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Loss of Reservoir Capacity through Sedimentation in Hawai‘i: Management Implications for the Twenty-First Century¹

Kim Falinski^{2,3,5} and David Penn⁴

Abstract: Hawai‘i’s reservoirs face increasing scrutiny due to heightened dam safety and flood control concerns, growing water demands, and uncertain water pollution effects. To promote long-term reservoir sustainability, it is vital that we improve our understanding of reservoir capacity. Because many of Hawai‘i’s reservoirs are privately owned and unmonitored, the state of Hawai‘i lacks data on actual reservoir capacity. To conduct a statewide survey of reservoir capacity, we (1) collected, organized, and analyzed existing physical data characterizing reservoir capacity in the five main Hawaiian Islands; (2) interviewed reservoir managers throughout the state to assess current knowledge of reservoir capacity and its loss due to sedimentation; and (3) analyzed images to estimate available capacity and sedimentation. Results show that sedimentation is a serious concern for managers and is rarely measured and poorly documented. Approximately 79% of the total capacity of Hawai‘i’s reservoirs are currently in use, and 40% of reservoirs (representing 24% of total capacity) are affected by sedimentation. Of these reservoirs, 60% are less than 1.23 million m³ (1,000 ac-ft) in size. Lack of maintenance for sediment is especially common in privately owned reservoirs. In the face of changing land use, reservoirs could be adapted for more appropriate uses in Hawai‘i, including flood control, hydropower, and recreation. Reservoir maintenance, including assessment and removal of sediments, is a critical consideration for proper stewardship of Hawai‘i’s abundant water resources.

Keywords: reservoirs, sedimentation, water supply, dams, reservoir management

WORLDWIDE, sedimentation is a leading cause of reduced capacity in small reservoirs (Wang and Hu 2009, Morris 2014). Global

water use is rising with population and development, but long-term water availability in small island states is declining due to changes in rainfall and sea level rise, posing challenges for resource managers. Water needs and constraints in Hawai‘i follow this pattern (Water Resources Associates 2003, Bassiouni and Oki 2013). Similar to other islands in the Pacific, the Hawaiian Islands face a rapidly growing population, increasing development, and a diversified agricultural sector, under a changing climate. Hawaiian resource planners and managers must carefully consider how to meet growing water demand while balancing human welfare, economic impact, and ecological sustainability. Reduced reservoir storage capacity has real economic costs, including less available water, higher maintenance costs (i.e., dredging), greater risk of dam breach, less capacity to reduce flooding and capture sediments, and lower potential for electricity generation (Hawai‘i Department

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of Agriculture 2010, Randle et al. 2013, Podolak and Doyle 2015).

In addition to providing water storage capacity, small reservoirs are also effective sediment retention basins that positively impact downstream nutrient and suspended sediment concentrations (Liu et al. 2014, Juracek 2015). Small reservoirs potentially increase water availability and reduce the peak flow of storm runoff (Deitch et al. 2013). Aquatic ecosystems can benefit from small dams that reduce the amount of sediment and nutrients carried in surface runoff (Verstraeten and Prosser 2008). The ability to retain sediment is especially important for Hawai'i, where very small watersheds (often <20 km²) are directly connected to coastal waters that are highly valued for their coral reef systems and recreational use. Excess sedimentation from anthropogenic disturbances is considered to be the primary driver of coral ecosystem decline in Hawai'i (Jokiel et al. 2014).

Reservoir sedimentation data are used widely to better understand the relative contribution of watershed characteristics to sediment and nutrient export (Verstraeten et al. 2003). Modeling approaches that calculate annual sediment yield based on land use, such as InVEST (Tallis and Polasky 2009) and N-SPECT (2004), are limited by a lack of spatially distributed sediment data for calibration. For Pacific high islands such as Hawai'i and Guam, the particular watershed physical characteristics, land use, and management actions that determine sediment export remain difficult to quantify (Nakama 1992, Hoover and Mackenzie 2009, Storlazzi et al. 2009). Watershed-scale sedimentation rates would provide data to calibrate and validate sediment export in lumped hydrologic models, because reservoir sediment accumulation integrates physical and human processes over longer periods of time than most in-situ sampling efforts can achieve. Reservoir sedimentation rates also include the effect of extreme events that may not be adequately sampled or not directly sampled at all.

Regardless of whether reservoir sedimentation data are used to infer changes in water storage capacity or to better understand watershed processes that contribute to sediment export, measures of reservoir sedimentation

processes are critical to surface water management (Angulo et al. 2011, Ignatius and Jones 2014). The National Subcommittee on Reservoir Sedimentation, in conjunction with the U.S. Geological Survey (USGS) and the Army Corps of Engineers, maintains nationwide information about reservoir sedimentation. However, the database currently does not contain any records for Hawai'i reservoirs, and we found no previously published data quantifying reservoir sedimentation in Hawai'i. Hindering previous efforts is the fact that 70% of reservoirs are privately owned and are not monitored regularly by county, state, or federal agencies. There are few publicly available management records. Monitoring efforts vary greatly across agencies and owners, leading to the overall lack of information about the current state of Hawai'i's reservoirs.

The objectives of this study were therefore: (1) to document reservoir type, capacity, and management issues that affect reservoir capacity and effectiveness; (2) to conduct semistructured interviews with reservoir managers and owners to augment and explain archival information and available reservoir records; and (3) to estimate the impact of sedimentation on the total capacity of Hawai'i's reservoirs.

