible to contamination from various human activities. Land uses such as agriculture or urban and suburban development can alter both the quantity and quality of water recharging an aquifer. Leaks and inappropriate disposal of industrial solvents and petroleum products, such as motor oils, have contaminated ground water in many areas. Similarly, pesticides and nutrients introduced by agricultural practices have also contaminated ground water in some areas.

Improper handling of human sewage can result in potentially serious contamination of ground water by harmful bacteria and other microscopic organisms, particularly where the ground water is close to the surface or where the soil and aquifer permit fast vertical movement. Sewage contamination of ground water may come from leaking, poorly constructed, or failing cesspools, pit latrines, or septic systems, as well as from leaking sewer pipes or failing and overflowing sewage-pump stations. For example, several years ago failing sewage-pump stations in some areas of Guam resulted in large spills of untreated wastewater on the ground surface. Owing to the high permeability and hydraulic conductivity of the soil and underlying limestone there, public water-supply wells (some as deep as 300 feet and some as far away as several miles) tested positive for microbial indicators of sewage after these spills. Microbial indicators were commonly detected within very short time periods, sometimes hours to days, after a wastewater spill.

Geochemical and biologic reactions in aquifers alter the chemical composition of ground water from the time it infiltrates to the time it discharges. Weathering of volcanic and carbonate (limestone or coral) aquifer materials, primarily driven by carbon dioxide (CO_2) in rainwater and biologic respiration in soil, adds dissolved salts to ground water. Organic matter in ground water is biodegradable by the bacteria naturally present in an aquifer, a process that produces CO_2 and may result in additional chemical weathering. Ground water on the islands of many atolls (islands that sit atop ring-shaped coral reefs with central lagoons) has high levels of bacterial activity, and USGS studies on some atolls suggest that contamination from petroleum products is at least partly removed by microbial activity in ground water.

Effects of Ground-Water Pumping

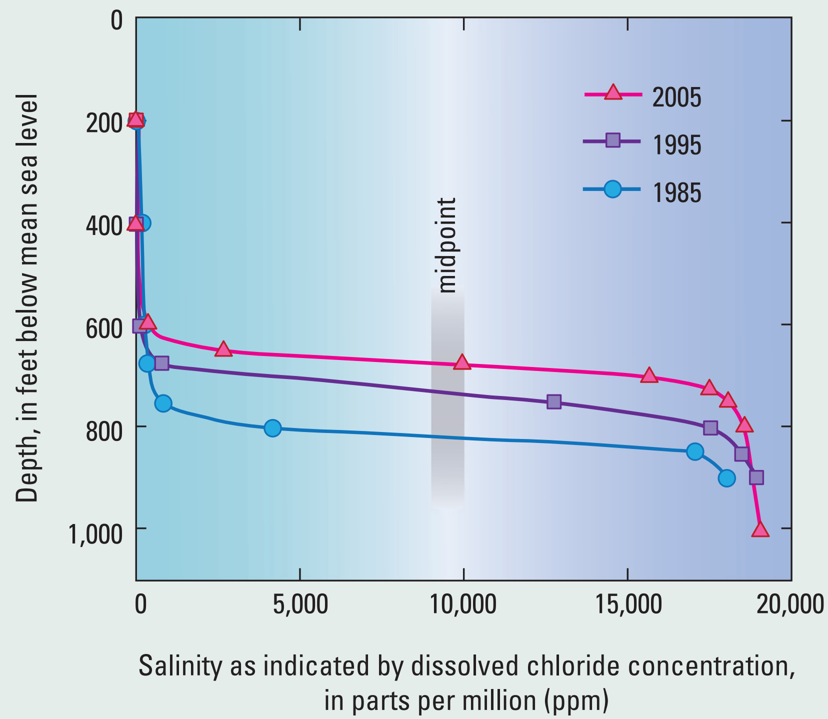
Pumping ground water from a well both lowers the level of the water table and removes water from storage in the aquifer, causing a decrease in the amount of ground-water discharge equal to the amount of pumping. In settings where ground water discharges to streams, the lowering of water-table levels by pumping can result in reduced streamflows. In a freshwater-lens system, pumping also shrinks the freshwater lens, resulting in upward movement of the transition zone. These effects are greatest near the source of water withdrawal. Over time, the water table and transition zone reach a new balance or "equilibrium."

The effects of pumping may be localized or widespread, depending on the natural patterns of ground-water flow, pumping rate (pumpage), and geologic structures that affect flow. For example, pumping from a freshwater-lens system does not affect an overlying perched aquifer, whereas pumping from a perched aquifer can affect the underlying freshwater-lens system by decreasing the amount of water that recharges the lens. Also, buried dikes and other low-permeability features that block or slow ground-water flow may reduce the effects of pumping in nearby areas and increase the time before such effects are observed.

If too much ground water is pumped, a freshwater lens may shrink enough that brackish water from the transition zone is drawn into the well. This process, known as saltwater intrusion, can result in the need to shut down wells and may reduce the availability of drinking water. Saltwater intrusion can either affect individual wells or degrade an entire aquifer. One remedy is to reduce pumpage. Because of the delay between the start of pumping and the rise in the transition zone, it may take several years before it becomes apparent that a well is being overpumped or that a well is recovering from the effects of overpumping. The time lag for a particular well to reach a new equilibrium is determined by, among other things, the location and depth of the well, pumpage from that well and others in the same aquifer, the physical properties of the aquifer, and the volume of ground water flowing through the aquifer.

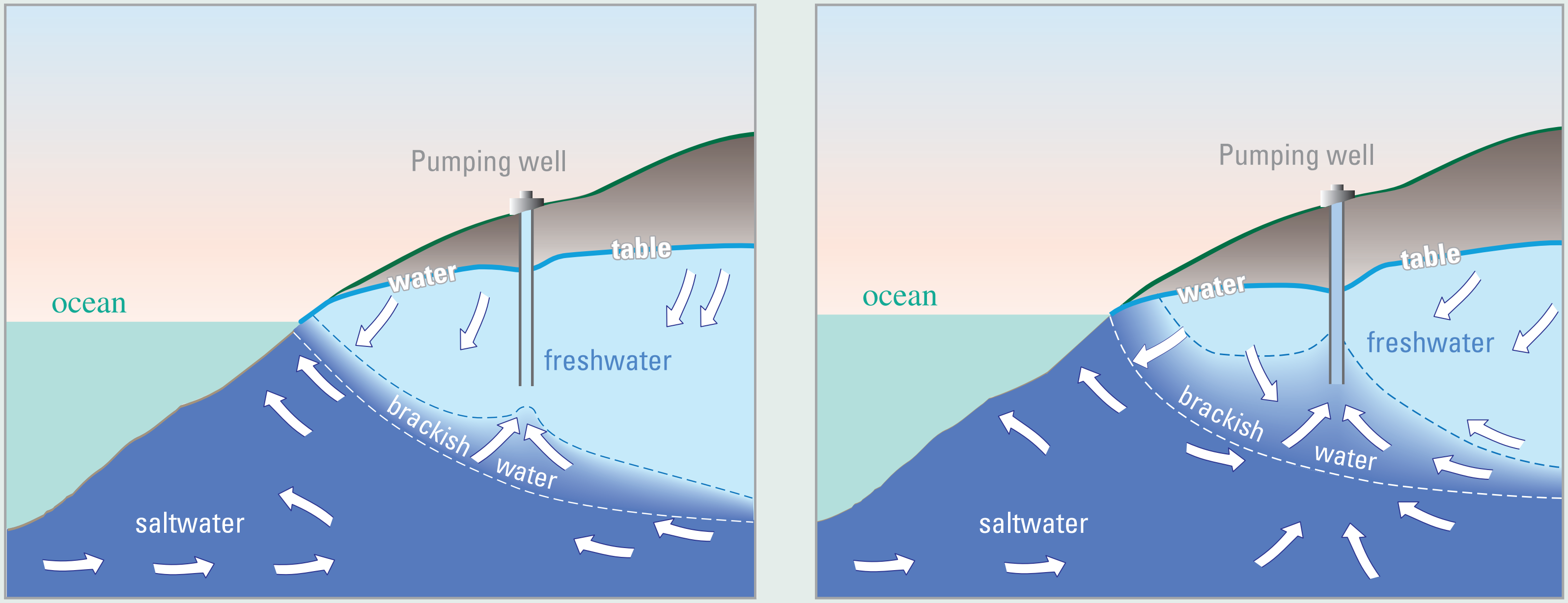
On many tropical Pacific islands, horizontal wells that skim water from near the water table are used to spread the effects of pumping over a larger area. Such wells can provide an effective water supply even in settings with only a thin freshwater-lens system.

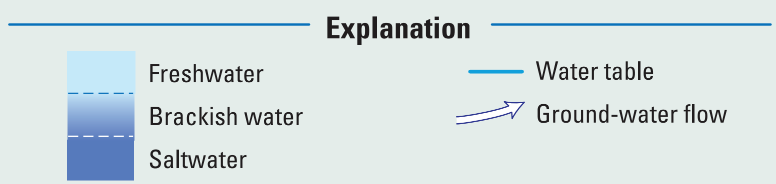
Ground-Water Pumping Can Cause the Transition Zone to Rise



Profiles of freshwater lenses and transition zones are used to evaluate the response of an aquifer to pumpage. They can also be used to estimate the sustainable yield of nearby ground-water wells and are helpful in calibrating numerical models of ground-water flow. Upward movement in the transition zone between freshwater and saltwater, as measured at the "midpoint" (see The Ghyben-Herzberg Principle on pages 6-7) is caused by pumping large volumes of freshwater from nearby wells. This diagram shows the change in the depth of the transition zone over 20 years in the Waiehu Deep Monitoring Well on the Island of Maui, Hawai'i.

The Effects of Overpumping Ground Water





The effects of overpumping may take some time to become evident. Once ground water is pumped from an aquifer, the water table falls, and the zone of brackish water—the "transition zone" (see The Ghyben-Herzberg Principle on pages 6 and 7)—beneath the well rises (left). The rise in the transition zone is slower than the lowering of the water table. If too much water is pumped, the transition zone rises high enough that the salinity of water pumped from the well becomes too high for human consumption (right).

The Need for Ground-Water Data

Accurate field data are required to determine the effects of ground-water pumping. Water-level and salinity data are needed to estimate the availability of fresh ground water and so are important for effective ground-water management. Water-level measurements provide information about aquifer conditions, changes in the amount of recharge, and the response of ground water to pumping. In general, measurements in wells dedicated to monitoring ground water provide more accurate data than measurements taken in wells that are used for pumping ground water. The water level in an actively pumped well is lower than the water table immediately adjacent to the well because of frictional resistance as water enters the well. The difference in water level in a pumped well and the adjacent aquifer, known as "well loss," is a measure of a well's efficiency in transmitting water; a small difference indicates a more efficient well.

In freshwater-lens systems, salinity data collected at different depths in an aquifer are of great value in monitoring the position of the transition zone. Salinity profiles created using data from wells that penetrate the transition zone have been used to provide information about the thickness of freshwater-lens systems and the mixing characteristics of aquifers in the Hawaiian Islands, on the Island of Guam, and on the Island of Saipan. Changes in the thickness of a freshwater lens over time provide important information about the effects of pumping; however, care is needed in using data from such wells, because measurements have shown that the vertical flow of water within some boreholes can result in a profile that is not wholly representative of conditions in the adjacent aquifer.

This U.S. Geological Survey hydrologist is using a steel tape to measure the water level in a monitoring well on the windward side of the Hawaiian Island of O'ahu. Understanding ground-water resources requires accurate information that often must be collected with careful field measurements. Water level is frequently measured with a plastic tape that has an electric sensor that shows when water is reached in the well, but steel tapes are preferred in some settings because they have greater accuracy and durability. (USGS photograph by Delwyn Oki.)

Long-term information about water-level, rainfall, salinity, irrigation, and pumpage is needed to evaluate the historical effects of pumping and climate on ground-water levels. Similarly, data collected from wells over an extensive area provide a regional description of an aquifer. Also, data from aquifer-pumping tests can be used to calculate the physical properties of an aquifer that control the flow of ground water.

Ecological Importance of Ground Water

The ecological importance of ground water on tropical Pacific islands is often underestimated. When it discharges to streams such that they flow perennially, ground water allows biological communities to develop that are specialized for life in the typically small and fast-flowing island streams. The animals found in these streams have, in nearly all cases, evolved from marine ancestors, and biologically different species have similar ecological niches or roles on different Pacific island groups. Most native aquatic species found in these streams must return to the ocean in the early stages of their lives. These instream communities are valuable for both their biological diversity and cultural importance. For example, shrimp and fish from perennial freshwater streams were important foods for Native Hawaiians, and streamwater was used to irrigate taro, the principal staple in the Polynesian diet. Ground water from springs was also used for religious and ceremonial practices, such as cleansing and blessing.

The discharge of ground water at the coastline can also be ecologically important. In settings such as sheltered bays or extensive coral reef flats, freshwater discharge can lead to estuarine conditions that provide important habitat for some marine animals, even without input from perennial streams. Ground water may contain nutrients that increase the biologic productivity of coastal areas, and the lower salinity may be important to creating suitable habitat for some species. There is scientific debate as to the importance of coastal ground-water discharge in sustaining biological productivity, but it is clear that many native peoples on tropical Pacific islands recognized the importance of such discharge. In particular, Native Hawaiians built extensive fishponds in some areas with enhanced ground-water discharge. Because the walls enclosing the ponds were assembled with many large rocks moved by hand, the construction of a fishpond represented a considerable investment in

The native Hawaiian fish ʻoʻopu nākea (Awaous guamensis) in ʻĪao Stream, on the Island of Maui. Adults like this individual live in freshwater streams with perennial flow sustained by ground-water discharge. Revealing their evolutionary origins, all native freshwater fishes found in Hawaiian streams must spend the early stages of their lives in the ocean and thus need a stream that at least periodically flows continuously along its length to the ocean to complete their life cycle. (USGS photograph by Reuben Wolff.)

Aerial view of Keawa Nui Fishpond, on the Island of Molokaʻi, Hawaiʻi. This centuries-old fishpond encloses an area of 72 acres, and although vegetation covers the wall at left, this pond is still used to cultivate fish. Before European contact, such fishponds were important sources of protein for Native Hawaiians, and they carefully managed them to provide a sustainable supply of food. The productivity of fishponds is believed to be enhanced by ground-water discharge, and Native Hawaiians often constructed them in areas with coastal springs and estuaries sustained by such discharge. (Photograph from U.S. Environmental Protection Agency.)

manpower. These fishponds often formed extensive complexes that were carefully managed as vital sources of food.

The demand for freshwater has led to some adverse ecological impacts on tropical Pacific islands. Perennial streams are often diverted because they provide a cheap and reliable source of freshwater. Many times, the need for water is so great that the diversion is designed to capture most of the ground-water discharge, leaving the stream channel downstream of the diversion dry (except during storms) and unfavorable for aquatic life. Perhaps more significantly, the dry section of stream prevents young native stream animals from parts of the stream above the diversion from reaching the ocean and thus greatly reduces the ability of stream animals to maintain their life cycles. Ground-water pumping can also reduce streamflow. Although it is unusual for ground-water pumping to cause a section of a stream to go dry, it has been observed in some settings. Less understood is the impact of reducing the amount of ground water discharging at coastlines. More research is needed to evaluate the impacts of ground-water discharge on the ecology of nearshore biological communities, and the consequences of reduced discharge resulting from pumping or other causes.