MATERIALS AND METHODS

Study Site and Background

The five main Hawaiian Islands, located in the north central Pacific Ocean, have a total land area of about 16,000 km² (U.S. Geological Survey 1981). The formation of the volcanic islands created high, steep, rain-catching ridges and dikes that confine freshwater in basal and high-level aquifers. The Islands have few natural freshwater lakes and 376 perennial streams. Nearly all water for domestic and industrial use is obtained from groundwater supplies (Tribble 2008). Flashy streams in short watersheds prevent stream sediment deposition in floodplains. Streams supply more than 50% of irrigation water in Hawai'i, which is often stored in reservoirs (Oki 2003).

The sugar industry was a major driver of Hawai'i's economy from the mid-1800s until

the mid-1900s. The first successful sugarcane plantation began on Kaua'i in 1835. As the forests were cut down to create more land for sugar, records indicate that the amount of rainfall decreased as well (MacLennan 2007). Ambitious irrigation ditch systems were created to bring water from higher elevations to the plantations, and reservoirs were used to store that water. The major irrigation systems include the Pioneer Mill irrigation system in West Maui, the Waimea irrigation system on Hawai'i Island, the Waiāhole Ditch system on O'ahu, and the East Kaua'i irrigation system on Kaua'i (Wilcox 1996). The sugar industry began to falter in the 1930s and continued to decline into the 1940s and 1950s, when pineapple rose in prominence as a cash crop. Pineapple was farmed commercially in the Islands until the late 1990s to early 2000s, when industrial farms stopped production. Land use changes (urbanization) in the last century led to decreases in overall water demand but increases in potable water demand. Climate change impacts may create conditions that become drier in some areas, and wetter in others, which could change vegetation patterns. Similarly, climate change is expected to increase the frequency and intensity of large storm events, leading to more erosion into reservoirs and increased reservoir sedimentation storage (Timm and Diaz 2009).

The Department of Land and Natural Resources (DLNR) regulates the 140 reservoirs in Hawai'i that are greater than 60,000 m³ (50 ac-ft) in size. In addition, there are an estimated 500 smaller reservoirs that fall below the regulatory limit (J. Dawley, DLNR Dam Safety, pers. comm.). Agriculture in many parts of the Islands depends on a steady irrigation supply, yet Hawai'i's 140 largest reservoirs that store water for irrigation are currently being breached and decommissioned at a rapid rate. This is due to a variety of factors, including tighter dam safety regulations that took effect following the 2006 Kaloko (Ka Loko) dam break; the risk of structural instability due to age, construction deficiencies, and deferred maintenance; the loss of storage and operational capacity caused by sedimentation, debris accumulation, and clogging of inlet and outlet structures; and the lack of paying customers for reservoir-based

water service (Chow et al. 2008). Combined, these factors translate into an increased risk of liability for reservoir owners. Figure 1 shows the location, size, and use type for DLNR-regulated reservoirs in Hawai'i. Reservoir water use in Hawai'i was valued at \$436 million by the U.S. Department of Agriculture in 2003. The Hawai'i Dam Safety Act, which specified that the landowner was responsible for the maintenance of reservoirs on their land, was passed by the state legislature in 1987. On 16 March 2006, the Kaloko Reservoir in northeastern Kaua'i broke during heavy rains, killing seven people (Godbey 2007). The Dam Safety Act was updated in 2007 to enable the DLNR to more closely supervise the safety of the remaining reservoirs (Hawai'i State Legislature 2007).

We combined archival data with interview data to best understand the state of Hawai'i's reservoirs. Specifically, we collected, organized, and analyzed existing physical data characterizing reservoir capacity in the five main Hawaiian Islands; assessed stakeholder knowledge of reservoir capacity and its loss due to sedimentation through interviews with reservoir managers; and analyzed orthoimages to estimate capacity and sedimentation as of 2013. To house this information, we created a database in Microsoft Access that mimics the structure of the national Reservoir Sedimentation Database (RESSED) for data input. (A geospatial version of the database is available at <https://doi.org/10.5281/zenodo.893100>). We combined and cross-checked the data from both the National Inventory of Dams and Hawai'i Dam Safety Program (HDSP) databases with the RESSED fields. We expanded the database by adding data fields that are not part of the official RESSED structure, yet allow for more detailed analysis of the data set, including operational water level, excavation history, and level of sedimentation.

Government Records

We obtained permission from the U.S. Army Corps of Engineers to access the National Inventory of Dams (NID) via its secure online portal. At an initial meeting with the staff of the HDSP, we obtained similar permission to

FIGURE 1. Reservoirs classified by use type. The total number of reservoirs in the Hawai'i Dam Safety database (as of March 2013) is listed next to the island name. The size of the squares is proportional to the normal storage. Some reservoirs have since been decommisioned. (GIS data made available from the state of Hawai'i Office of Planning, the Coastal Geology group at the University of Hawai'i at Manoa, and the Department of Land and Natural Resource Dam Safety Program.)

access the HDSP inventory. The NID and HDSP contain the size, capacity, spillway characteristics, year built, and ownership of most of the 140 regulated reservoirs in Hawai'i. Ownership spans five categories: federal, state, local, private-agriculture, and private-development (defined as private owners who manage three reservoirs or less by a single private owner). The NID specifies small reservoirs as less than 1,000 ac-ft (1,233,481 m³) and greater than 50 ac-ft (61,674 m³); intermediate reservoirs are between 1,000 ac-ft (1,233,481 m³) and 50,000 ac-ft (61,674,092 m³); and large reservoirs are greater than 50,000 ac-ft (61,674,092 m³). Academic literature generally considers small reservoirs to be less than 100,000 m³.