Upstream view of the diversion of ʻĪao Stream in the central part of the Island of Maui, Hawaiʻi. On many tropical Pacific islands perennial streams are often diverted because they provide a cheap and reliable source of freshwater. Perennial flow in the ʻĪao Stream is sustained by the discharge of high-level ground water impounded by dikes at the back of the valley. Essentially all of the average ground-water discharge of 20 million gallons per day that supplies the stream is captured by the diversion for use in agricultural irrigation and other societal needs, leaving the stream below the diversion dry most of the time. Native fish thrive in the stream's upper reaches, but the diversion restricts the ability of larvae to reach the ocean and complete their life cycle to times of high flow from heavy rainfall. (Hawaiʻi State Office of Hawaiian Affairs photograph.)

Ground-Water Management

To ensure a continued supply of fresh ground water, this vital resource must be carefully managed. “Ground water sustainability” is the development and use of ground-water resources in a way that can be continued indefinitely without causing unacceptable environmental, economic, or social consequences. Simply put, an aquifer that is pumped too much will not provide a reliable long-term source of water. Managing ground water on the basis of this definition of sustainability calls for resource managers to recognize the relation between water quality and water availability, the connection between ground water and surface water, and the economic and social importance of a reliable source of drinking water.

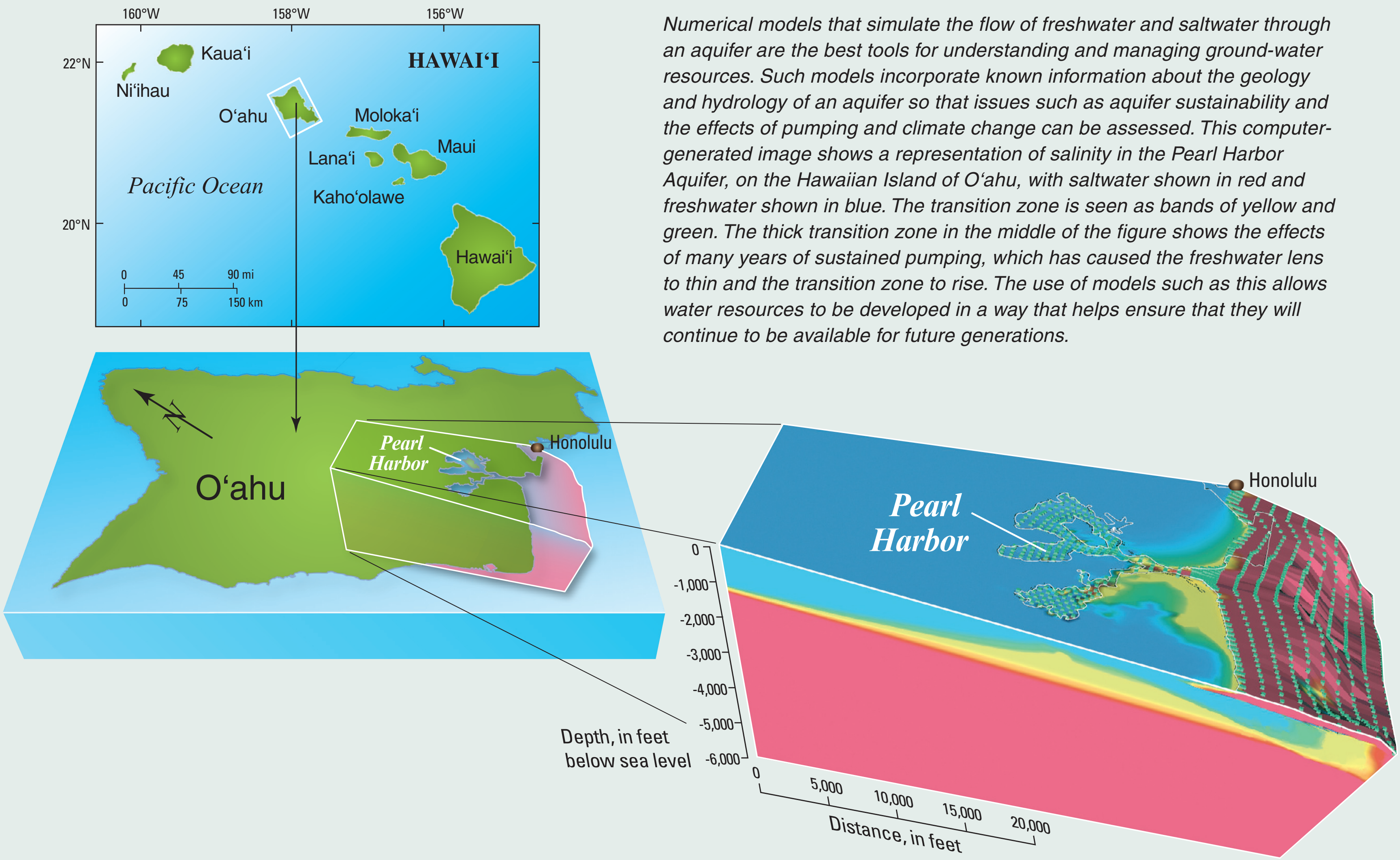
Management of ground-water resources on tropical Pacific islands largely focuses on maintaining a supply of water with acceptable salinity, because most water is pumped from freshwater-lens systems. In other words, the volume of water available from a freshwater-lens system is mainly limited by salinity. To reduce the potential for pumping brackish water, wells in a freshwater-lens system are ideally located where the freshwater lens is thickest.

In addition to location, how a water well is constructed is also vital to ensuring that it provides freshwater. The intake or bottom of a well must not be so deep in the aquifer that brackish water from the transition zone is pumped. Similarly, both the depth of the well and the desired pumpage must be considered when installing a pump. As noted earlier, overpumping a well can result in saltwater intrusion or excessive lowering of the water table.

Ground-water resources are managed by several methods. The simplest method is to measure the salinity of the pumped water and reduce the pumpage if the salinity reaches unacceptable levels. A somewhat more proactive method is to monitor the elevation of the water table or the transition-zone salinity some distance from the pumped well, generally between the pumped well and the coast. Neither of these methods predicts or provides information about the overall sustainability of the freshwater supply in an aquifer. In the Hawaiian Islands and on the Island of Guam, an algebraic model has been used to estimate regional aquifer sustainability and to manage the use of ground-water resources. The model is based on straightforward calculations and could be readily applied to aquifers on other tropical Pacific islands, but its accuracy is limited by theoretical shortcomings and its inability to account for the complexity of most aquifers.

The most rigorous and powerful approach to ground-water management is the use of a calibrated numerical model to simulate freshwater flow through an aquifer. A numerical model is the best available method to represent ground-water-flow patterns, assess the effects of pumping, and evaluate the sustainability of alternative scenarios for ground-water development. USGS scientists use numerical models to synthesize water-budget data, aquifer properties, and ground-water data into a mathematical representation of water flow through an aquifer. Although constructing and using a numerical model that provides useful information for ground-water management can be time consuming and costly, this expense may be offset by the value of understanding (1) variations in both the timing and the three-dimensional distribution of ground-water flow, (2) the effects of proposed ground-water pumping on natural discharge and water-supply wells, and (3) the overall sustainability of ground-water resources.

Numerical Models of Ground-Water Flow



Numerical models that simulate the flow of freshwater and saltwater through an aquifer are the best tools for understanding and managing ground-water resources. Such models incorporate known information about the geology and hydrology of an aquifer so that issues such as aquifer sustainability and the effects of pumping and climate change can be assessed. This computer-generated image shows a representation of salinity in the Pearl Harbor Aquifer, on the Hawaiian Island of O'ahu, with saltwater shown in red and freshwater shown in blue. The transition zone is seen as bands of yellow and green. The thick transition zone in the middle of the figure shows the effects of many years of sustained pumping, which has caused the freshwater lens to thin and the transition zone to rise. The use of models such as this allows water resources to be developed in a way that helps ensure that they will continue to be available for future generations.

Examples of Ground-Water Use on Tropical Pacific Islands

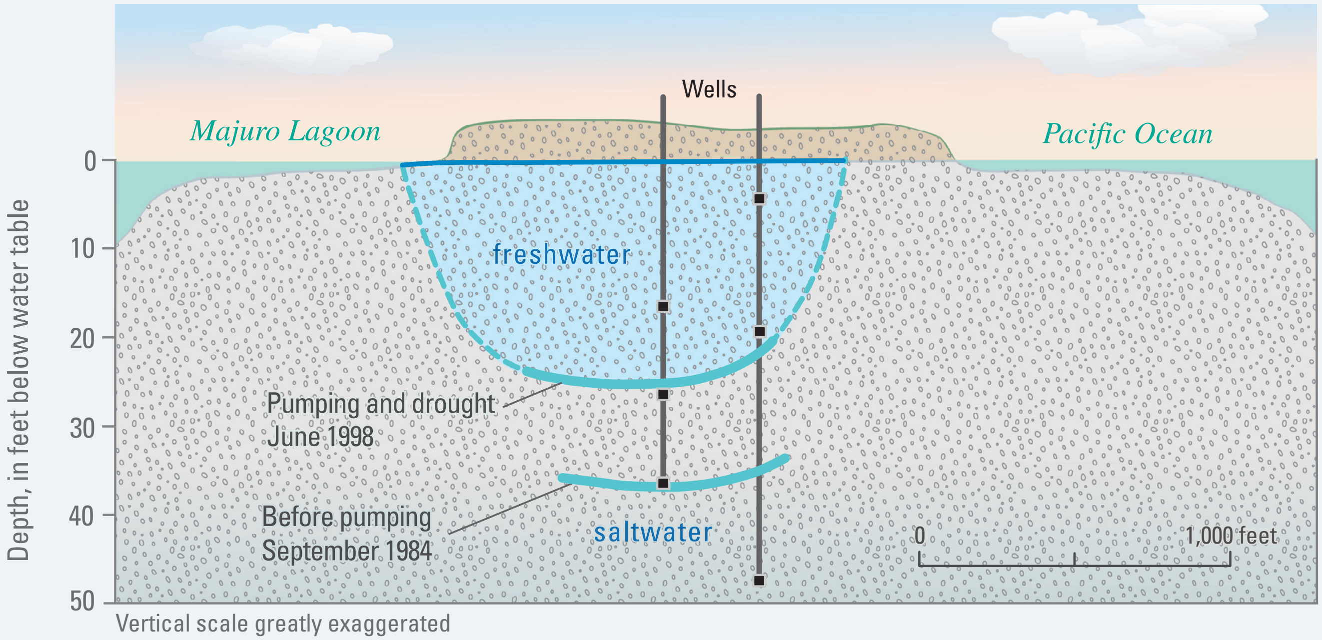
Although many tropical Pacific islands are similar in their climate, geology, and culture and how these influence their ground-water or "hydrologic" systems, each island is unique. The following examples illustrate only a few of the many issues in ground-water use on tropical Pacific islands. These examples come from the research of the U.S. Geological Survey scientists who work to understand ground-water resources on these islands and help ensure their availability.

Laura Area of Majuro Atoll, Republic of the Marshall Islands—A Freshwater-Lens System Provides Relief During Drought

On many small tropical Pacific islands, rain is the preferred source of freshwater, and ground water is used only incidentally, because it commonly contains salt and bacteria. However, ground water may provide an important and underutilized resource that can partially reduce the hardships caused by drought. Ground water in the Laura area on Majuro Atoll, Republic of the Marshall Islands, is one example.

Majuro Atoll receives an average of about 130 inches of rainfall annually. Although rainfall collected in catchment systems has historically been the primary source of drinking water for many households, ground water is becoming increasingly important. The freshwater lens in the Laura area has a maximum thickness of about 50 feet. Water levels are only a few feet above sea level and are affected by tidal changes in the ocean. Because the island is nearly flat, there is little surface runoff from precipitation, and ground-water recharge has been estimated at about half of the total rainfall. The aquifer consists of unconsolidated permeable sand- and cobble-size coral-reef debris, underlain by highly permeable marine limestone.

During droughts, rainfall decreases by about a third or less of average amounts, and during the 1998-99 drought most domestic rain-catchment systems were depleted. In response, ground-water pumpage from the Laura area was increased from 191,000 to 286,000 gallons of freshwater per day. The reduced recharge and increased pumpage resulted in thinning of the freshwater lens. Ground water pumped from the Laura aquifer provided about 60 percent of the municipal water supply during the drought, in contrast to about 25 percent before the drought. During the drought, monitoring wells were used to assess the status of the freshwater lens and manage pumpage to avoid saltwater intrusion into water-supply wells. Continued monitoring of these wells during dry as well as wet periods will provide better information on the sustainability of ground-water resources in the area and help in the planning of mitigation efforts for future droughts. (See Hamlin and Anthony, 1987, and Presley, 2005, for more information.)



This diagram is a generalized cross section of the Laura aquifer on Majuro Atoll, showing the estimated extent of freshwater both before ground-water pumping in the area began in September 1984 and during a period of both pumping and drought in June 1998. "Freshwater" in this case is defined as water containing less than 500 milligrams (mg) of dissolved chloride (Cl^-) per liter (L). As a comparison, the U.S. Environmental Protection Agency's recommended standard for dissolved chloride in drinking water is 250 mg/L, or about 1.3 percent of the chloride concentration of seawater.

Explanation

- Approximate extent of potable freshwater (chloride concentration less than 500 mg/L) in June 1998.
- Water table
- Carbonate sand and coral reef debris
  - Unsaturated
  - Saturated
- Approximate line of 500 mg/L chloride concentration for date shown; dashed where inferred.
- Well — Monitoring-well site. Squares represent the depth of each sampling point.

This aerial photograph shows part of Majuro Atoll. The Laura area is the wide, middle part of the island. The substantial width of this area promotes the formation of a ground-water lens that is an important source of freshwater, especially during droughts. (USGS photograph by Jeff Perreault.)