With the federal and state inventories as the foundation, we conducted literature searches and gathered references that documented reservoir-specific physical characteristics (e.g., geotechnical investigations, dam safety inspections, emergency action plans, and environmental assessments). We collected the HDSP reports to the legislature from 2007 to 2015 describing changes in the dam status (see also Dam and Reservoir Safety Program 2011) and private reports on se-

lected reservoirs, obtained with the permission of reservoir owners and the cooperation of reservoir managers.

Reservoir Owner and Manager Interviews

We contacted the 42 dam owners and operators covering the 140 reservoirs in the HDSP inventory; 22 were interviewed between 2013 and 2014. Interviews followed a semistructured interview survey instrument. The survey instrument used in the follow-up phone and on-site interviews is presented in Table 1. The survey was designed to locate and acquire existing information and to provide a semi-structured opportunity for reservoir managers to describe possible problems related to sediment accretion and mitigation efforts. After the interview was conducted, we summarized open-ended responses into themes (Wengraf 2001). Interviewees are not identified by name in this report, and information provided about specific reservoirs was acquired through public records.

Between April and August 2013 we visited publicly and privately owned reservoirs on the islands of O'ahu, Maui, and Hawai'i and gathered other information through e-mail

TABLE 1
Survey Instrument for Hawai'i's Regulated Reservoir Owners and Managers

	Question	Answer Format
1	When was the last time your reservoir(s) was (have been) surveyed/measured?	Year
2	Original plans available?	Yes/No
3	As-built drawings available?	Yes/No
4	How many times has it been surveyed?	Number
4a	Who did the survey?	Name
4b	What method?	Acoustic, bathymetric, sediment sampling
4c	How much did it cost?	Number
5	Why did you do it?	Open
6	What will you do with the results?	Open
7	Are you willing to share those results with us?	Yes/No
8	What is your level of interest in conducting new surveys/measurements to find out how much the reservoir has filled in with sediment? (1–5)	Scale: 1 (Low)–5 (High)
9	Is sedimentation a significant issue in the reservoirs you manage?	Open
10	What mitigation efforts have you used to prevent additional sediment buildup?	Open
11	What are your incentives for continuing to use/maintain the reservoir?	Open
12	Would you like to continue to talk with us and help us gather more information on reservoir sedimentation in Hawai'i?	Yes/No

and phone calls. The primary purpose of the site visits was to visually survey and assess the extent of reservoir sedimentation in comparison with available imagery and to gather otherwise unavailable copies of documents describing sedimentation. Through extensive collaboration with the Hawai'i Department of Agriculture, Agricultural Reserves Management Division (ARMD), we obtained particularly significant information about five reservoirs.

Remote Sensing Photo Interpretation

We accessed remote sensing products, including World View 2 (2.4 m resolution), to determine whether a reservoir was being maintained dry or not dry and to estimate relative severity of sedimentation in each reservoir. High-resolution imagery was collected by Digital Globe World View 2 satellites in late 2010 or 2011 by the U.S. Department of Agriculture–National Resource Conservation Service–National Geospatial Center of Excellence to obtain orthophotos of the reservoirs. The images were analyzed in natural color. The photos were compared to and supplemented with Google Earth imagery obtained from Quickbird and Ikonos multispectral satellites between 2013 and 2014. In addition, because this exercise was conducted after the interviews, the information provided during the interviews was corroborated with the data obtained from the imagery.

For each reservoir, we made two qualitative classifications. First, we categorized the operating level of the reservoir using a combination of visual inspection and information from the database. The categories used in this analysis were Dry, Intermittently Wet, <50% Full, Managed to Capacity, and Partially Breached. When calculating the total capacity currently in use, we set Managed to Capacity reservoirs at 100% of the normal storage, the <50% Full would be carrying 50% of normal storage, the Intermittently Wet would carry 20% of the normal storage, and Dry and Partially Breached reservoirs would not have a contributing volume.

Next, we visually inspected the images for evidence of sedimentation, including bars,

buildup of sediment at the inlet or outlet, channelization, and dead zones. We categorized the level of sedimentation in each reservoir as “Significant,” “Moderate,” or “Minimal.” Dams assigned a “Significant” designation showed clear signs of sediment buildup that was impacting the surface area of the reservoir; “Moderate” was assigned when signs of sediment buildup were visible but did not substantially impact the surface area of the reservoir; and “Minimal” was used if it was clear that the reservoir was lacking evidence of sedimentation buildup in the image. In cases when the level of sediment was not clear due to geomorphology or vegetation cover, the reservoir sedimentation status was categorized as “Unknown.” Reservoirs that were considered “Dry” were given a sedimentation designation of “Unknown.” When possible, the sedimentation categories were compared with the reports, documentation, site visits, and interview details collected to estimate if the visual observations were correct.

RESULTS

The database collected is provided in a geodatabase available in the Appendix [<https://doi.org/10.5281/zenodo.893100>]. Although there were 140 regulated reservoirs in the state of Hawai'i, only one was documented sufficiently to populate the record fields required by the national RESSED database: Kāne'ohe Reservoir, O'ahu (see Wong 2001). Seven reservoirs that were local or state owned had partial information that could be provided to the RESSED database, including Nu'uuanu Dam and Kalihiwai Reservoir (Aqua Technex 2009), which have bathymetric surveys. Of the 23 regulated dams removed statewide since the program began, most of the dams were decommissioned after the 2006 Kaloko Dam disaster and the 2007 regulatory response (11 on O'ahu, three on Maui, five on Hawai'i, and four on Kaua'i) (see Table 2). An additional two reservoirs have been proposed to be removed.