‘Īao Aquifer, Maui, Hawai‘i—A Freshwater-Lens System Stressed by Rising Demand

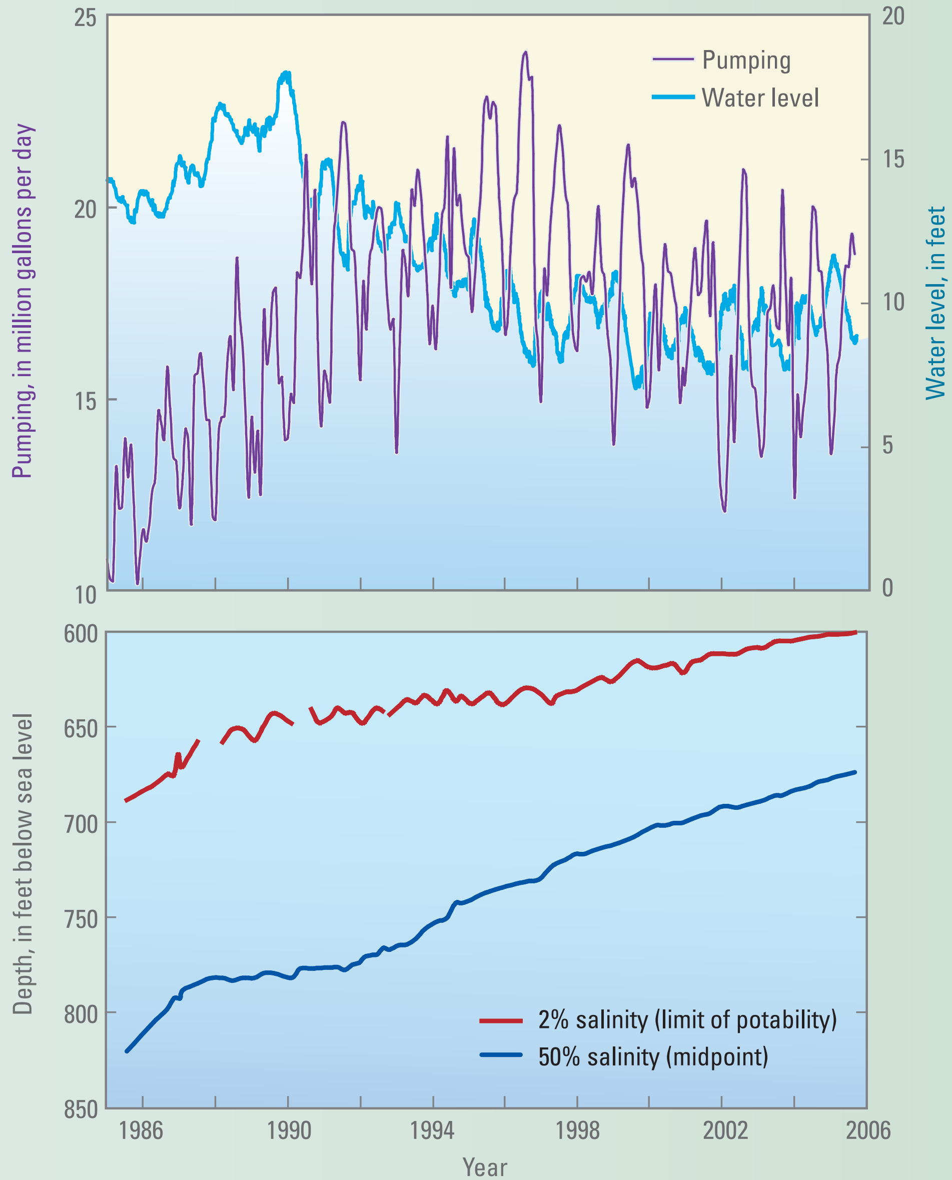
The ‘Īao aquifer on the Hawaiian island of Maui is formed by highly permeable layered volcanic rocks. Low-permeability coastal deposits, which are a mix of eroded volcanic material, coral-reef debris, and marine sediments, block or slow the discharge of freshwater into the ocean, resulting in the formation of a thick freshwater lens. Average annual rainfall in the area ranges from less than 30 to more than 350 inches, and recharge has been estimated to be about 42 percent of rainfall and fog drip.

The growing community of Wailuku overlies part of the ‘Īao aquifer on the Island of Maui, Hawai‘i. Water from this area is the largest source of municipal water supply on the island. (USGS photograph by Gordon Tribble.)

Ground-water pumpage from the ‘Īao aquifer increased from less than 2 million gallons per day (Mgal/d) in 1950 to more than 20 Mgal/d in 1995. As of 2000, the aquifer provided more than half of the municipal water supply on Maui. In response to this sustained pumping, water-table levels declined to as much as half of their estimated predevelopment levels in parts of the aquifer. This decline in water-table levels has been mirrored by a shrinking of the freshwater lens and increasing salinity in several freshwater-supply wells. The average pumpage during 2002 was about 17 Mgal/d. During this time, water-table levels appeared to be stabilizing in response to decreased pumping, although the transition zone was still moving upward.

Several estimates have been made of the sustainable yield of the ‘Īao aquifer. As of 2005, the most current estimate is that the aquifer has a sustainable yield of 20 Mgal/d. This estimate was made using an algebraic method that calculates the sustainable yield as a fraction of total recharge. Based on the limitations of this method and the historical response of the aquifer to pumping, this estimate is probably too high for the current distribution of wells. Construction of a numerical model of ground-water flow can provide a more precise analysis of aquifer sustainability and can be used to revise sustainability estimates as aquifer conditions change and additional data become available. A numerical model can also be used to test alternative distributions of pumped wells, as well as the effect of changing land-use practices on the extent of ground-water recharge. (See Meyer and Presley, 2001, Oki and Meyer, 2001, and Engott and Vana, 2007, for more information.)

Graphs of ground-water levels in the ʻĪao aquifer from 1985 to 2005. The graph at top shows the rate of ground-water pumping from the aquifer (purple line) along with corresponding changes in the water level observed in a monitoring well (Test Hole B) (blue line). Overall, as the rate of pumping increased, water levels in the well have decreased. The graph at bottom shows the rise of the zone of brackish ground water, called the "transition zone" (see The Ghyben-Herzberg Principle on pages 6 and 7), in response to the pumping, as measured in the Waiehu Deep Monitoring Well. In this case, the transition zone is represented by the area between the depth of water with a salinity of about 2 percent (limit of potability) and 50 percent (the "midpoint") of seawater.



Saipan, Mariana Islands—Challenges of Pumping From a Thin Freshwater Lens

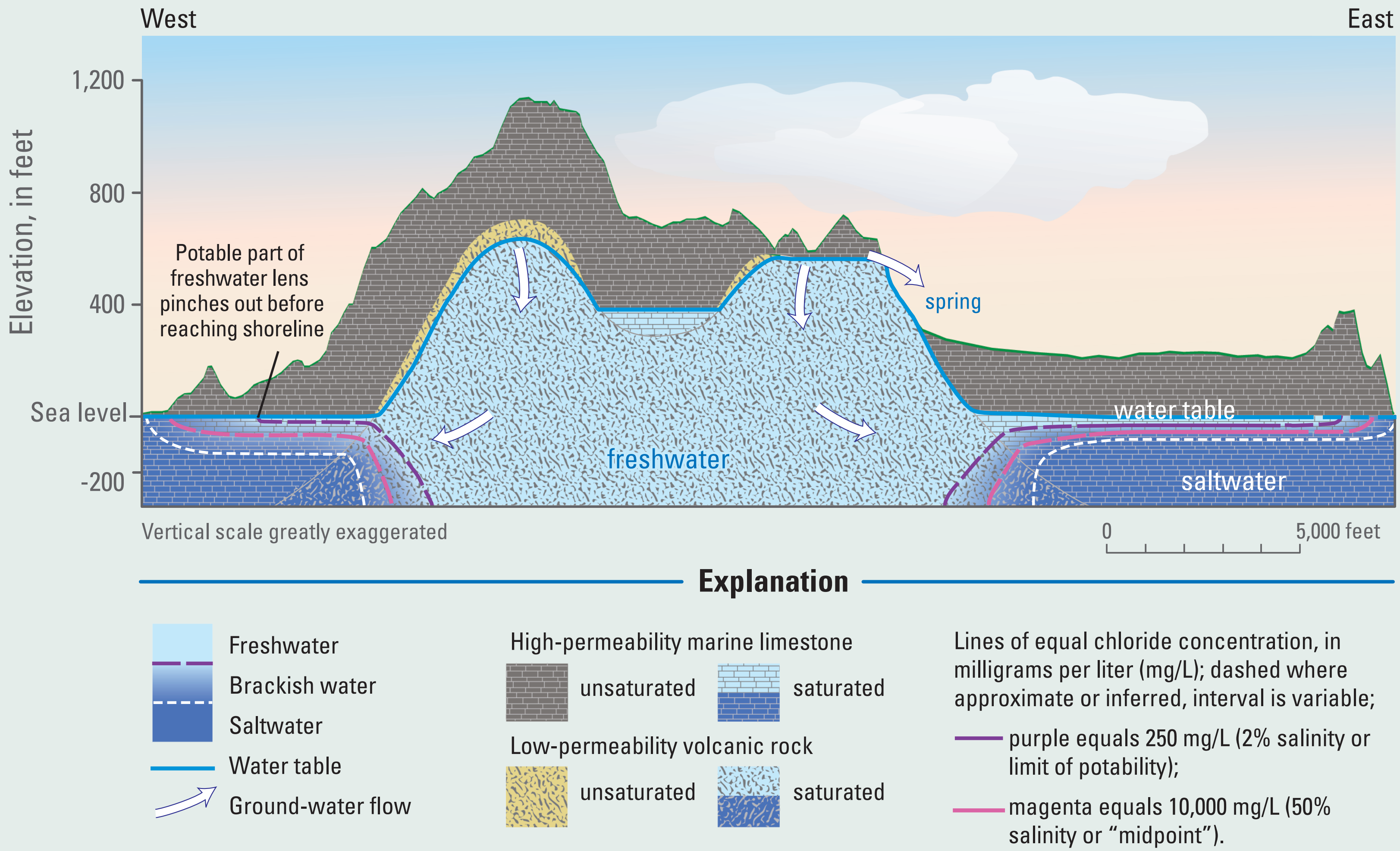
The Island of Saipan is formed of highly permeable limestone that overlies low-permeability weathered volcanic rocks. The high permeability of the limestone allows the freshwater lens to react quickly to changes and also allows freshwater to readily discharge to the ocean. As a result, water levels in the freshwater lens throughout much of the island are 5 feet or less above sea level. Because the high permeability of the limestone facilitates mixing between freshwater and saltwater, ground water in many areas of the island is brackish, even in the absence of pumping. This situation has limited the areas where water-supply wells can be located on Saipan.

Wells in the highly permeable limestone are capable of yielding large volumes of water. Although some wells on Saipan produce water with a dissolved chloride (Cl^-) concentration less than the 250 milligrams per liter (mg/L) recommended by the U.S. Environmental Protection Agency as an upper limit for chloride in drinking water (an indicator of the presence of seawater), other wells that have been drilled too deep or pumped at high rates are subject to saltwater intrusion and commonly produce brackish water. Total pumpage increased from 2.4 million gallons per day (Mgal/d) in 1978 to more than 11 Mgal/d in 2000, and the average chloride concentration of pumped ground water rose from 690 to 1,100 mg/L during that same period.

Although most of Saipan has only a thin freshwater lens and most wells produce brackish water, alternative well-field designs can improve the situation. For example, the Isley well field was expanded beginning in the late 1970s. Wells there were typically drilled to a depth of 15 to 45 feet below the water table and pumped at rates of 50 to 120 gallons per minute (gal/min). The chloride concentration of water from this well field averages about 850 mg/L. In contrast, the nearby Obyan well field was developed in the late 1990s with wells that penetrated only 6 to 10 feet below the water table and pumped at rates of 35 to 50 gal/min. By using lower pumping rates and shallower wells, an average chloride concentration of about 300 mg/L was being maintained by 2003.

Some interior parts of Saipan have water tables in limestone that are several hundred feet above sea level because the limestone overlies low-permeability volcanic rocks that extend above sea level. Wells in this setting are less likely to be affected by saltwater intrusion and may yield significant volumes of freshwater. However, water levels may decline substantially in response to pumping. Wells drilled directly into the volcanic rocks yield only small volumes of water, owing to the low permeability of the material. (See van der Brug, 1985, and Carruth, 2003, for more information.)

This photograph is an aerial view looking eastward of the Island of Saipan, identifying important geologic and geographic features. (Copyrighted photograph courtesy of Del Benson.)



This diagram is a generalized cross section showing geology and ground-water occurrence on the Island of Saipan. It shows both freshwater-lens systems and high-level ground water elevated by underlying low-permeability volcanic rocks.

Tutuila, American Samoa—Contrasts in Aquifer Permeability Affect Well Performance

The Island of Tutuila, American Samoa, has two large areas of contrasting aquifer permeability. Most of the island, particularly the rugged mountains in the north, is composed of relatively old, low-permeability volcanic rocks, whereas the southwest, an area known as the Tafuna-Leone Plain, is composed of younger, high-permeability volcanic rocks. Geologic differences between the two areas result in different responses to ground-water pumping, illustrating the importance of understanding how ground water interacts with local geology when developing ground-water resources.

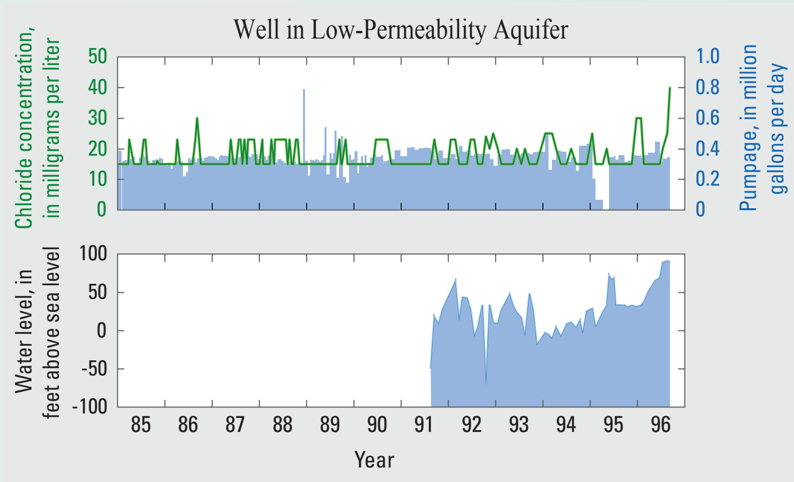
Ground-water levels in the low-permeability area may attain elevations of tens to hundreds of feet above sea level; much of this ground water discharges from elevated springs to sustain the perennial flow of streams on the island. With few exceptions, most wells in this area yield only modest volumes of water, yet water levels may decline many tens of feet as a result of pumping. In some wells, pumping has caused water levels to decline below sea level, resulting in minor saltwater intrusion and an increase in dissolved chloride (Cl^-) concentration—an indicator of the presence of seawater—from which the wells are slow to recover despite reduced pumpage.