We identified recent engineering studies for 34 reservoirs that were conducted for dam safety compliance purposes, many involving

dam breach, removal, or reengineering to reduce the size below regulatory limits. Our research indicated that each reservoir has a unique history of maintenance, sediment buildup, and water use. Acquiring sedimentation data for specific reservoirs required a detailed, recorded history of how each was managed and operated in the past. Evidence was mostly anecdotal, and the documents available typically did not include formal sedimentation surveys. The most complete data sets are associated with public works reservoirs and reservoirs owned by large corporations. During this investigation, we found that many irrigation systems are spatially disconnected from the watersheds that provide the system water; instead of a single watershed providing its own irrigation water, watersheds on the wet, windward sides of the islands are used to provide water transported in ditches to drier, leeward areas where the water is used. The water source was often many kilometers away from the irrigated areas, usually with multiple surface-water inputs along the way.

Data Analysis of Reservoirs in Hawai'i

DESIGN RESERVOIR CAPACITY. Hawai'i's reservoirs have the capacity to store 44.7 million cubic meters of water at normal levels, with the majority of the capacity (43%) located on Kaua'i (Table 2, Figure 2). Statewide, most reservoirs are used for irrigation purposes (80%), as seen in Table 2, and only 10 reservoirs are purposed for municipal water supply. Normal storage is defined as the total storage space in a reservoir below the normal retention level, including dead and inactive storage and excluding any flood control or surcharge storage. For normally dry flood control and sediment retention dams, the normal storage was a zero value (U.S. Army Corps of Engineers 2009).

Twenty-six out of 140 dams were identified as having multiple uses. In these cases, we selected the primary use type for analysis. Some calculations were difficult, especially when reservoirs were listed with multiple uses (in 26 out of 140 dams). An example was Alexander Reservoir on Kaua'i, used for both

hydroelectric power generation and irrigation. Multiple uses of reservoir water allow for multiple benefits to the hydrologic systems. Only Kualapu'u Reservoir on Moloka'i is used for both irrigation and drinking water supply, and its normal operating level is kept near to capacity. In general, we found that the reservoirs were managed only at levels near to capacity when they were used for drinking water supply (80% of maximum) or for fish and wildlife ponds (97% of maximum) (Table 3). The operating level for irrigation reservoirs, which represent 80% of all reservoir use, averages at 67% capacity. There is only one hydroelectric dam that is currently regulated in Hawai'i.

Compared to other worldwide locations where significant information for watershed sedimentation processes is collected from sediment deposition rates, 80% of the reservoirs used for irrigation in Hawai'i often have water delivered far from the stream, and often only a portion of the stream is used to supply the reservoir. These "off-stream," and sometimes off-ditch, reservoirs do not offer enough information about the watershed source and volume of surface water supplied to be able to discern larger watershed processes. However, they are still relevant to understanding the loss of capacity due to sedimentation.

Although 64% of the reservoirs are considered small in size, 74% of the capacity is provided by intermediate-sized reservoirs ($n = 49$). Hawai'i is lacking in reservoirs that are large by mainland standards and has only three reservoirs (Alexander and Pu'u Lua on Kaua'i and Kualapu'u on Moloka'i) that are classified as Large. Of these, Alexander is the only hydroelectric dam.

The majority (70% by number) of reservoirs are owned wholly or in part by private owners, including large farms (56%) and a diverse array of other owners, including small farms, housing developments, and recreation and tourism facilities (14%) (Figure 2). Notably, a large percentage (89%) of all reservoirs in Hawai'i are classified as having a High or Proposed High hazard status.

AGEING INFRASTRUCTURE. Many of Hawai'i's reservoirs are approaching 100 yr old. The rate of reservoir building slowed

TABLE 2

Characteristics of Hawaiian Reservoirs by Island (Unless Otherwise Noted, the Number Represents the Number of Reservoirs in That Category as of 2013)

Parameter	Hawai'i	Kaua'i	Maui	Moloka'i	O'ahu	Total
Storage						
Normal storage (thousand m ³) ^a	1,532	19,184	5,362	5,261	13,325	44,665
Maximum storage (thousand m ³) ^b	3,681	33,872	8,349	6,269	25,655	77,825
Percentage of maximum	42%	57%	64%	84%	52%	57%
Decommissioned	5	4	3	0	11	23
Size ^c						
Small	7	34	43	0	5	89
Intermediate	4	18	14	0	12	48
Large	0	2		1	0	3
Small (thousand m ³)	933	5,192	3,660	0	260	10,046
Intermediate (thousand m ³)	599	11,632	1,701	5,261	13,065	32,259
Large (thousand m ³)	0	2,361	0	0	0	2,361
Management type						
Federal					1	1
Local government	3	3	12		3	21
State	5	11	2	1	1	20
Private-Agriculture	1	28	38		12	79
Private-Development	2	12	5			19
Primary use						
Debris control, flood control			4			4
Debris control, flood control, other			1			1
Fish and wildlife pond, irrigation, other		1				1
Fish and wildlife pond, other		1				1
Fish and wildlife pond, recreation, other		1				1
Flood control	1		2			3
Flood control, recreation		1			2	3
Hydroelectric, irrigation		1				1
Irrigation	6	37	44		11	98
Irrigation, other		7			1	8
Irrigation, recreation		3				3
Irrigation, water supply				1		1
Other	1	2			3	6
Water supply	3		6			9
Hazard status ^d						
High	6	24	35	1	10	76
Low		4	1			5
Proposed high	2	23	15		7	47
Proposed low	1	2	1			4
Proposed significant	1	1				2
Significant			1			1
Undetermined	1		4			3
Number of reservoirs as of 2013	11	54	57	1	17	140

^a The total storage space in a reservoir below the normal retention level, including dead and inactive storage and excluding any flood control or surcharge storage. For normally dry flood control dams, the normal storage will be a zero value. If unknown, the value is blank and not zero.

^b The total storage space in a reservoir below the maximum attainable water surface elevation, including any surcharge storage.

^c Small reservoirs are defined as less than 1,000 ac-ft (1,233,481 m³) and greater than 50 ac-ft (61,674 m³); Intermediate reservoirs are between 1,000 ac-ft (1,233,481 m³) and 50,000 ac-ft, (61,674,092 m³); and Large reservoirs are greater than 50,000 ac-ft (61,674,092 m³).

^d Status indicates the potential hazard to the downstream area resulting from failure or mis-operation of the dam or facilities. High status reflects possible loss to human life, Significant reflects possible economic or environmental loss, and Low hazards are losses primarily to the owner's property.

FIGURE 2. Storage capacity of Hawai‘i’s reservoirs by management type.

TABLE 3
Data for Reservoir Use Types across the Hawaiian Islands

Reservoir Type	Storage (thousand m ³)	Maximum Storage (thousand m ³)	Number of Reservoirs	% of Total	% Capacity	High Hazard Status (%) ^a
Debris control	191	773	5	4	25	100
Flood control	1,298	13,791	11	8	9	91
Fish and wildlife pond	1,771	1,826	3	2	97	67
Recreation	2,456	12,184	7	5	20	100
Hydroelectric	1,320	3,133	1	1	42	100
Irrigation	38,957	58,164	112	80	67	88
Water supply	6,297	7,876	10	7	80	80
Other	4,188	5,653	17	12	74	82

^a Hazard classification refers to the design capacity of the dam spillway relative to the probable maximum inflow flood.

considerably after 1920, and no new reservoirs were built immediately before or after World War II (1935–1951) or between 1958 and 1965. Figure 3 presents the cumulative

age of reservoirs for the four counties of Hawai‘i. With the exception of Kualapu‘u on Moloka‘i, finished in 1969, the engineering design size of the reservoirs also declined

FIGURE 3. Age distribution of reservoirs by county for the state of Hawai'i. Note that nearly 60% of the reservoirs were completed by 1920. The most recent dams have been constructed for flood prevention and sediment retention.

over time, by about 4,800 m³ per year, on average. Kualapu'u, as a large reservoir, was created during the water engineering boom post-1950 that was seen nationwide (Gleick 2000). The results are more striking if you consider the many reservoirs that were built and decommissioned from use before the Hawai'i Dam Safety Program was established in 1987, known today only through archival and historical records (see Humbert 1951, MacLennan 2014). Some of these accounts emerged from conversations with reservoir managers.

AVAILABLE DOCUMENTATION. Few of the 140 reservoirs had enough information to quantitatively estimate capacity loss due to sedimentation. As part of the new dam safety regulations, many reservoirs commissioned engineering studies, but in most cases these

studies did not include bathymetric information. Critical to assessing sedimentation rates is knowledge of inflow into and outflow from the reservoir over time, along with as-built drawings or area capacity curves. Many of the pre-1920 irrigation reservoirs did not have such documentation, or documentation was not available. We also discovered that county offices do not keep consistent records of how much flocculant is needed to remove sediment from drinking water, or how much sediment was excavated from these sediment retention basins. Larger agricultural owners kept records of ditch flow and of dates of excavation, but these records were not public. A small subset of reservoirs had enough information to approximate rates of sedimentation and buildup over time, including Kāne'ohe Reservoir (Wong 2001).

TABLE 4
Summary of Survey Responses by Owner Type

Parameter	Federal	State	Local Government	Private-Agriculture	Private-Development	Total
Number of owners	1	4	6	16	15	42
Number responded to survey	1	4	6	2	14	27
Concern with reservoir sedimentation (1–5)	5	4	5	5	3.4	

Current Status of Management and Maintenance of Reservoirs

We interviewed 27 reservoir owners and managers, for a response rate of 64% (Table 4). We first identified the person within each organization that was the most knowledgeable about the reservoir, including the owner, the property manager, the water manager, or a government representative who was managing the resource. Most respondents across different management groups were very interested in learning how to manage their reservoirs better for sediment, as shown by mean interest levels of above 3 for all management groups.

Interviews and field visits established that compliance with dam safety regulations, including maintenance of vegetation, repairing inlet and outlet structures, and coordinating efforts for engineering safety reviews, were primary concerns for reservoir managers during the last decade. However, sedimentation was a major concern for the maintenance of reservoirs when the reservoir was in compliance and being operated at capacity. In some cases, sediment buildup led to changes in reservoir use, and in others, sedimentation led to a loss in capacity or an increase in excavation costs.

MANAGEMENT AND REGULATORY COMPLIANCE. Hawai'i's private owners manage 70.8% of the total reservoir capacity, and 70% of the reservoirs, compared to a national average of 59%. The percentage of total reservoir capacity stored in privately managed reservoirs (71%) is similar to that of states in the southeastern United States, including

Alabama, Georgia, South Carolina, and North Carolina. Nationwide it is Alaska (90%) that has the largest percentage of privately owned reservoirs.