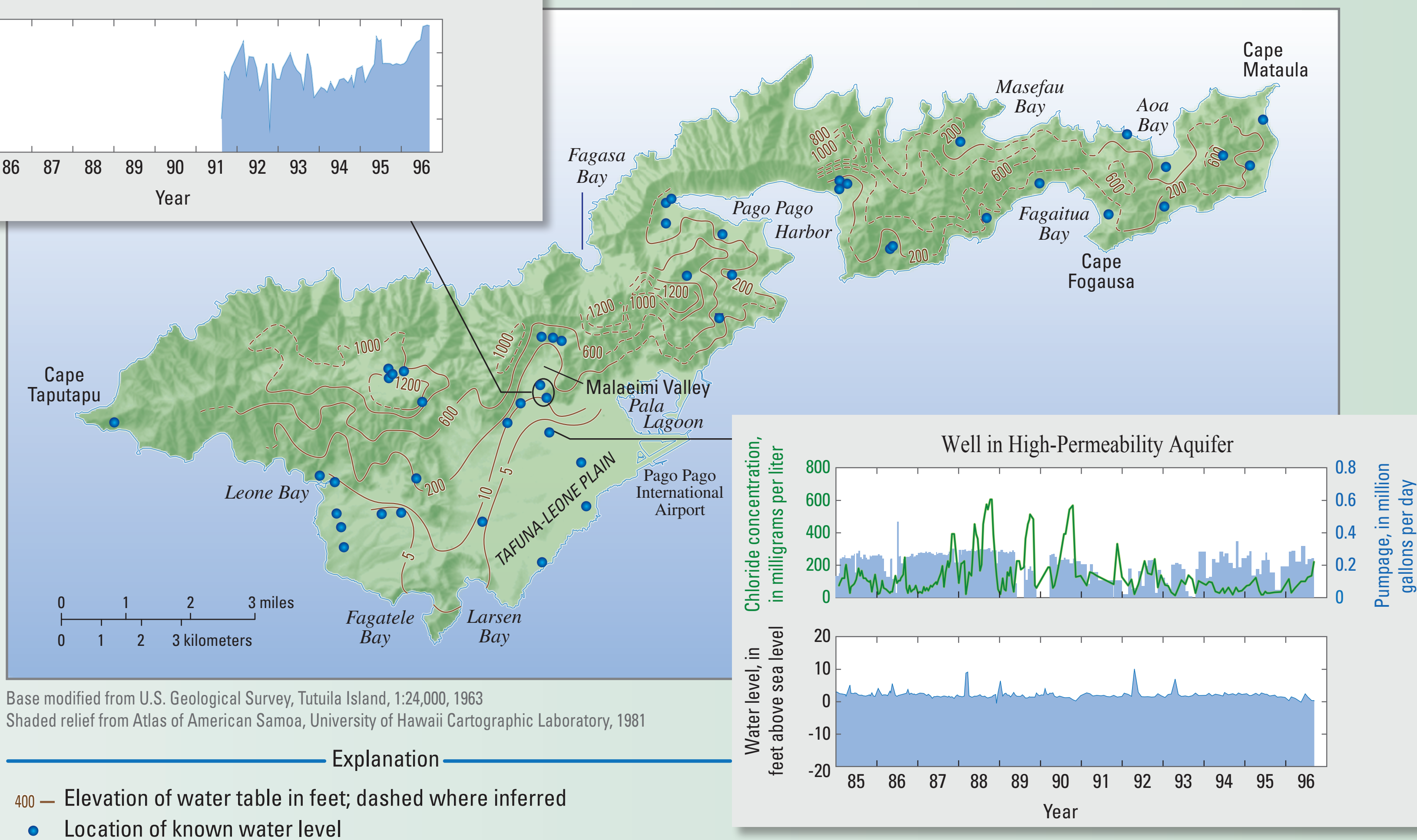
In contrast, ground-water levels in the high-permeability area are typically less than 10 feet above sea level, and the area has no streams with perennial flow. Because of the high permeability and ease of access, wells in this area produce about 70 percent of the ground water pumped on the island. Occasional increases in chloride concentration in wells occur during extended periods of low rainfall, but chloride concentrations return to low levels soon after normal rainfall resumes or pumping is reduced. The rapid response of chloride concentration to rainfall is consistent with the high permeability of the aquifer and the short distance between the ground surface and the water table that is characteristic of this part of Tutuila. (See Izuka, 1999, for more information.)

This photograph shows the Tafuna-Leone Plain on the Island of Tutuila, American Samoa. This plain is constructed of relatively young, high-permeability volcanic rocks. (Photograph courtesy of Troy Curry.)

This photograph shows the city and harbor of Pago Pago and the older, rugged low-permeability volcanic interior of the Island of Tutuila, American Samoa. (USGS photograph by Scot Izuka.)

Generalized water-table map of the Island of Tutuila, with graphs showing the relation between (1) ground-water pumping; (2) dissolved chloride (Cl^-) concentration (in milligrams per liter; mg/L), which is used to indicate the presence of salt from seawater; and (3) water levels in wells in low- and high-permeability areas on the island. The U.S. Environmental Protection Agency's recommended standard for dissolved chloride in drinking water is 250 mg/L, or about 1.3 percent of the chloride concentration of seawater.





Acknowledgments

The author is deeply indebted to the many scientists who have contributed to our current understanding of ground water on tropical Pacific islands. Special thanks are due to the following individuals who reviewed earlier drafts of this report: Jim Anthony, Robert Carruth, Devin Galloway, Stephen Gingerich, Roy Hardy, Scot Izuka, William Meyer, Jill Nishimura, Delwyn Oki, Jeff Perreault, Rachel Ross, Jonathan Scheuer, and Jane Schoonmaker. Editorial, graphic, and layout assistance was graciously provided by George Havach, Keith Kirk, Luis Menoyo, Twyla Thomas, Jeanne DiLeo, Susan Mayfield, Peter Stauffer, and especially Jim Hendley. Finally, the author thanks Michael Dworsky, who asked the question "Your USGS reports are really complete and full of science, but do you guys ever write anything that someone without a Ph.D. can understand?" His concern provided the motivation for this Circular, which I hope now gives an affirmative answer to his question.

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Glossary

Aquifer—A water-bearing geologic formation or layer that will yield water in usable quantities to wells or springs.

Atoll—A coral reef appearing from a plan (or top) view as roughly circular (sometimes elliptical or horseshoe-shaped) and largely or completely enclosing a shallow (typically less than 300 feet deep) lagoon. Low coral islands typically lie atop some parts of the reef and are generally no more than 1 to 2 miles long, less than ½ mile wide, and extend less than 15 feet above sea level; land of a non-reef origin is absent or rare. Atolls develop from reefs fringing volcanic islands. As first hypothesized by Charles Darwin, and confirmed by ocean drilling done by British scientists a century ago, reefs fringing volcanic islands build vertically to sea level, forming steep-walled barrier reefs. As a volcanic island subsides, or sinks, with time, the growing reef keeps pace with the rising water level. When the island eventually submerges, the ring-shaped reef forms an atoll with a central lagoon.

Basalt—A general term for dark-colored extrusive igneous rocks of relatively low silica (SiO_2) content; basalt is the most common rock erupted by oceanic volcanoes.

Chloride (Cl^-)—An "anion" of chlorine typically found dissolved in seawater at a concentration of about 19,500 milligrams per liter (mg/L). Common table salt, sodium chloride (NaCl), is the most well-known chloride compound. Chloride concentration is commonly used to measure the amount of saltwater from the ocean that is mixed with freshwater in an aquifer. The U.S. Environmental Protection Agency recommends that drinking water not exceed a chloride concentration of 250 mg/L.

Coral reef—A chemically cemented, wave-resistant mound or ridge created by colonies of "hard corals," their accumulated skeletal fragments, and the remains of calcareous algae, mollusks, and other shallow-water tropical marine organisms that form calcareous skeletons.

Dike-impounded system—A ground-water system in which the flow of water is blocked or slowed by a volcanic dike. Dike-impounded systems typically have a water table elevated hundreds or more feet above sea level.