Private owners currently have less institutional support to maintain and manage their reservoirs and are less likely to document changes in capacity over time. As a result of the new regulations after the Kaloko Reservoir breach, many owners are shifting toward decommissioning their reservoirs. Historically, Private-Agriculture reservoirs were maintained through public-private partnerships, but lack of finances and demand combined with a more robust dam safety regulatory structure led to their disuse. Individuals, trusts, and smaller business associations that generally managed only one or two reservoirs (private/other) are facing greater struggles to understand and comply with the new dam safety regulations, and some have made substantial investments in engineering studies to substantiate their position with dam safety regulators (e.g., Kalihiwai homeowners and the County of Honolulu Board of Water Supply).

Notably, in this study we found that many former and current large agricultural landowners with multiple reservoirs employed a single point person to manage all the reservoirs. These managers made few written records available, but shared their institutional knowledge and expertise. Larger agriculture owners acknowledged sedimentation as a fact of life, actively used reservoirs as detention basins, and implemented schedules for dredging accumulated sediments. It appears that this group may be an important source of

formal records and represents some of the most useful sites for field surveys of sedimentation rates.

Reservoir owners and managers reported that there are at least 300–400 unregulated dams with no reporting requirements that would otherwise provide information to facilitate the achievement of watershed research objectives. It is not surprising that there is a trend toward taking a regulated reservoir and converting it to a smaller nonregulated reservoir. Increasingly, watershed management plans are suggesting that smaller dams (often smaller than the regulated limit), including gabion dams, be used as retention basins to mitigate sedimentation into coastal waters [e.g., the Ala Wai Watershed Management Plan (2013) and the Lānaʻi Community Plan (Lānaʻi Planning Commission 2014)]. The longevity of these structures and their ability to withstand flood events remains unclear.

The interviews and government document research revealed that many owners and operators are conducting or have conducted new investigations to support dam removal and compliance with newly revised dam safety regulations. These investigations (often by consulting companies) typically do not include measurement of reservoir bathymetry and determination of base elevation and changes in bed elevation over time, thereby neglecting possible capacity loss to sedimentation. Investigations primarily consist of structural analyses and presenting recommendations for maintaining the reservoir in a safe condition.

OPERATIONS AND MAINTENANCE. Many of the interviewees perceived that there is an ideal method for removing sediment from a reservoir. Current practice is to drain the reservoir, which may take several weeks, and then manually remove sediment using backhoes and other mechanical equipment. If the reservoir was not originally designed to allow access for these types of vehicles, then the sediment must be removed manually. This was done recently at Waikoloa Reservoir No. 2 on Hawaiʻi Island, used as water supply, which suffered earthquake damage in 2006. Private agricultural companies have the heavy

earth-moving and forming equipment available and can also divert water to allow the reservoir to be dredged. The dredge spoils can then be placed on land. If the landowner does not have a use for the excavated sediment, transport and disposal pose additional challenges. Material, including sediment-sorbed contaminants, may prevent disposal of the sediments to other properties or landfills.

All reservoirs in Hawaiʻi are earthen, with the exception of Waikamoi No. 2 on Maui. Earthen reservoirs are more likely to have problems with seepage and to have their banks contribute to erosion. Reservoirs that were not initially used for irrigation often do not have access points designed to allow equipment access for dredging. The earthen banks of many reservoirs were not designed to withstand heavy equipment, and thus are inaccessible to mechanized removal methods. Kahana Reservoir on Maui suffered severe sedimentation due to a landslide shortly after it was built but has not been able to be dredged because poor drainage limits heavy machinery.

Reservoirs that are operated and maintained for public water use consider sediment in their maintenance costs. For example, at the Waikoloa reservoirs, sediments are removed through flocculation processes (requiring flocculant additives), and the water is treated in sedimentation basins. The sediments must periodically be dredged and treated per Department of Health requirements.

Interviewees suggested that although the sugarcane plantations frequently dredged out small reservoirs to retain full capacity, large reservoirs were not usually dredged unless sediment and debris blocked the reservoir inlets. In most cases, sedimentation is not the only limitation to water capacity. Most of the aging reservoirs require the installation of new High Density Polyethylene (HDPE) style liners (or equivalent) to prevent seepage, as well as vegetation removal and structural improvements for earthen embankments that have degraded over time. Maintenance permits are most often requested to improve dilapidated spillways and pump systems and to remove vegetation.

Erosion of irrigation channels is a concern that is separate from normally modeled channel processes, yet participants acknowledged that the irrigation channels were also in a state of disrepair. Because many of the reservoirs are off-stream, they are often disconnected from watershed-scale hydrologic processes. The ditch system that once fed reservoirs today diverts water directly into streams, including Honokōwai and Wāhikuli Streams on Maui (Lau 2011) and streams in the Upper Kapa'a region on Kaua'i. Reservoirs connected to the often earthen irrigation ditch systems were reported to have excessive sedimentation (e.g., Wāhikuli Reservoir, Twin Reservoirs). The Lower Hāmākua Ditch on Hawai'i Island reported an approximate 0.3 m (1 ft) depth of sediment buildup when it was refurbished in 2004 after approximately 40 yr without maintenance. However, the reservoirs fed by the neighboring Upper Kohala Ditch were comparatively free from sediment buildup (e.g., Pu'u Pulehu and Pa'auilo). For the Maunawili Ditch system on O'ahu leading to Waimānalo Reservoir, interviews revealed that hired workers manually clean the ditches of silt and debris on a daily basis, and that the reservoir has comparatively minimal sedimentation buildup as a result. On other subtropical islands, many off-stream reservoirs are fed by irrigation ditches, and sedimentation is not a noteworthy issue (Morris 2010). Sedimentation in the reservoir is still evident, although minimal, from the degradation of the channel leading into the reservoir.