El Niño-Southern Oscillation (ENSO)—A global event arising from large-scale interaction between the ocean and the atmosphere. When the waters of the eastern Pacific are abnormally warm (an El Niño event), there is a weakening of the low-latitude easterly trade winds. This is accompanied by a drop in sea-surface atmospheric pressure in the eastern Pacific and a rise in sea-surface atmospheric pressure in the western Pacific. El Niño events typically result in below-average rainfall and drought conditions on many tropical Pacific Islands. El Niño is a term originally used by fishermen along the coast of Ecuador and Peru to refer to a warm, nutrient-poor, ocean current that typically first appears in affected years around Christmastime (El Niño means Christ child in Spanish) and lasts several months. The Southern Oscillation, a more recent discovery, refers to an oscillation in the sea-surface atmospheric pressure between the southeastern tropical Pacific and the Australian-Indonesian region, as measured between Tahiti and Darwin, Australia.

Ephemeral—A stream, river, or other surface-water body that flows only in direct response to rainfall.

Estuary—The seaward end of a stream or river where freshwater comes in contact and mixes with seawater and where tidal effects are evident.

Freshwater-lens system—A lens-shaped body of fresh ground water that overlies saltwater. A zone of brackish water with transitional salinity typically separates the freshwater lens and saltwater.

Ground water—Water located beneath the ground surface in pore spaces, fractures, and other voids in geologic formations. Water enters the ground as rain that percolates through the soil and root zone. On islands, ground water flows towards the ocean, but along the way it may be intercepted by streams or withdrawn by wells for human uses.

Ground-water sustainability—The development and use of ground-water resources in a manner that can be continued indefinitely without causing unacceptable environmental, economic, or social consequences.

High-level ground water—The occurrence of ground water at high elevations. In such situations the water table is many tens to several thousand of feet above sea level.

Holocene Epoch—The most recent geologic time period, which started about 11,000 years ago. Sea level rose rapidly during the early part of the Holocene in response to the melting of glacial ice from the most recent ice age.

Hydraulic conductivity—The capacity of a rock to transmit water, typically expressed as the rate of flow (in gallons per day) through a cross section of one square foot under a standard driving force or "unit hydraulic gradient."

Hydrologic systems—An assemblage of geologic, climatic, ecologic, and socioeconomic factors that influence the flow of water through a given area, and how that water is used as a natural resource.

Limestone—A sedimentary rock composed of calcium carbonate minerals. On tropical Pacific islands, most limestone is precipitated by coral-reef organisms as the minerals aragonite and magnesium calcite. Over time, chemical reactions convert the minerals to calcite and dolomite and cement the individual particles into a solid framework.

Midpoint—In a freshwater-lens system, the midpoint is the depth in the aquifer, usually given relative to "mean sea level," where the water is an equal mix of freshwater and seawater.

Perched systems—Perched systems include a saturated body of high-level ground water separated from an underlying freshwater-lens system by a zone of unsaturated rock. Perched systems typically occur where low-permeability rocks significantly impede the downward movement of freshwater.

Perennial—A stream, river, or other surface-water body that flows continuously over time. On tropical Pacific islands, the water in perennial streams is sustained by the discharge of ground water from springs and seeps.

Permeability—A measure of the ability of a material to transmit a fluid; it is a measure of the relative ease of fluid flow under pressure. For a rock or aquifer that is transmitting water, permeability is usually expressed as hydraulic conductivity.

Pleistocene Epoch—The unit of geologic time preceding the Holocene Epoch. It began about 1.8 million years ago and was characterized by repeated cycles of continental glaciation and warm periods similar to the Earth's current climate. At times during the Pleistocene, sea level was lowered by more than 300 feet as a result of the volume of water frozen as glacial ice.

Porosity—A measure of the void (empty) spaces in a material, usually expressed as a fraction (between 0 and 1) or as a percentage. "Effective porosity" refers to the fraction of the total volume in which fluid flow can effectively take place. Effective porosity excludes dead-end pores or unconnected cavities and is a more useful term in discussing the flow of water through an aquifer.

Potable—Water that is safe to drink. Water can be made nonpotable by excess salinity, the presence of pathogens, or contamination from pollutants.

Rain-catchment system—A mechanical system used to collect and store rainwater for future use. Rain-catchment systems can range from a simple barrel that collects runoff from a roof to large paved areas (such as an airport runway) designed to drain into a collection trench that is connected to a water-treatment plant.

Recharge—The movement of water from the land surface, past the zone where it can be taken up by plants, to an underlying aquifer. Also refers to the rate at which new water reaches an aquifer.

Saltwater intrusion—The landward and upward movement of saltwater in a freshwater-lens system, typically caused by overpumping of ground water or reduced recharge. The amount of water drawn from freshwater-lens systems needs to be carefully managed to prevent degradation of the quality of the pumped water by saltwater intrusion.

Saturated zone—The zone below the water table, in which the voids and interstices are filled with water (ground water) under pressure greater than that of the atmosphere. Also known as the "phreatic zone."

Sea level—Sea level, or more precisely "mean sea level," is the average or the mean level of the ocean's surface halfway between high and low tide as measured at a given place over a 19-year period. It is used as the reference elevation for geographic and hydrologic features and sea depths. Sea level varies over geologic time periods (millennia) as a result of climatic cycles such as ice ages.

Sedimentary deposits—Rock and (or) unconsolidated material derived from the mechanically formed fragments of older rocks (for example, sandstone and sand) or by chemical or organic processes (for example, limestone deposits formed by the precipitation of calcium carbonate minerals by coral-reef organisms).

Transition zone—The zone of mixing in a freshwater-lens system, where the salinity ranges from nearly fresh in the upper part of the zone to a salinity close to seawater in the bottom part of the zone.

Unsaturated zone—The zone between the land surface and the water table. Water in the unsaturated zone has a pressure less than atmospheric pressure. Also known as the "vadose zone."

Vertically extensive freshwater-lens system—A ground-water-flow system that is saturated with freshwater from below sea level to elevations hundreds or more feet above sea level. Vertically extensive freshwater-lens systems are found in areas with low regional hydraulic conductivity.

Volcanic ash—Finely pulverized rock, mineral, and volcanic-glass fragments that are ejected from a volcano into the air. These fragments often settle in a layer over a wide area that may be subsequently covered by lava flows or other material. Over time, weathering processes can cause buried ash layers to have a low hydraulic conductivity. Such ash layers have been associated with perched ground-water bodies on tropical Pacific islands.

Volcanic dike—An intrusive sheet of volcanic rock that cuts across other rock layers. Volcanic dikes are more common near the center of a volcano and along "volcanic rift zones." Because of their orientation and low permeability, steep or vertical volcanic dikes can block or slow the flow of ground water and result in the development of significant bodies of fresh water at elevations high above sea level.

Volcanic rock—Rock formed by volcanic processes. On tropical Pacific islands, basalt is the most common type of volcanic rock.

Water table—The level in an aquifer at which the water pressure is equal to the atmospheric pressure. Geologic materials above the water table are considered "unsaturated" by water, whereas materials below the water table are "saturated" by water.

Well—A constructed hole in the ground from which water is withdrawn. Wells can range from shallow open pits dug with simple tools to deep holes lined with metal casings that are constructed with a powerful drill rig. Similarly, the pumps used to withdraw water from wells can range from simple hand-operated devices to complex designs that deliver large volumes of water from significant depths. On some tropical Pacific islands, horizontal trenches that penetrate just below the water table have been used to skim the freshest water from the top of a freshwater-lens system. On the Hawaiian island of Maui (and elsewhere), wells are large tunnels, excavated from the land surface to the water table, that obtain water from horizontal "galleries."

Well loss—The difference between the water level inside a well used for pumping water and the water level in the aquifer immediately adjacent to the well. Well loss is caused by turbulence as water flows to the well and is used by engineers as one measure of a well's efficiency in pumping.

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Tribble—Ground Water on Tropical Pacific Islands—Understanding a Vital Resource—Circular 1312

ISBN 978-1-4113-1859-5

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