CHANGES IN RESERVOIR USE. The Private-Development managers are more likely to be using the reservoirs for development or other urban reservoir uses, including for aesthetic reasons. Unlike the private and agriculture owners, smaller private owners are less likely to have the resources to repair or excavate reservoirs.

Reservoirs (both regulated and nonregulated) are commonly used for fire mitigation, especially those that are managed by larger agricultural plantations. It is estimated that 0.5% of the total state land area burns each year (Hawai'i Wildfire Management Organization 2014), and fire is recognized as a major

threat to native species in remaining forest lands (Conry 2010). Interviewees, especially managers of agricultural lands that had gone fallow, from local and state agencies used reservoirs to combat human and natural forest fires, especially managers of lands with high carbon loads such as grasslands and leeward dry areas. Previously, plantation and ranch personnel served as fire wardens, but changing land use practices reduced the number of people willing and knowledgeable to serve in this role. In combination with the reduction of reservoirs operating at capacity, reduced capacity from sedimentation presents a threat.

Many reservoir managers ($n = 14$) reported that the use of their reservoirs changed over time. For some managers, reducing the size of the reservoir below the regulatory limit was a solution more amenable than creating a new reservoir or maintaining the old reservoir at regulatory size. Other managers maintain their reservoir in a dry state, yet keep the reservoir in the system for possible future use or until it can be breached (for example, Manuhonuhonu Reservoir, Kaua'i). Private-Development managers consider the reservoir that is now among homes and golf courses as an aesthetic asset, and the homeowners' association or builder adopts the responsibility of maintaining the reservoir and the safety documents (e.g., Kaua'i Lagoons, Kaua'i). These reservoirs are often still tagged for irrigation use, flood control, or other use in the database but are providing a new ecosystem service to residents within their viewshed.

Two reservoirs on O'ahu are notable for providing different uses than originally intended. Wahiawā Reservoir, otherwise known as Lake Wilson, is a state recreation area known for its bass fishing. It also provides the important function of flood mitigation of the Kaukonahua Stream leading to populated Hale'iwa. Although one of the largest reservoirs, no study has ascertained its current bathymetry, but it is assumed that sedimentation has reduced its capacity. Nu'uuanu Dam No. 4, also used for flood protection, is currently being dredged (R. M. Towill Corporation 2013). A bathymetric survey was com-

pleted in 2010, acknowledging that sediments had reduced capacity. Neither reservoir was originally designed for flood control. Similarly, the reservoirs built in West Maui in the 1980s for debris control (Honokōwai Structure No. 8, Māhinahina, Kahana, and more) today are being used to capture sediment, yet their design does not permit efficient trapping of sediments during larger storms.

Current Capacity of Hawai‘i’s Reservoirs

Nearly one in five (17%) of Hawai‘i’s reservoirs was seen to be dry as of 2013 (Figure 4). The estimated current volume in use is only

FIGURE 4. Percentage of reservoirs by observed capacity level. Estimates were derived from orthoimagery obtained between 2010 and 2014.

14.6% of the total available capacity (Table 5). These calculations neglect possible reduced capacity from sedimentation.

For sedimentation, analysis of orthoimages revealed that 26% ($n = 36$) of reservoirs showed “Significant” buildup of sediments, 14% ($n = 19$) showed “Moderate” sedimentation, 15% ($n = 21$) showed “Minimal” sedimentation, and 46% ($n = 64$) of reservoirs could not be determined. If rough estimates are made as to the capacity loss from “Minimal,” “Moderate,” and “Significant” sedimentation as 0%, 10%, and 20% of capacity, then the total capacity loss of the Hawai‘i reservoir system due to sedimentation is 5.4% (Table 5). Drinking water supply reservoirs were less likely to have sedimentation (five of nine reservoirs showed “Minimal” sedimentation), and flood control and debris reservoirs showed greater evidence of sediment buildup (Figure 5). Irrigation reservoirs showed the most sedimentation, with 37% showing “Moderate” or “Significant” sedimentation. Reservoirs managed by local government were less likely to have sedimentation (38% were “Minimal”) than Private-Agriculture (25% “Significant”) or Private-Development (38% “Significant”). It is interesting that Private-Development owners were less likely to be concerned about sedimentation (see Table 1), either because they were not interested in using the total capacity of their reservoirs or because they did not have the resources to maintain the reservoir at full capacity.

TABLE 5
Estimated Current Storage and Capacity of Hawai‘i’s Reservoirs (thousands m³)

Category	Total Design Normal Capacity	Multiplier to Reflect Capacity Being Used	Estimated Current Storage	Estimated Current Capacity with Sediment Loss	Total Current Storage
Managed to capacity	32,976	1	32,976	31,841	31,841
<50% full	4,640	0.5	2,320	4,008	2,004
Intermittently wet	510	0.2	102	445	89
Dry	3,514	0	0	3,495	0
Partially breached	3,024	0	0	2,473	0
Total	44,665		35,399	42,261	33,934

Note: Normal storage is the design operative volume of the reservoir.

FIGURE 5. (A) Reservoir sedimentation by reservoir use type, shown as a percentage of the total in that category. The number of reservoirs in each category is indicated by parentheses. (B) Sedimentation in reservoirs broken down by whether the reservoir was off-stream or on-stream.

DISCUSSION

Redeveloping agriculture in Hawai'i will require reliable access to water for irrigation, and projected increases in population will create a demand for reliable drinking water. Yet, the overall number of reservoirs in the state of Hawai'i is in a steady decline, and only 14.6% of reservoir capacity is currently in use. Irrigation reservoirs, which make up a majority of the reservoirs, have been decommissioned in the last 5 yr at a disproportionately high rate. Some of the reservoirs that were classified as "Dry" are in the process of being decommissioned.

Reservoir managers reported that sedimentation is not the highest concern (structural and dam safety concerns were most important), however 40% of reservoirs showed evidence of "Moderate" or "Significant" sedimentation. Total capacity loss due to sedimentation was estimated at 5.4%, which is lower than estimates made by Wong (2001) for Kāne'ohe Dam. Kāne'ohe Dam was built for flood control between 1977 and 1980 and is one of the few on-stream reservoirs. Wong used a time series of bathymetric studies (1983 to 1992) to calculate that the design value 2 ac-ft (2,500 m³) of sedimentation was the long-term rate. The cumulative effect (if extrapolated to 2015) would be 70 ac-ft (8,600 m³) out of a total capacity of 218.1 ac-ft (269,000 m³), or 32% of total capacity lost to sedimentation if no maintenance measures were taken. Waimea Reservoir is a state-managed 60MG (227,000 m³) off-stream reservoir used for irrigation built in 1957 (Fischer 2007). Using scuba and sonar, the inspection team found very little evidence of sedimentation. This reservoir was built with extensive riprap to reduce bank erosion, and there were no reports that it had ever been excavated. The lower overall estimate calculated here (5.4%) assumed that there was no sedimentation loss in the 64 reservoirs designated Unknown. Estimates of sedimentation from the orthoimages were also made to be conservative and could only capture sedimentation processes that visibly changed the surface area of the reservoir. Moreover, the database information analyzed here presents only

part of the story, because there are many smaller reservoirs that are not regulated that serve important water capacity, fire prevention, flood regulation, and sediment retention services.

No new reservoirs have been built since 2006, and a majority of the reservoirs built in the last three decades were built on Maui for a distinctly different purpose: to prevent debris from reaching the coral reef ecosystem offshore. Figure 3 represents only the ages of the reservoirs that are currently in the database; archival research indicates that many more reservoirs existed pre-1950 that were removed from use before the Dam Safety Program was created. Similar to the responses of managers of larger agricultural holdings today, sugarcane-era documents support the observation that reservoir building and maintenance occupied a substantial amount of workers' time (MacLennan 2014). Lacking this maintenance, sedimentation of reservoirs and degradation of irrigation ditches will continue to be a problem.

Funding is a critical issue for all aspects of reservoir sustainability. In 2014, Hawai'i voters approved a legislatively referred amendment to the state constitution that authorizes the state to issue special-purpose revenue bonds and use the proceeds from the bonds to offer loans to qualifying dam and reservoir owners to improve their facilities to protect public safety and provide benefits to the general public as important water resources (Hawai'i State Legislature 2014a). In addition, the state budget typically includes line items for generic reservoir safety improvements in state-owned irrigation systems and for specified capital improvements at particular public reservoirs.

The recent biennium budget (July 2013–June 2015) included \$9 million for land acquisition, design, and construction for state-wide reservoir safety improvements (deemed necessary to qualify for federal aid financing and/or reimbursement) and \$7 million for compliance-related improvements to three specific reservoirs (Hawai'i State Legislature 2014b). However, the legislature did not approve separate measures that proposed to spend an additional \$1.8 million for dam

rehabilitation and remediation at a different public reservoir (Hawai'i State Legislature 2014c), and to require that a state agency prepare all studies to determine the safe removal or retirement of a dam or reservoir upon the request of a homeowner association or homeowner of property where a dam or reservoir is situated (Hawai'i State Legislature 2014d).

Although the methods used in this study did not physically measure reservoir sedimentation, the approach allowed for a broad assessment of the status of reservoirs in the state. Like other studies in water resources engineering that used interviews combined with imagery to facilitate dialogue with managers and planners (Grady et al. 2013), the interdisciplinary techniques used here can help inform a rapid assessment of reservoir health. Future work that targets individual reservoirs to more clearly understand sedimentation rates in the different use categories defined would provide useful complements to this study.

CONCLUSION

The reservoirs of Hawai'i serve multiple purposes: they are essential for irrigation, provide a safety net for water supply, provide habitat for aquatic ecosystems, and perform roles for fire mitigation, flood, and sediment control. Many reservoirs act like sediment retention basins and reduce sediment transport to coastal waters, thereby preventing possible water quality problems. Our findings indicate that many reservoir managers consider sedimentation an operational concern, and that the current bathymetric data available do not allow for reliable estimates of watershed-scale sediment export. We estimate that 40% of reservoirs have Moderate or Significant sediment buildup, and 15% of reservoirs are currently dry. The decommissioning of 23 reservoirs between 2007 and 2015 indicates that dam safety regulations combined with the economics of changing land use is reducing the incentive to maintain reservoirs within regulated size limits. The State of Hawai'i may not have sufficient resources and interest to support the development and implementation of extensive reservoir sustainability mea-

sures. It remains to be seen how many more dams will be removed due to safety concerns and economic constraints. However, sediment deposition in reservoirs is an ongoing problem, and leaving issues unaddressed until problems become acute leads to costly, ineffective solutions.

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